

**A SELECTION OF
PUBLISHED PAPERS**

**VOL. III
(1991-1999)**

S. LEE

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(1991-1999)**

S. LEE



**NANYANG TECHNOLOGICAL UNIVERSITY
NATIONAL INSTITUTE OF EDUCATION**



A Selection of Published Papers

Vol. III
(1991-1999)

S. Lee

1. S. Lee
A sequential Plasma Focus
IEEE Trans. On Plasma Science. USA (1991) 19: 912-919
2. G. Cottrell, I.R. Jones, S. Lee and S. Xu
An Inexpensive Rotamak Device
Rev. Sci. Instr. USA (1991), 62: 1787-1792.
3. S. Lee, S.H. Saw, Abdelmagid A. Elfetouri, A.M. Shengher, E.O. Shummaki and N.A. Hassan
Magnetic Reynolds Number and Current Sheath Structure
J. Fiz. Mal, Malaysia (1991), 12: 25-29.
4. M.Favre, S. Lee, S.P. Moo and C.S. Wong
X-ray Emission in a Small Plasma Focus Operating with H₂-Ar Mixtures
Plasma Sources Science & Technology. UK (1992), 1: 122-125.
5. S. Lee
Bench-marking the 3 kJ Plasma Focus
Chinese Physics Letters. China (1993), 10: (Supplement-Invited Review Paper) 33-41.
6. S. Lee, Suresh Kumar, T.C.Chia, A. Serban and S.V.Springham
Pulse-charging of Capacitors for Reduction of Voltage Stress
Rev of Sci Instru. USA (1994), 65: 2408-2409.
7. S. Lee, *at al.*
Executive summary
The International Science Programmes of Uppsala University, An Evaluation Report, by Olle Eqvist, Berhanu Abegaz, Lee Sing, and Barry Noller (1994), 5-12
8. A. Serban and S. Lee
A Simple Optical Fibre Axial Speed Detector
Rev Sci Instru. USA (1995), 66: 4958-4960.
9. S. Lee
Research Transfer as an Educational Process- A Model and some Experience
J Moscow Physical Soc (Series B) "Physics in Higher Education" Russia (1995) 1:99-126.
10. X. Feng, S. Lee and S.Kumar
Effect of Three-Wave phase development on the Stimulated Raman Scattering in an Electron Plasma
Applied Phys B: Lasers and Optics. Germany (1996) B62: 309-311.
11. S. Lee & A. Serban
Dimensions & Lifetime of Plasma Focus Pinch. IEEE Trans Plasma Science
USA (1996) 1101-1105.
12. K.A.Toh, K.C.Yap, S. Lee, S.V.Springham and P.Chua
Developing Curriculum in Singapore: Teacher-Academic Partnerships
J Curriculum Studies. UK (1996) 28: 683-697

13. S. Lee, G.X. Zhang, V.A. Gribkov, X. Feng, A.V. Dubrovsky, P. Lee, A. Serban, S.V. Springham, M.H. Liu, C. Selvam, T.K.S. Wong and K. Wira
A Repetitive Compact Plasma Soft X-ray Source
Singapore J Phys. (1996). Singapore. 12: 69-76.
14. A. Serban and S. Lee
Neutron Time-of-Flight Measurements for Studies of Neutron Yield Enhancement in Plasma Focus
Singapore J Phys (1996). Singapore. 12: 53-67.
15. S. Lee
Pulsed Plasmas for Technology, Training and Cooperation
Invited Paper. International Symposium for Cooperation in Plasma Science and Technology, UNU, Tokyo, Japan, Sep 16-19 1996.
16. A. Serban and S. Lee
Soft X-ray Emission from a Small Plasma Focus Operated in Deuterium
Plasma Sources Science and Technology. USA (1997) 6: 78-85.
17. X. Feng and S. Lee
Electromagnetic Wave Pulse Amplification induced by the Reflection from Relativistic Plasma Fronts
Optics Communications (1997). USA. 136:385-389
18. X. Feng, M.H. Liu and S. Lee
A Transmission Grating Spectrograph and its Application in both Laser Plasma and Plasma Focus
Rev Sci Instru (1997.) USA. 68:1-6
19. Lee Sing and Chia Teck Chee
Microcomputer Simulated Experiments in the Teaching of Multi-Channel Laser Systems in an Undergraduate Course
J of Computers in Mathematics and Science Teaching (1997).USA. 16:25-36
20. P.Lee, X.Feng, G.X.Zhang, M.H. Liu and S.Lee
Electron Lithography using a Compact Plasma Focus
Plasma Sources, Science & Technology (1997). U.K. 6:343-348.
21. S. Lee, P. Lee, X. Feng, G.X. Zhang, A. Serban, M.H. Liu, T.K.S. Wong and C. Selvam
Compact Plasma Focus Soft X-ray Source with High Repetition Rate and High Intensity
SPIE (1997). USA. 3183: 112-122.
22. S.T. Tsai, S. Lee, J.L.Hu and Y.P.Chen
Time Averaged spontaneous Power Radiation in Plasma Focus
ACTA Physica Sinica (1997). China (Overseas Ed). 6:690-696.
23. Z.W. Huang, T.C. Chia, C.H. Diong, S. Lee, W. Zheng and S.S. Xie
In vitro laser light distribution in human lung tissues at 406.7nm using isotropic fibre-optic probe
Singapore J Phys (1997). Singapore.13:
24. P. Lee, T. Halim, C.H.J. Koh, M.H. Liu and S. Lee
Dynamics of Spark produced blast wave
Singapore J Phys. (1997) 13:29-38
25. S.Lee, et al.
(IAEA) Research Coordination Meeting, Vienna, Austria, 15-17 Dec 1997. Final Meeting Report of the CRP on "Development of Plasma Heating and Diagnostic Systems in Institutes in Developing Countries using Middle- and Small-Scale Plasma Devices" IAEA-HQ, Vienna, Austria, pg 24-31.

26. S. Lee, P. Lee, G X Zhang, V.A. Gribkov, X. Feng, M.H. Liu and A Serban
High Repetition High Performance Plasma Focus as a Radiation source
Invited Paper. International Symposium. Plasma '97. Research and Applications. Opole Jarnoltowek, Poland, 10-12 June 1997. Procs Vol 2. Invited Papers. 86-93.
27. Tan Jiayi Isabelle and Lee Sing
Pressure Measurement and Correct Yield of Powerful Soft X-ray Source
Third Youth Science Conference, 1997 Singapore, 16 Aug 1997. Procs. pg52-57.
28. S. Xu, Han-shi Li, Yin-an Li, S. Lee, C.H.A. Huan
On the structure and Composition of Polycrystalline Carbon Nitride Films Synthesized by Reactive RF Magnetron Sputtering
Chem. Phys. Lett (1998). Netherlands, 287: 731-736
29. Bogolyubov EP, Bochkov VD, Veretennikov VA, Vekhoreva LT, Gribkov VA, Dubrovskii AV, Ivanov Yu P, Isakov AI, Krokhin ON, Lee P, Lee S, Nikulin V Ya, Serban A, Silin PV, Feng X and Zhang GX
A Powerful Soft X-ray Source for X-ray Lithography Based on Plasma Focusing
Physica Scripta (1998). Sweden. 57:488-494.
30. M.H. Liu, X. Feng, S.V. Springham and S. Lee
Soft X-ray Measurement in a Small Plasma Focus Operated in Neon
IEEE Trans Plasma Sc. USA. (1998) 26(2):135-140.
31. P Lee, S Kumar, and S Lee
Simulations of Laser Produced Plasma Dynamics in an Ambient Gas
Laser and Particle Beams, USA.(1998).16(2): 317-325.
32. S. Lee, P. Lee, G. Zhang, X. Feng, V. Gribkov, M. Liu, A. Serban and T.K.S. Wong
High Rep Rate High Performance Plasma Focus as a Powerful Radiation Source
IEEE Trans Plasma Science. USA(1998) 26(4): 1119-1126
33. S. Lee, X. Feng, M Liu and G Zhang
A Crystal Spectrograph and its Application in Plasma Focus
J Fiz Mal. Malaysia.(1997) 18(1): 1-9
34. S. Lee, P. Lee, G. Zhang, A. Serban, M. Liu, V. Kudryashov¹, X. Feng, S.V. Springham, T.K.S. Wong, C. Selvam
Powerful Soft X-ray Sources and High Resolution Lithography
Singapore J Phys (1998) 14 (1): 1-10.
35. A. Serban and S. Lee
Experiments on Speed-Enhanced Neutron Yield
J Plasma Phys. (1998) USA. 60(1): 3-15
36. S Lee
Scaling of the Plasma Focus- Plasma Dynamics Viewpoint
Invited paper. International Workshop on Plasma Focus Research (PF '98), Kudowa, Poland, July 1998. To appear in Procs.
37. Y L Lam, P Lee, M H Liu, S Lee, RS Rawat, P Arun Videswar, A Huan
Argon Ion Induced changes on Antimony Telluride thin films using dense plasma focus device
International Congress on Plasma Phys, Prague, June 1998. To appear in Procs.
38. Guixin Zhang, Paul Lee, Xianping Feng, Mahe Liu and Sing Lee
High Repetitive Rate X-ray Pinhole Camera based on CCD and its Applications in Plasma X-ray Source
International Congress on Plasma Phys, Prague, June 1998. To appear in Procs.

39. M H Liu and S Lee
SXR Radiation Modelling for Neon Plasma Focus
 International Congress on Plasma Phys, Prague, June 1998. To appear in Procs.
40. S.C. Tam, W.P. Neo, H.C. Chua, A.T.S. Ho, S. Lee
A Novel Technique for Measuring the Pulsewidth of Nanosecond Laser Pulses
 IEEE Trans. Instru. And Meas., (1998), 47(4): 997-1000
41. Huang Zhiwei, Chia Teck Chee, Diong Choeng Hoong, Lee Sing, Zheng Wei, Chen Jinkai
The collisional energy transfer between the D^1P and d^3P states of the NaK dimer induced by argon buffer gas
 Appl. Phys. B (1998) 66: 471-474
42. A Serban and S Lee
The Effect of High Axial Sheath Velocity on Neutron Yield in Plasma Focus
 Fusion Technology. USA. (1999) 35:54-61.
43. Y.L. Lam, P. Lee, M.H. Liu, S. Lee, R.S. Rawat, P. Arun, A.G Vidheshwar and A.C.H. Huan
Argon ion induced changes on antimony telluride thin films using dense plasma focus device
 Accepted for Singapore J Physics. (1999)
44. S Lee
Twelve Years of UNU/ICTP PFF-A Review. Opening Chapter of the Review Book "Twelve Years of UNU/ICTP PFF-A Review" Ed S.Lee, S.P.Moo, C.S.Wong & A.C.Chew. International Centre for Theoretical Physics (Italy) Pre-print. Pp 4-33
45. S. Lee
Radiation Enhancement and Applications – Scaling from the UNU/ICTP PFF
 Invited Paper. International Meeting on Frontiers of Physics, Satellite Meeting: 12 Years of UNU/ICTP PFF-A Review, 30 Oct 1998, Kuala Lumpur. ICTP (Italy) Pre-print:34-46

LEE SING

- Present appointment** : Professor
Head of Division of Physics
School of Science
Nanyang Technological University
National Institute of Education
469, Bukit Timah Road
Singapore 259756
- Academic Qualifications** : BSc Hons University of Malaya 1964
MSc University of Malaya 1966
PhD Australian National University 1970
- Professional Qualifications** : Fellow, Institute of Physics (UK)
C. Physicist, Institute of Physics (UK)-since July 1983
Fellow (Life), Malaysian Institute of Physics-since 1972
Fellow, Malaysian Scientific Association-since 1989
Member (Life), Samahang Pisikang Pilipinas-since 1986
Member, Educational Research Association, (Singapore)-since 1993
Fellow, Singapore Institute of Physics-since 1993. Fellow (Life) since 1994
- Working Experience** : Feb 1964 - Jun 1964 Teacher, Bukit Bintang Girls' School, Malaysia
1964 - 1966 Tutor, Physics Dept, Universiti Malaya
Nov 1969 - Dec 1969 Research Assistant, Australian National University
1970 - 1975 Lecturer, Universiti Malaya
1975 - 1984 Associate Professor, Universiti Malaya
1975-1976 Visiting Research Scientist, Nuclear Research Centre, Juelich, Germany
1981-1982 Visiting Scientist, Imperial College of Science & Tech, London, UK
1984 - 02 Oct 1991 Professor of Applied Physics, Universiti Malaya; (Head, Physics Department December 1989- October 1991)
1986 - 1987 Visiting Professor & United Nations University Special Fellow, Flinders University of South Australia
04 Oct 1991 - 03 Oct 2000 Professor, Nanyang Technological University
01 Mar 1992 - 28 Feb 2000 Head/Division of Physics, Nanyang Technological University

Professional Activities

- President, Asian African Association for Plasma Training-since 1988 (re-elected Oct 1998-Sept 2002).
- Far East Representative for International Centre for Theoretical Physics (1988 -1996).
- Associate Director (Hon), AAAPT Research & Training Center, Institute of Physics, Chinese Academy of Sciences, Beijing (May 1995-1999)
- Member of International Working Group for the proposed International Centre for Dense Magnetised Plasmas-since 1989; Member of Steering Committee-since 1994
- Member, Council, Institute of Physics, Singapore-since 1993; Vice President (1999-2000)
- Member, Scientific Council of the Joint Plasma Focus Laboratory (Russia-Poland)-since 1993
- Member of Steering Committee of the Third World Plasma Research Network-since 1989.
- Coordinator for International Centre for Theoretical Physics-Affiliated Centre (ICAC-UM) (1988-1991).

Vice-President, Institute of Physics Malaysia (1980-1991). President (1982/83).

Vice President ASEAN Institute of Physics (1982-1991).

Director, United Nations University Training Programme on Plasma and Laser Technology (1985-1988); ICTP Programme (1985-1991). Supervised 8 UNU Fellows and 19 ICTP/TWAS/ICAC Fellows.

Chief Editor, Jurnal Fizik Malaysia (1981-1991). Hon. Advisory Editor (1991 - to-date).

Chairman/Co-Chairman First-Fourth Tropical College on Applied Physics (1983-1990).

Alexander von Humboldt Research Fellow (1975/76) KFA Juelich, West Germany;

Commonwealth Academic Staff Fellow (81-82) Imperial College London;

UNU Special Fellow, Flinders University South Australia (86/87).

Director, Spring College on Plasma Physics, ICTP Italy (1989-1993). Advisor (1994-1995)

Member, International Organising/Advisory Committee, International Conference on Plasma Physics (ICPP) at New Delhi, November (1989); Innsbruck, May (1992); Foz do Iguassu, Brazil, October (1994); Nagoya (Sep 1996)

Member, International Advisory Committee/ Invited Speaker of various International Symposia such as: Beijing Plasma Diagnostics College, Beijing, November (1989); (Member IOC) Second Regional Symposium on Optoelectronics, Jakarta, November (1989); (Member IOC)

SEALS II, Jogjakarta, January, (1991); (Member IOC)

Int. Symp. Laser-Plasma Interaction, Shanghai (1992); (Member IOC)

5th Asia Pacific Physics Conference, Awana, Malaysia, August (1992) (Co-chairman up to August 1991);

International Conference on Physics & Technology in the 1990's, Manila Dec (1992); (Member IOC)

Third International Conference on Dense Z-Pinches, Imperial College, London, April (1993); (Member IOC)

International Conference on Plasma Physics, Changsa City, China, May (1993); (Member IOC)

Second International Workshop on the Physics and Modern Applications of Lasers, Harare, Zimbabwe, September 1993 (Member IOC)

World Optical Congress '93, Shanghai, China, August (1993). (Member IOC)

International Conference on Plasma Science and Technology '94, Chengdu, China, June 1994 (Member IOC)

International Workshop on Laser Plasma Interaction 1995, Indore, India (Member IOC)

International Conference of Electromagnetic Compatibility 1995, Kuala Lumpur, Malaysia (Member IOC)

Defence Nuclear Agency 22nd IEEE International Conference on Plasma Science 1995, Madison, Wisconsin, USA (ex officio committee member)

1st Asia Pacific Plasma Theory Conference, Aug 96, Taejeon, Korea (Member IOC)

International Conference on Physics of Dusty Plasmas, October 1996, Goa, India (Member IOC)

XI PSSI Symposium on Plasma Science & Technology, 28-31 Oct 1966, Bhopal, India (Member IOC)

International Symposium on Cooperation of Plasma Science & Technology at United Nations University, Tokyo
Sept 16-18 1996. (Member IOC)

4th International Conf on Computational Physics, Singapore, 2-4 June 1997. (Member LAC)

International Symposium PLASMA '97. Opole-Jarnoltowek, Poland. June 9th-12th 1997.

Workshop on Thin Films and Plasma Applications, NUST, Zimbabwe, September 1997 (Invited Speaker)

1997 Asian Pacific Plasma Theory Conference, Toki Japan, September 1997 (Member IOC)

International Topical Conference on Plasma Physics: New Perspective of Collective Effects. ICTP Trieste. 10-14
November 1997.

IAEA Research Coordination Meeting on Plasma Heating and Diagnostics using small and Medium Fusion
Devices. IAEA. Vienna. 15-17 Dec 1997.

International Topical Conference on Non-ideal Plasmas, Goa, India, Mar 23-27 1998 (Member International
Advisory Board)

1998 International Congress on Plasma Physics combined with 25th European Physical Society Conference on
controlled Fusion and Plasma Physics, June 29-July 3 1998, Prague. (Member IAC)

1998 International Plasma Focus Workshop, Kudowa, Poland combined with ICDMP Steering Committee Meeting,
July 5-9, 1998 (Member International Program Comm and Invited Speaker)

International Meeting on Frontiers of Physics, Oct 25-29 1998, K.L., Malaysia (Member IOC & Invited Speaker)

Twelve years of UNU/ICTP PFF- A Review Meeting (Satellite Meeting of IMFP '98), Oct 25-30 1998, Kuala
Lumpur, Malaysia (Chairman of Organizing Committee)

External Examiner for Ph.D. theses:

Quaid-I-Azam University, Pakistan (1989, 1998; on PhD Review Panel);
Universiti Teknologi Malaysia, Malaysia; (1990, 1992)
University of Malaya, Malaysia; (1991, 1994)
Institut Teknologi Bandung, Indonesia; (1993)
University of Delhi, India (1993:1997)

Assessor for professorial appointment:

Arabian Gulf University;
Universiti Teknologi Malaysia

Reviewer for journals including Singapore J. Phys., J. Fiz. Mal., Pertanika, ICTP LAMP Reports (Italy), IEEE
Trans. on Plasma Science (USA), South African J of Science.

Consultant to various Companies including Baugh & Weedon (UK), Britex (Malaysia), Kris Stained Glass
(Malaysia)-occasional service.

Consultant to Swedish Agency for Research Cooperation (SAREC) to review and give recommendations for the
International Science Programmes of Upsala University (1992-1993)

Consultant/Reviewer (Hon) to Third World Academy of Sciences (Italy); to International Centre for Theoretical

Physics, Trieste, Italy, to International Science Foundation (USA) to review Research Grants

Member, Editorial Board, Journal of Moscow Physical Soc (Series B) "Physics in Higher Education" (since 1994)

Member, International Advisory Comm, Prince of Songkla University (Thailand) PhD Program. (since Oct 1994)

Representative of NSTB at the Inter-Government and Governmental Agencies Meeting on the International Centre for Dense Magnetised Plasmas in Prague, 9 Oct 1995.

Member, NSTB team on site visit to IBM New York and NTT Tokyo, May 1996.

Member, Protem Committee, Conference on Fundamental Science, Singapore, 1998-1999.

INIS (International Nuclear Information System) Liaison Officer for Singapore

Member, Programme Committee, IAEA/TCM RUSFD Committee (1998-)

Postgraduate Theses:

Ph D: S.Lee Transverse Ionizing Shock Waves in a Planar Electromagnetic Shock Tube. PhD thesis. ANU, Australia, 1970.

M.Sc: S.Lee Some Shock Wave Phenomena in a Ring Electrode System. MSc thesis. UM, Malaysia, 1966.

Postgraduate Theses supervised:

Ph D:

1. Y.H.Chen. Parametric Study of Focus Optimization. PhD thesis. UM, Malaysia, 1978
2. C.S.Wong. Experimental and Numerical Studies of a Laser-initiated Vacuum Spark. PhD thesis. UM, Malaysia, 1983. (Wong Chiow San is currently Full Professor at University of Malaya, Malaysia)
3. T.Y. Tou. Pinch Radius Ratio of the Plasma Focus. PhD thesis. UM, Malaysia, 1987. (Tou Teck Yong is currently Full Professor at Telecoms Multimedia University, Malaysia)
4. K.H.Kwek. Pinch Structure of a Plasma Focus. PhD thesis. UM, Malaysia. 1989.
5. Jalil bin Ali. Development and Studies of a Small Plasma Focus. PhD thesis. UTM, Malaysia, 1990.
6. S.H.Saw. Experimental Studies of a Current-stepped Pinch. PhD thesis. UM, Malaysia, 1990
7. A.C.Chew. Design and Development of a Small Tokamak. PhD thesis. UM, Malaysia, 1991
8. Susetyo Mulyodrono. Parameter Rancangan Tabung Kejut Elektromagnetik Koaksial Bubu Berkemampuan Memfokus Plasma (Kemungkinan Penerapannya Dalam Sistem Propulsi Plasma). Doctoral thesis. Institut Teknologi Bandung, Indonesia, 1993
9. A.Serban. Anode Geometry and Focus Characteristics. PhD thesis. NTU, Singapore, 1995.
10. Suresh Kumar. Investigation of Laser-Matter Interaction Dynamics. NTU, Singapore, 1997.
11. M.H.Liu. Soft X-Rays from Compact Plasma Focus. PhD thesis. NTU, Singapore, 1997.
12. G.X.Zhang. Plasma Soft X-ray Source for Microelectronic Lithography. NTU, Singapore, 1999.

M.Sc. Theses:

1. Y.H.Chen. Study of Coaxial Plasma Gun in Mode I Operation. MSc thesis. UM, Malaysia, 1972.
2. S.P.Chow. Current Sheath Studies in a Coaxial Plasma Focus Gun. MSc thesis. UM, Malaysia, 1972.
3. A.C.Chew. Plasma Focus in an Axial Magnetic Field. MSc Thesis. UM, Malaysia, 1974.
4. Y.C.Yong. Multiple Ionization in an Argon Plasma Focus. MSc thesis. UM, Malaysia, 1978.
5. Y.H.Chin. Shadowgraphic Studies of a Plasma Focus. MSc thesis. UM, Malaysia, 1981.
6. Jalil Ali. The Enhancement of Pinch Compression-A numerical Study. MSc thesis. UM, Malaysia, 1986.
7. C.K.Chakrabarty. Plasma Focus Neutrons: Some Measurements and Application. MSc thesis. UM, Malaysia, 1989.
8. H.W.Lee. The Construction and Operation of a Ruby Laser-Amplifier. MSc thesis. UM, Malaysia, 1990.
9. C.T.Yong. Construction and Some Measurements on a Field-Reversed Plasma Device. MSc thesis. UM, Malaysia, 1990.
10. Suresh Kumar. Temporal Behaviour of Sparks using Laser Diagnostics. MSc thesis. UM, Malaysia, 1991.
11. Halil Hussain. Studies of a Negative Polarity Plasma Focus. MSc thesis. UTM, Malaysia, 1993.

Research Grants/Projects:

Development of MegaAmp capacitor bank and Plasma Laboratory-UM	MR600K 1964-66 Student 1970-71 Co-Investigator 1972-74 P. Investigator
Transverse Ionising Shock Waves – ANU, Australia	AUD110K 1966-69 Student
Plasma nuclear physics-UM	MR300K 1974-87 PI
Neutrons and x-ray from vacuum spark- KFA Juelich, W Germany	DM60K 1975-76 Co-Investigator
Laser initiated sparks- AVH Foundation/KFA/UM	MR100K 1977-85 PI Dm180K
Laser-initiated gas-embedded Z-Pinch-Imperial College, UK	Ster10K 1981-82 PI
Solar-powered electronics-UM	MR10K 1983-85 PI
Pulsed electronics modular systems-UNESCO/UM	USD5K 1985-86 PI
Ruby laser systems-UM	MR45K 1985-87 PI
United Nations University/ICTP Plasma Fusion Facility-development and training programmes-UNU/ICTP/UM	USD250K 1985-91 PI

Asian African Association for Plasma Training	USD200K 1988- Principal
Transistorised Rotamak – Flinders U, Australia	AUD20K 1986-87 Co-Investigator
Coordinated projects under the Plasma Group and the Pulsed Technology & Instrumentation Group- UM Tokamak	)
Laser-plasma interaction	)
Neutron, x-rays from plasmas	)
Laser density diagnostics	)
Glow Discharge technology	)
Current-step pinch	) MR3570K 1988-91 PI
RF driven plasmas in FRC	)
Compression Enhancement	)
Applied Optics	)
Pulsed & high Power Devices	)
Computer-based instrumentation	)
Teaching systems and devices	)
Pulse Technology and Physics Applications-RP6/92LS NIE	\$100K 1992-94 PI
Benchmarking a 3 kJ Plasma Focus – GRO193-IAEA-LS	USD18K 1993-96 PI
Dynamics and Radiations of the Plasma Focus - RP9/LS NIE	\$150K 1994-97 PI
Plasma Radiation Sources for x-ray Lithography & NAA – ARC5/94 NTU/NIE	\$879K 1995-98 PI
Demonstration Lithography using Plasma Focus Soft X-ray Source RG12/97 LS	\$215K 1997-99 PI
Total grants as PI/Principal: MR4625K+AUD130K+DM240K+Ster10K+USD467K+SD1344K Approximately equivalent to SD\$4500K	
Several other projects of NIE and NTU/NIE as Co-investigator.	

Professional Honours

Conferred Honorary Fellowship by the Malaysian Institute of Physics (July 1993)

A University Gold Medal Prize “PINGAT EMAS PROFESSOR LEE SING” has been set up by former students and colleagues; presented annually (from 1992) to the best Physics Honours Student at the University of Malaya.

Publication List

(I) (II) (III) = included in Selection of Published Papers Vol I, Vol II and Vol III respectively.

(A) Refereed Journals - International

1. H.H. Teh and S. Lee. Transition from electromagnetic to hot-gas driver in an electric shock experiment. Int. J. Electronics, UK (1967), 22: 193-196. (I)
2. S. Lee, Y.H. Chen, S.P. Chow, B.C. Tan, H.H. Teh and S.P. Thong. High speed photography of a plasma focus. Int. J. Electronics, UK (1972), 33: 85-90. (I)
3. S. Lee and R.J. Sandeman. Bow-shock effects on a probe measurements. J. Appl. Phys., USA (1972), 43: 3980-3983. (I)
4. S.P. Chow, S. Lee and B.C. Tan. Current sheath studies in a coaxial plasma focus gun. J. of Plasma Phys., UK (1972), 8: 21-31. (I)
5. Y.H. Chen and S. Lee. Coaxial plasma gun in Mode I operation. Int. J. Electronics, UK (1973), 35: 341-352. (I)
6. S. Lee and H. Conrads. Measurements of neutrons and X-rays from a vacuum spark. Phys. Letters. Netherlands (1976), 57A: 233-236. (I)
7. C.S. Wong and S. Lee. The vacuum spark as a fusion device. Fusion energy - 1981 (IAEA-SMR-82), Austria (1982), p. 336-341. (I)
8. A.E. Dangor, M.B. Favre Dominguez and S. Lee. Observations of radial equilibrium and transition to a helix of a gas-embedded z-pinch. Phys. Rev. A, USA (1983), 27: 2751-2754. (I)
9. S. Lee. Radius ratio of argon pinches. Australian J. Physics, Australia (1983), 35: 891-895. (II)
10. S. Lee. An energy consistent snow-plough model for pinch design. J. Phys. D : Applied Phys., UK (1983), 16: 2463-2469. (II)
11. S. Lee. The application of energy balance to compute plasma pinch ratios. J. Appl. Phys., USA (1983), 54: 3603-3605. (I)
12. S. Lee. Energy balance and the radius of electro-magnetically pinched plasma column. Plasma Physics, UK (1983), 25: 571-576. (I)
13. C.S. Wong and S. Lee. The vacuum spark as a reproducible X-ray source. Rev. Sci. Instrum., USA (1984), 55(7): 1125-1128. (II)
14. S. Lee. A current-stepping technique to enhance pinch compressions. J. Phy. D : Applied Physics, UK (1984), 17: 733-741. (II)
15. C.S. Wong and S. Lee. Simple method of pulsed plasma discharge current analysis. J. Appl. Phys., USA (1985), 57: 5102-5104. (II)
16. A.J. Smith, K.H. Kwek, T.Y. Tou, A.V. Gholap & S. Lee. Measurement of nitrogen laser channel current, inductance & resistance. IEEE J. Quantum Electronics, USA (1987) QE-23: 283-286. (II)
17. S. Lee, T.Y. Tou, S.P. Moo, M.A. Elissa, A.V. Gholap, K.H. Kwek, S. Mulyodrono, A.J. Smith, Suryadi, W.Usala, M. Zakaullah. A simple facility for the teaching of plasma dynamics and plasma nuclear fusion. American J. Phys., USA (1988), 56: 62-68. (II)

18. S. Lee. Density ratios in compressions driven by radiation pressure. *Laser and Particle Beams*, UK (1988), 6: 597-606. (II)
19. T.Y. Tou, S. Lee and K.H. Kwek. Non-Perturbing Plasma Focus Measurements in the Run Down Phase. *IEEE Trans. Plasma Science*, USA (1989), 17: 311-315. (II)
20. K.H. Kwek, T.Y. Tou and S. Lee. A Preionised Nitrogen Laser as a Diagnostic Light Source for Fast Pulse Experiments. *IEEE Trans. Instrumentation & Measurements*, USA (1989), IM-38: 103-107. (II)
21. T.Y. Tou and S. Lee. Multi-slit streak photography for plasma dynamics studies. *Review Sci. Instruments*, USA (1989), 59: 2370-2374. (II)
22. C.S. Wong, S. Lee, C.X. Ong and O.H. Chin. Compact Low Voltage Flash X-ray Tube. *Japan J. Appl. Phys.*, Japan (1989), 28: 1264-1266. (II)
23. S. Lee, K.H. Kwek, Jalil Ali, M.V.H.V. Prabhakar, Y.S. Shishodia and A.G. Warmate. Sequenced Nitrogen Lasers. *J. Appl. Phys.*, USA (1989), 65: 4133-4137. (II)
24. S.H. Saw, C.S. Wong and S. Lee. A Low Cost High Power Fast Response Voltage Probe. *Rev. Sci. Instr.*, USA (1990), 61: 534-537.
25. K.H. Kwek, T.Y. Tou & S. Lee. Current Sheath Structures of the Plasma Focus in the Run-down Phase. *IEEE Trans Plasma Sc. USA*. (1990). 18: 826-830. (II)
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3. S. Lee. Plasma Research at the University of Malaya. Invited Paper. Second Tropical College on Applied Physics, Kuala Lumpur, Malaysia, March 1986. Procs. "Laser and Plasma Technology" - World Scientific (1988). 278-287. (II)
4. S. Lee. The Plasma Focus - An approach to plasma fusion studies for developing countries. Review paper by invitation. 16th AINSE Plasma Physics Conference, Feb 1987, Lucas Heights, Australia - Conference Handbook p 16 Paper 6R.

5. S. Lee. The sharing of fusion-related technology among developing countries. Invited paper. Energy Independence Conference. August 1987; Rio de Janeiro, Brazil; also appeared in revised version in Majalah Fizik. Proc. Fusion Energy and Plasma Physics, World Scientific (Ed. : P.H. Sakanaka). (1988). 754-781. (II)
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16. S. Lee. Computer Circuit Analysis for Pulsed Laser Systems. Invited paper. Second International Workshop on the Physics and Modern Applications of Lasers, Harare, Zimbabwe, 6-14 September 1993; Volume of Abstracts pg 44; to appear in Procs., 18 pages.
17. S. Lee. Alternative Sources. Invited Paper. Seminar on X-ray Lithography, NUS, Singapore, September 1995. (unpublished)
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3. S. Lee and Y.H. Chen. The plasma focus - radial trajectory computation. Procs. Twelveth Int. Conf. on Phenomena in Ionized Gases, Eindhoven, Netherland (1975), paper 353. (I)
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A Sequential Plasma Focus

S. Lee

Abstract—Recent shadowgraph studies suggest that a target disc placed downstream of the anode of a plasma focus may become an auxiliary anode producing a second focusing event when the current sheet climbs over it after the first focus event. A model is set up, with each event assumed to comprise three phases: an axial phase, a radial phase, and a radial extension or expanded column phase. This model is seen to produce the current dip, voltage spike, and high radial speeds characteristic of a plasma focus. With two separated discs acting as auxiliary anodes downstream of the usual anode, there are now three focus events with nine phases in the computation. The equations are written in generalized form in terms of n , so that an equation, for example, applicable to the first axial phase (nA , $n = 1$), is also applicable to the second (nA , $n = 2$) and third axial phase (nA , $n = 3$) by putting $n = 1, 2, 3$ successively in the equation. The results of the model indicate that each anode produces sequentially the current dip, voltage spike, and high radial speeds characteristic of the plasma focus. These computations suggest the possibility and design of a sequential or cascading plasma focus.

I. INTRODUCTION

IN a recent study, shadowgraphs [1] were taken of a flat disc target placed near and downstream of the anode of a plasma focus in order to assess whether the target disturbed the focusing dynamics. The term "focusing dynamics" here stresses the geometry of the focusing action as observed by some visual means, as distinct from its inferred properties of, for example, neutron ion beams [6] and X-ray yield. It was found that when the target was at a distance from the anode greater than the anode radius, there was no disturbance on the dynamics of the focus proper. This visual observation on focus dynamics is in general agreement with observations inferred from neutron and ion-beam emission characteristics [6]–[10]. However, it was further observed that after the focus proper the current sheet moved axially until it reached the disc target, whereupon the current sheet propagated around the disc target and pinched or focused again beyond it [1] onto the rod holding the disc target. It was as though the disc target had become a new "anode." The question then arose naturally whether a series of separated discs placed downstream of the main anode could each become sequentially a new anode to the advancing plasma current sheet, resulting in a series of sequential or cascading plasma focus. Practically, it would of course be necessary to "float" the discs in some manner so as not to have the rod holding the disc to obstruct the focus mechanism. Such a sequential plasma focus may

have applications for the production of sequenced bursts of neutrons and soft X rays for neutron radiographic and soft X-ray cinematography.

In this paper a model is set up for the case of two discs to produce three sequential or cascading focus events. Each focus event [2] is divided into three parts: an axial run-down phase (denoted by A), a radial collapse phase (denoted by R), and a radial extension expanded column phase (denoted by C). There are altogether nine phases—($1A, 1R, 1C, 2A, 2R, 2C, 3A, 3R, 3C$)—in this model with two auxiliary disc anodes, as depicted in Fig. 1.

In the axial phases (nA , $n = 1, 2, 3$), a snow-plow model coupled to the circuit equation is found to be adequate to depict the gross dynamics in terms of speed and trajectory. In the radial phases (nR , $n = 1, 2, 3$), a circuit-coupled slug model [2] with a slug [3] bounded by a shock front at position r_s and a magnetic piston at position r_p may be used to give a trajectory ending in a realistic end-point radius for the current sheet, or magnetic piston position at maximum compression. Following the maximum compression, experimental observations show that the plasma column breaks up into a large volume plasma. It is a characteristic of shadowgraphs taken at this time that no plasma column is visible, indicating that for the purpose of modeling, one may take as a first approximation the current path to be large and uniformly spread out as shown in phase $1C$ (Fig. 1(c)), where the current path linking the anode to the moving current sheet is depicted as flowing uniformly in a column. This is distinct from the case of phase $1A$ (Fig. 1(a)) or phase $1R$ (Fig. 1(b)), where all current paths are thin and indicated by a single arrow. In this model we also assume that phase $1R$ moves instantaneously into phase $1C$. Although this must be considered a deficiency of this model (resulting in too fast a voltage drop from peak voltage), it is not too far (from the viewpoint of gross dynamics) from experimental observations in which the transition from phase $1R$ to phase $1C$ is astonishingly rapid, particularly for small machines. For the expanded column phase, a snow-plow model coupled to the circuit equation is used similarly to the axial phase.

From phase $1C$, we depict in this model a transition to phase $2A$ (Fig. 1(d)), hence to phase $2R$ (Fig. 1(e)), phase $2C$ (Fig. 1(f)), phase $3A$ (Fig. 1(g)), phase $3R$ (Fig. 1(h)), and finally to phase $3C$ (Fig. 1(i)).

II. THEORY

The equivalent circuit of the capacitor discharge of the plasma focus is shown in Fig. 2, with the external inductance depicted as L_0 . The inductance of the plasma focus tube L_p in each of the 9 phases is listed below. Here, b is the radius

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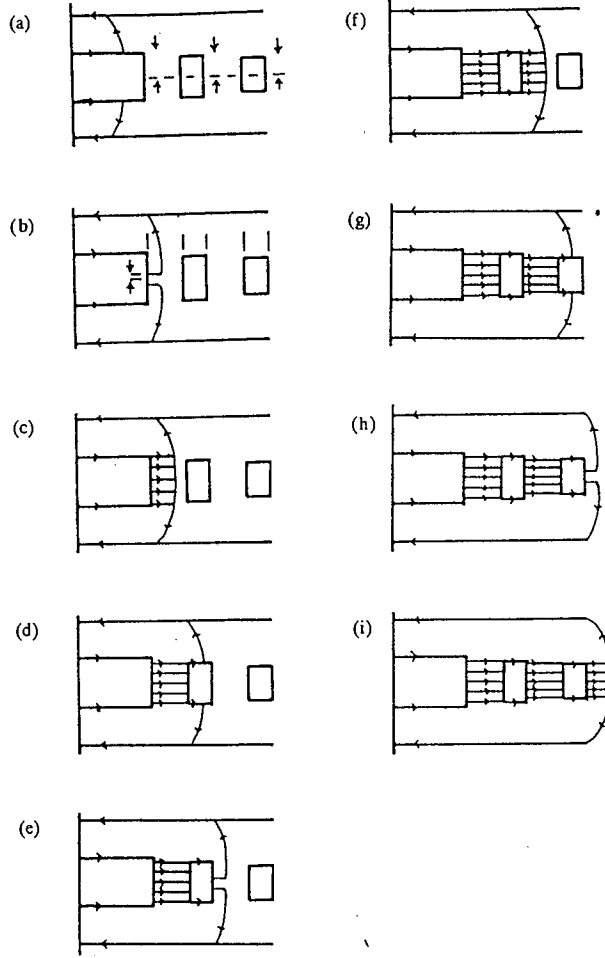


Fig. 1. The 9 phases of the sequential plasma focus model with 3 focus events. First focus event ($n = 1$): (a) phase 1A; (b) phase 1R; (c) phase 1C. Second focus event ($n = 2$): (d) phase 2A; (e) phase 2R; (f) phase 2C. Third focus event ($n = 3$): (g) phase 3A; (h) phase 3R; (i) phase 3C.

of the outer electrode, a_0, a_1 , and a_2 are the radii of the inner electrode, first disc, and second disc, respectively, and z_0, z_1, z_2, z_3 , and z_4 refer to the positions of the end of the anode and the ends of the discs, respectively (refer to Fig. 1). In the notation used in this paper, subscripts of 0, 1, 2, 3 are allowed. A quantity with a negative subscript has a value of zero.

For each of the 3 axial phases nA ($n = 1, 2, 3$, successively),

$$L_{nA} = \mu' \left[(\ln c_{n-1})(z - z_{2n-4}) + (\ln c_{n-2})(z_{2n-4} - z_{2n-6}) + (\ln c_{n-3})(z_{2n-6}) + \frac{1}{4}(z_{2n-3} - z_{2n-4} + z_{2n-5} - z_{2n-6}) \right] \quad (1)$$

(i.e., to obtain the inductance of phase 1A, L_{1A} , put $n = 1$ in (1); to obtain the inductance of phase 2A, L_{2A} , put $n = 2$ in (1); and likewise for L_{3A}), where $\mu' = \mu_0/(2\pi)$, where

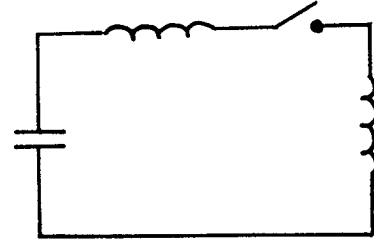


Fig. 2. Equivalent circuit of the sequential plasma focus. L_p is the plasma tube inductance.

μ_0 is the permeability of free space, and $c_n = b/a_n$, z is the time-varying axial position of the current sheet).

For each of the 3 radial phases nR ($n = 1, 2, 3$ successively),

$$L_{nR} = \mu' \left[\left(\ln \frac{b}{r_p} \right) z_f + (\ln c_{n-1})(z_{2n-2} - z_{2n-4}) + (\ln c_{n-2})(z_{2n-4} - z_{2n-6}) + (\ln c_{n-3})(z_{2n-6}) + \frac{1}{4}(z_{2n-3} - z_{2n-4} + z_{2n-5} - z_{2n-6}) \right] \quad (2)$$

where $z_f = z - z_{2n-2}$.

For each of the 3 expanded column phases nC ($n = 1, 2, 3$ successively),

$$L_{nC} = \mu' \left[(\ln c_{n-1})(z - z_{2n-4}) + (\ln c_{n-2})(z_{2n-4} - z_{2n-6}) + (\ln c_{n-3})(z_{2n-6}) + \frac{1}{4}(z - z_{2n-2} + z_{2n-3} - z_{2n-4} + z_{2n-5} - z_{2n-6}) \right] \quad (3)$$

For the axial phases [2] and the expanded column phases, the snow-plow equations require the mass loading. These and the corresponding axial-pointing $J \times B$ forces are listed as follows:

Mass loading for each of the 3 axial phases nA ($n = 1, 2, 3$ successively),

$$m_{nA} = \pi \rho_0 a_0^2 \left[(c_0^2 - d_{n-1}^2)(z - z_{2n-4}) + (c_0^2 - d_{n-2}^2)(z_{2n-4} - z_{2n-6}) + (c_0^2 - d_{n-3}^2)(z_{2n-6}) \right] \quad (4)$$

where $d_n = a_n/a_0$ and ρ_0 is the ambient mass density.

The corresponding force for each of the 3 axial phases is:

$$F_{nA} = \frac{\mu'}{2} I^2 (\ln c_{n-1}). \quad (5)$$

Mass loading for each of the 3 expanded column phases nC ($n = 1, 2, 3$, successively):

$$m_{nC} = \pi \rho_0 a_0^2 \left[(c_0^2(z - z_{2n-2} + (c_0^2 - d_{n-1}^2)(z_{2n-2} - z_{2n-4}) + (c_0^2 - d_{n-2}^2)(z_{2n-4} - z_{2n-6}) + (c_0^2 - d_{n-3}^2)(z_{2n-6})) \right] \quad (6)$$

The corresponding force for each of the 3 expanded column phases:

$$F_{nC} = \frac{\mu'}{2} I^2 \left[(\ln c_{n-1}) + \frac{1}{4} \right]. \quad (7)$$

III. THE EQUATIONS GOVERNING THE VARIOUS PHASES

A. The Axial Phases nA ($n = 1, 2, 3$, Successively)

For each of these 3 axial phases, we may write two governing equations as follows:

$$\text{Axial Motion: } \frac{d}{dt} \left[m_{nA} \frac{dz}{dt} \right] = F_{nA} \quad (8)$$

where m_{nA} and F_{nA} are given in (4) and (5), respectively, and

$$\text{Circuit: } \frac{d}{dt} [L_0 + L_{nA}] I = V_0 - \int I dt / C_0 \quad (9)$$

where L_{nA} is given by (1).

These two coupled equations are to be solved for z and I step-by-step, starting at $t = 0$ for the first axial phase, $n = 1$, with known starting conditions.

B. The Radial Phases nR ($n = 1, 2, 3$, Successively)

For each of these 3 radial phases, we need 4 governing equations in order to follow the trajectories of r_s , the radial shock front, and r_p , the driving radial magnetic piston, together with the increasing length z_f of the open-ended pinching column and the current I . The equations of r_s and r_p for a constant current pinch have been discussed by Potter [3], and this slug-model has been modified for an elongating pinch with the circuit-coupled current [2] to give the following equations:

$$\text{Radial shock position: } \frac{dr_s}{dt} = - \left[\frac{\mu_0}{\rho_0} (\gamma + 1) \right]^{\frac{1}{2}} \frac{I}{4\pi r_p} \quad (10)$$

where γ is the ratio of the specific heat of the plasma;

$$\text{Axial elongation: } \frac{dz_f}{dt} = - \left(\frac{2}{\gamma + 1} \right) \frac{dr_s}{dt} \quad (11)$$

where $z_f = z - z_{2n-2}$;

$$\begin{aligned} \text{Radial piston position: } \frac{dr_p}{dt} = & \frac{\frac{2}{\gamma+1} R \frac{dr_s}{dt} - \frac{r_p}{\gamma I} (1 - R^2) \frac{dI}{dt} - \left(\frac{1}{\gamma+1} \right) (1 - R^2) \frac{dz_f}{dt} \frac{r_p}{z_f}}{\left(\frac{\gamma-1}{\gamma} \right) + \frac{1}{\gamma} R^2} \end{aligned} \quad (12)$$

where $R = r_s/r_p$; and

$$\text{Circuit: } \frac{d}{dt} [(L_0 + L_{nR}) I] = V_0 - \int I dt / C_0 \quad (13)$$

where L_{nR} is given in (2).

C. The Expanded Column Phases nC ($n = 1, 2, 3$, Successively)

For each of these 3 expanded column phases, we may write 2 governing equations as follows:

$$\text{Axial Motion: } \frac{d}{dt} \left[m_{nC} \frac{dz}{dt} \right] = F_{nC} \quad (14)$$

where m_{nC} and F_{nC} are given in (6) and (7), respectively; and

$$\text{Circuit: } \frac{d}{dt} [(L_0 + L_{nC}) I] = V_0 - \int I dt / C_0 \quad (15)$$

where L_{nC} is given in (3).

IV. NORMALIZATION OF EQUATIONS AND INTEGRATION PROCEDURE

As an aid to parametric analysis, the equations are normalized as follows:

$$\begin{aligned} \tau &= \frac{t}{t_0} \quad \text{where } t_0 = \sqrt{L_0 C_0} \\ \iota &= \frac{I}{I_0} \end{aligned}$$

where $I_0 = V_0 / \sqrt{L_0 / C_0}$.

For axial phases and expanded column phases: $\zeta = \frac{z}{z_0}$

$$\text{For radial phases: } \kappa_s = \frac{r_s}{a_0}, \kappa_p = \frac{r_p}{a_0}, \zeta_f = \frac{z_f}{a_0}$$

where $z_f = z - z_{2n-2}$ for each phase $1R$ ($n = 1$), $2R$ ($n = 2$), and $3R$ ($n = 3$).

The normalized equations written as governing equations suitable for numerical integration are as given below.

A. The Axial Phases nA ($n = 1, 2, 3$, Successively)

There are two governing equations for each phase. These are, in normalized form:

1) Axial Motion:

$$\frac{d^2 \zeta}{d\tau^2} = \frac{\alpha^2 f_{n-1} \iota^2 - h_{n-1} \left(\frac{d\zeta}{d\tau} \right)^2}{\zeta_{2n-6} + h_{n-2} (\zeta_{2n-4} - \zeta_{2n-6} + h_{n-1} (\zeta - \zeta_{2n-4}))} \quad (16)$$

where

$$f_{n-1} = \frac{\ln c_{n-1}}{\ln c_0}, h_{n-2} = \frac{c_0^2 - d_{n-2}^2}{c_0^2 - 1},$$

$$h_{n-1} = \frac{c_0^2 - d_{n-1}^2}{c_0^2 - 1}, d_{n-1} = \frac{a_{n-1}}{a_0},$$

$$d_{n-2} = \frac{a_{n-2}}{a_0}, \zeta_{2n-6} = z_{2n-6}/z_0, \zeta_{2n-4} = z_{2n-4}/z_0$$

and so on¹.

¹In this paper, subscripts of 0, 1, 2, 3 are allowed. A quantity with a negative subscript has a zero value.

2) Circuit:

$$\frac{d\iota}{d\tau} = \left[\left(1 - \int \iota d\tau - \beta f_{n-1} \iota \frac{d\zeta}{d\tau} \right) / \left[1 + \beta \zeta_{2n-6} + \beta f_{n-2} (\zeta_{2n-4} - \zeta_{2n-6}) + \beta_1 (\zeta_{2n-3} - \zeta_{2n-4} + \zeta_{2n-5} - \zeta_{2n-6}) + \beta f_{n-1} (\zeta - \zeta_{2n-4}) \right] \right] \quad (17)$$

where

$$f_{n-2} = \frac{\ln c_{n-2}}{\ln c_0}, \zeta_{2n-3} = z_{2n-3}/z_0, \\ \zeta_{2n-5} = z_{2n-5}/z_0, \beta_1 = \beta/4\ell n c_0.$$

In these two governing equations, the scaling parameters are α and β , where

$$\alpha^2 = t_0^2/t_a^2$$

scales the electrical characteristic time t_0 to the characteristic axial transit time $t_a^2 = [(4\pi^2 \rho_0 (c_0^2 - 1) z_0^2) / ((\ln c_0)(I_0/a_0)^2)]$, and

$$\beta = \frac{\mu'(\ln c_0) z_0}{L_0}$$

scales the characteristic axial phase inductance $\mu'(\ln c_0) z_0$ to the external circuit inductance L_0 .

To start the numerical step-by-step integration, we consider the axial phase of the first focus event; i.e., phase 1A (put $n = 1$). We may set [2] at the start:

$$(\tau)_0 = 0, \quad \left(\int \iota d\tau \right)_0 = 0, \quad (\iota)_0 = 0, \quad \left(\frac{d\iota}{d\tau} \right)_0 = 1, \\ (\zeta)_0 = 0, \quad \left(\frac{d\zeta}{d\tau} \right)_0 = 0, \quad \frac{d^2\zeta}{d\tau^2} = \alpha \sqrt{2/3}.$$

We may take increments of time $\Delta\tau = 0.001$ and use standard linear approximation methods to link $\int \iota d\tau$ with ι and $d\iota/d\tau$, and similarly ζ and $d\zeta/d\tau$ and $d^2\zeta/d\tau^2$ to obtain 4 additional equations (linear approximation). These 4 linear approximation equations, together with the governing equations (16) and (17), may then be used to solve for the 6 quantities: $\int \iota d\tau, \iota, d\iota/d\tau$ and $\zeta, d\zeta/d\tau, d^2\zeta/d\tau^2$ at each integration step. To start the integration of the phases 2A and 3A, we use as starting values $\zeta = \zeta_{2n-3}$ and the final values of the preceding phase for $\tau, \int \iota d\tau, \iota, d\iota/d\tau, d^2\zeta/d\tau^2$. Each axial phase nA ($n = 1, 2, 3$) is integrated until $\zeta = \zeta_{2n-2}$. For details of one simple scheme of integration, [2] may be used.

B. The Radial Phases nR ($n = 1, 2, 3$, Successively)

There are 4 governing equations for each radial phase. These are, in normalized form:

$$\text{Radial\_shock: } \frac{d\kappa_s}{d\tau} = -\frac{\alpha \alpha_1 \iota}{\kappa_p} \quad (18)$$

where $\alpha_1 = \frac{[(\gamma+1)(c_0^2-1)]^{1/2} F}{2(\ell n c_0)}$ and $F = z_0/a_0$.

$$\text{Axial\_elongation: } \frac{d\zeta_f}{d\tau} = -\left(\frac{2}{\gamma+1}\right) \frac{d\kappa_s}{d\tau} \quad (19)$$

where $\zeta_f = (z - z_{2n-2})/z_0$.

1) Radial Piston:

$$\frac{d\kappa_p}{d\tau} = \frac{\left(\frac{2}{\gamma+1} R' \frac{d\kappa_s}{d\tau} - \frac{1}{\gamma} \frac{\kappa_p}{\iota} (1 - R'^2) \frac{d\iota}{d\tau} - \left(\frac{1}{\gamma+1} \right) \frac{\kappa_p}{\zeta_f} (1 - R'^2) \frac{d\zeta_f}{d\tau} \right)}{\left(\frac{\gamma-1}{\gamma} \right) + \left(\frac{1}{\gamma} \right) R'^2} \quad (20)$$

where $R' = \kappa_s/\kappa_p$.

2) Circuit:

$$\frac{d\iota}{d\tau} = \left[1 - \int \iota d\tau + \beta_f \iota \frac{\zeta_f}{\kappa_p} \frac{d\kappa_p}{d\tau} + \beta_f \left(\ln \frac{\kappa_p}{c_0} \right) \iota \frac{d\zeta_f}{d\tau} \right] / \\ \left[1 - \beta_f \left(\ln \frac{\kappa_p}{c_0} \right) \zeta_f + \beta \zeta_{2n-6} + \beta f_{n-2} (\zeta_{2n-4} - \zeta_{2n-6}) + \beta f_{n-1} (\zeta_{2n-2} - \zeta_{2n-4}) + \beta_1 (\zeta_{2n-3} - \zeta_{2n-4} + \zeta_{2n-5} - \zeta_{2n-6}) \right] \quad (21)$$

where $\beta_f = \beta/(F\ell n c_0)$.

To start the integration of each radial phase, we use as starting values the following values of the corresponding preceding axial phase of $\tau, \int \iota d\tau, \iota$, and $d\iota/d\tau$. Other initiating values are $\kappa_s = 1, \kappa_p = 1, \zeta_f = 0$ (or an inconsequential small value such as $\zeta_f = 0.00001$ to avoid the division of zero in (20)). The numerical integration proceeds for each case until $\kappa_s = 0$ at which point the minimum κ_p (an important quantity in experimental design) is reached.

C. The Expanded Column Phases nC ($n = 1, 2, 3$, Successively)

There are two governing equations for each expanded column phase. These are, in normalized form:

1) Axial Motion: See (22) below, where $e_{n-1} = (\ln c_{n-1} + \frac{1}{4}/\ln c_0, h = c_0^2/(c_0^2 - 1)$.

$$\frac{d^2\zeta}{d\tau^2} = \frac{\alpha^2 e_{n-1} \iota^2 - h \left(\frac{d\zeta}{d\tau} \right)^2}{h_{n-3} \zeta_{2n-6} + h_{n-2} (\zeta_{2n-4} - \zeta_{2n-6}) + h_{n-1} (\zeta_{2n-2} - \zeta_{2n-4}) + h (\zeta - \zeta_{2n-2})} \quad (22)$$

2) Circuit:

$$\frac{d\iota}{d\tau} = \left[1 - \int \iota d\tau - \beta e_{n-1} \iota \frac{d\zeta}{d\tau} \right] / \left[1 + \beta f_{n-3} \zeta_{2n-6} + \beta f_{n-2} (\zeta_{2n-4} - \zeta_{2n-6}) + \beta f_{n-1} (\zeta - \zeta_{2n-4}) + \beta_1 (\zeta - \zeta_{2n-2} + \zeta_{2n-3} - \zeta_{2n-4} + \zeta_{2n-5} - \zeta_{2n-6}) \right]. \quad (23)$$

To start the integration of each expanded column phase $nC(n = 1, 2, 3)$, we use as starting values the following final values of the corresponding preceding radial phase $nR(n = 1, 2, 3)$: τ , $\int \iota d\tau$, ι , and $\zeta = 1 + \zeta_f/F$ (renormalizing the value of ζ_f to z_0). We also use as a starting value the final value of $d\zeta/d\tau$ of the corresponding preceding axial phase $nA(n = 1, 2, 3)$.

The integration of each expanded column phase proceeds until $\zeta = \zeta_{2n-1}$, where for $n = 3$, $\zeta = \zeta_5$ may be taken as some convenient point such as $\zeta_5 = \zeta_4 + (\zeta_4 - \zeta_3)$.

V. VOLTAGE EQUATIONS

Besides the measurement of current, another common and informative measurement which may readily be made of the plasma focus is the voltage V_p across the input of the focus. This may be computed, noting that:

$$V_p = \frac{d}{dt}(L_p I) \quad (24)$$

where we have assumed a purely inductive model, where L_p in the various phases are given by (1)–(3) successively.

The voltage equation is written for each of the 9 phases in normalized form [2], with $\nu = V_p/V_0$, where V_0 = initial voltage on capacitor, as follows:

Axial Phase $nA(n = 1, 2, 3)$, successively):

$$\nu = \beta \frac{d\iota}{d\tau} \left[f_{n-3} \zeta_{2n-6} + f_{n-2} (\zeta_{2n-4} - \zeta_{2n-6}) + f_{n-1} (\zeta - \zeta_{2n-4}) + \frac{1}{4 \ln c_0} (\zeta_{2n-3} - \zeta_{2n-4} + \zeta_{2n-5} - \zeta_{2n-6}) \right] + \beta f_{n-1} \iota \frac{d\zeta}{d\tau}. \quad (25)$$

It is seen that the tube voltage contains two terms—the first being the product of displacement and rate of change of current, and the second, the product of current and speed. As the current peaks and stays near constant, the second, which we call the “speed term,” dominates.

Radial Phase $nR(n = 1, 2, 3)$, successively):

$$\nu = \beta \frac{d\iota}{d\tau} \left[f_{n-3} \zeta_{2n-6} + f_{n-2} (\zeta_{2n-4} - \zeta_{2n-6}) + f_{n-1} (\zeta_{2n-2} - \zeta_{2n-4}) + \frac{1}{4 \ln c_0} (\zeta_{2n-3} - \zeta_{2n-4} + \zeta_{2n-5} - \zeta_{2n-6}) - \frac{\beta_f}{\beta} \left(\ln \frac{\kappa_p}{c_0} \right) \zeta_f \right]$$

$$- \beta_f \iota \left[\left(\ln \frac{\kappa_p}{c_0} \right) \frac{d\zeta_f}{d\tau} + \frac{\zeta_f}{\kappa_p} \frac{d\kappa_p}{d\tau} \right]. \quad (26)$$

In the radial phase, the form of the voltage equation contains the two terms with the same dependence as in the axial phase. But in the radial phase the speed term has a much greater magnitude, especially the term involving the piston speed $d\kappa_p/d\tau$, since this term has κ_p in the denominator and has a larger effect as κ_p goes to smaller values.

Expanded Column Phase $nC(n = 1, 2, 3)$, successively):

$$\nu = \beta \frac{d\iota}{d\tau} \left[f_{n-3} \zeta_{2n-6} + f_{n-2} (\zeta_{2n-4} - \zeta_{2n-6}) + f_{n-1} (\zeta - \zeta_{2n-4}) + \frac{1}{4 \ln c_0} (\zeta - \zeta_{2n-2} + \zeta_{2n-3} - \zeta_{2n-4} + \zeta_{2n-5} - \zeta_{2n-6}) \right] + \beta \left(f_{n-1} + \frac{1}{4 \ln c_0} \right) \iota \frac{d\zeta}{d\tau}. \quad (27)$$

VI. RESULTS

Computations were carried out using this model with a view of designing a sequential or cascading focus system based on the 3-kJ plasma focus designated as the UNU/ICTP PFF [4]. The scaling parameters are $\alpha, \beta, \gamma, c_0, F, \zeta_1, \zeta_2, \zeta_3, \zeta_4, d_1$, and d_2 . In order to reduce the large number of possible combinations to arrive at a combination which will provide a good focusing characteristic (large voltage spike, significant current dip) for all 3 sequential focus events, we note that the speed scaling [4] in both the axial and radial phases is dependent on the factor $(I/a)/\sqrt{\rho_0}$, so that it is necessary to maintain the value of (I/a) during each of the sequential focusing events. Thus basically we adjust the scaling parameters from the values of the UNU/ICTP PFF so that the first focus of the sequential focus occurs earlier than the focus of the UNU/ICTP PFF. Also, to maintain the value of (I/a) , the auxiliary anodes are designed with radii a_1 and a_2 a little less than a_0 .

Thus whereas the UNU/ICTP PFF was numerically optimized with the parameters $\alpha = 1.26, \beta = 0.36, F = 16.8, c_0 = 3.37$, and $\gamma = 5/3$, the sequential plasma focus is redesigned with $\alpha = 1.7, \beta = 0.27, F = 12, c_0 = 3.37, \gamma = 5/3$, and with $\zeta_1 = 1.083, \zeta_2 = 1.167, \zeta_3 = 1.25, \zeta_4 = 1.333, d_1 = 0.85$, and $d_2 = 0.7$.

These parameters correspond to the sequential plasma focus operating with the following conditions: $V_0 = 15 \text{ kV}, C_0 = 30 \mu\text{F}, L_0 = 110 \text{ nH}, a_0 = 1 \text{ cm}, z_0 = 12 \text{ cm}, z_1 = 13 \text{ cm}, z_2 = 14 \text{ cm}, z_3 = 15 \text{ cm}, z_4 = 16 \text{ cm}, a_2 = 0.85 \text{ cm}, a_3 = 0.7 \text{ cm}$, and pressure = 1 torr in deuterium. (Due to current and mass shedding [4] that is not included in the present modeling, the actual operational pressure would be closer to 3 torr.)

The 3-event, 9-phase model was computed with the computation numerically carried out in the sequence 1A, 1R, 1C, 2A, 2R, 2C, 3A, 3R, and 3C using the normalized equations (16) and (17) for the axial phases, (18)–(21) for the radial phases, and (22) and (23) for the expanded column phases. The voltage was also computed using (25)–(27).

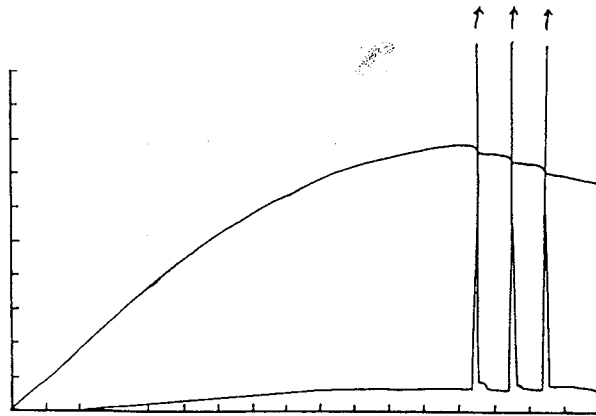


Fig. 3. Current i and voltage v for the sequential focus, with $\alpha = 1.7$, $\beta = 0.27$, $F = 12$, $c = 3.37$, $\gamma = 5/3$, $\zeta_1 = 1.083$, $\zeta_2 = 1.167$, $\zeta_3 = 1.25$, $\zeta_4 = 1.333$, $d_1 = 0.85$, and $d_2 = 0.7$. To help identify the 9 phases, their time intervals are as follows: phase 1A: $\tau = 0 - 1.335$; phase 1R: $\tau = 1.335 - 1.352$ (first voltage spike); phase 1C: $\tau = 1.352 - 1.369$; phase 2A: $\tau = 1.369 - 1.437$; phase 2R: $\tau = 1.437 - 1.449$ (second voltage spike); phase 2C: $\tau = 1.449 - 1.473$; phase 3A: $\tau = 1.473 - 1.539$; phase 3R: $\tau = 1.539 - 1.548$ (third voltage spike); and phase 3C: $\tau > 1.548$.

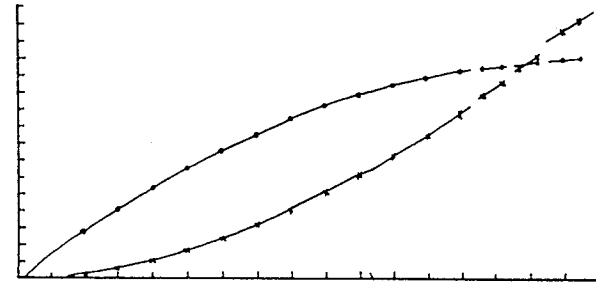
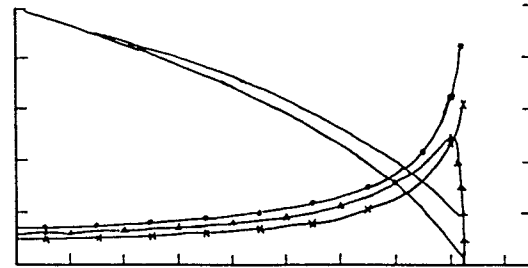


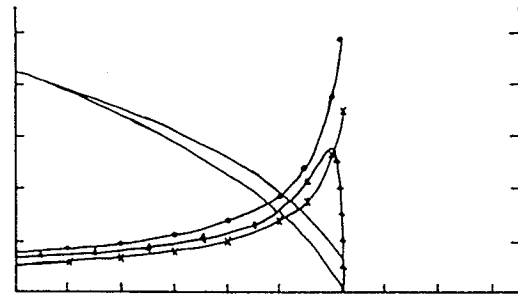
Fig. 4. Axial position ζ and axial speed during the phases 1A, 2A, 3A and 1C, 2C, 3C for the sequential focus with parameters given in the caption of Fig. 3. The three gaps represent the three phases 1R, 2R, 3R, results of which are given separately in Fig. 5(a)–(c).

The results are presented in Figs. 3–5. In Fig. 3, the current i and voltage v waveforms are presented. The current reaches a peak value of 0.787 at $\tau = 1.335$ at the end of phase 1A, just before the start of phase 1B (see Fig. 4). During this phase 1R, it drops to 0.765 or by 2.8% of the peak value, with the steepest part of the drop occurring at $\tau = 1.3515$. This steep drop of current corresponds to the peak voltage which spikes up to a value of $v = 8.28$, corresponding to a piston speed of 5.9 (see Fig. 5(a)) scaled to a characteristic speed of z_0/t_0 . These three effects—namely, the current dip, the voltage spike (contributed mainly by the term $(d\kappa_p/d\tau)/\kappa_p$ (see voltage equation [26]), and the fast radial piston speed—are the “classic” characteristics of a plasma focus. During this radial phase a further, though smaller, contribution to the voltage spike (see (26)) is the high axial elongation speed of up to 12.6.

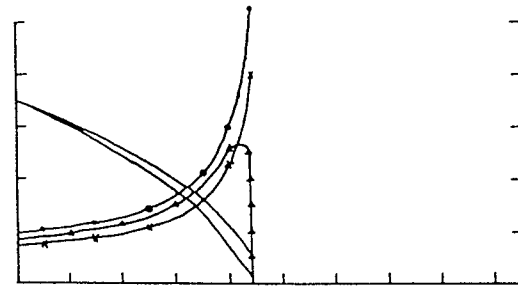
After the radial phase 1R, our model allows for a radial extension or expanded column phase 1C during which the current remains practically constant at $I = 0.7648$ (see Fig. 3), dropping gradually to 0.757. The tube voltage drops to



(a)



(b)



(c)

Fig. 5. (a) Radial phase 1R: trajectories of radial shock (κ_s) and radial piston (κ_p) for the sequential focus with parameters the same as in the caption of Fig. 3. Also given are the radial shock speed $d\kappa_s/d\tau$ ($\bullet$), radial piston speed $d\kappa_p/d\tau$ (Δ), and focus column elongation rate $d\zeta_p/d\tau$ ($\times$). (b) Radial phase 2R: trajectories of radial shock (κ_s) and radial piston (κ_p) for the sequential focus with parameters the same as in Fig. 3. Also given are the radial shock speed $d\kappa_s/d\tau$ ($\bullet$), radial piston speed $d\kappa_p/d\tau$ (Δ), and focus column elongation rate $d\zeta_p/d\tau$ ($\times$). (c) Radial phase 3R: trajectories of radial shock (κ_s) and radial piston (κ_p) for sequential focus with parameters the same as in Fig. 3. Also given are the radial shock speed $d\kappa_s/d\tau$ ($\bullet$), radial piston speed $d\kappa_p/d\tau$ (Δ), and focus column elongation rate $d\zeta_p/d\tau$ ($\times$).

a value of 0.347, slightly above the 1A final value of 0.27. This higher value is due to the extra inductance term of $\frac{1}{4}\mu'z_f$ (see (3) and (27)) during the 1C phase. The axial speed stays practically constant (see Fig. 4) at 1.23, only slightly higher than the final axial speed of phase 1A. Phase 1C moves on to phase 2A, characterized by an almost constant current, slightly lower tube voltage, and slightly higher axial speed.

At the end of phase 2A the second radial collapse phase 2R occurs, with the current dipping noticeable by another 2.5%, from 0.757 to 0.738 in a short time interval of 0.012 (see Fig. 3). The voltage spikes up to 9.14 at $\tau = 1.45$ contributed

mainly by the high piston speed. This radial collapse again has all three classic indications of a plasma focus. The phases $2C$ and $3A$ have similar characteristics as the earlier axial phases: almost constant current, tube voltage, and axial speed.

At the end of phase $3A$, the third radial collapse phase $3R$ occurs, this time with a current dip of 2.5%, from 0.729 to 0.711, and a voltage spike of peak value 10.5, corresponding to a peak piston speed of 10.1 at $\tau = 1.55$. This focus event also has all three characteristics of a strong plasma focus. Indeed, the parameters having been adjusted so that this third focus in the sequential series occurs at $\tau = 1.55$, and moreover, with the relevant anode having a radius of 0.7 of the main anode, this assures that there is an ample near-peak current so that the value of (I/a_2) ensures the highest radial speed and largest voltage spike during phase $3R$ of all three focus events.

Following this radial phase $3R$, we follow the plasma dynamics through one more axial phase $3C$ to bring the voltage down to the small values which characterize an axial phase. The current gradually drops further during this phase.

Fig. 5(a)–(c) shows the results of the computation on the radial phases $1R$, $2R$, and $3R$. These three graphs fill-in the three gaps in Fig. 4. On an expanded time scale, each of the three graphs of Fig. 5(a)–(c) show the shock trajectory κ_s and piston trajectory κ_p and the corresponding speed graphs $d\kappa_s/d\tau$ and $d\kappa_p/d\tau$ vs τ . Also displayed is the elongation speed $d\zeta_f/d\tau$.

In Fig. 5(a), showing the results for the first of the radial phases, the plasma starts pinching at $\kappa_s = \kappa_p = 1$ at the time $\tau = 1.335$. Up to $\tau = 1.347$, the speeds $d\kappa_s/d\tau$, $d\kappa_p/d\tau$, and $d\zeta_f/d\tau$ have risen to values of about 4 from initial values of about 1 (in a time interval of 0.012). But in the next smaller time interval of 0.003 from 1.347 to 1.350, the values of $d\kappa_s/d\tau$ and $d\zeta_f/d\tau$ have risen to over 16 and 12, respectively, while the value of $d\kappa_p/d\tau$ has risen to 9 and then drops sharply to 0 in the very last instant as the radially imploding shock front goes on axis.

The very large voltage spike of $1R$ of Fig. 3 is due to the large value attained by $d\kappa_p/d\tau$ in the small interval of 0.003 from 1.345 to 1.350, coupled to the decreasing value of κ_p during this short interval of time.

The feature of $\kappa_p \cdot \kappa_s$ and the speeds $d\kappa_s/d\tau$, $d\kappa_p/d\tau$, and $d\zeta_f/d\tau$ follow the same pattern for the other 2 radial phases, $2R$ and $3R$.

It may be commented that the radial collapse speed and the voltage spike, say of $1R$, coming out of these computations are too large when compared with voltage measurements on a plasma focus. There are two mechanisms contributing to this effect. First, the effect of current-shedding and mass-shedding. About 0.7 of the capacitance current flows in the plasma in both the axial and radial phases. Also in the axial phase the effective mass loading on the current sheath is known [5] to be considerably below that expected from the operational density. This reduced mass loading or mass-shedding effect is due primarily to the severe canting of the current sheath in the axial phase. In the radial phase, however, the mass-shedding effect is not expected to operate. Thus to reflect the similar current-shedding but different mass shedding, the model could use a differential pressure (density) method with

a considerably larger density in the radial phase than in the axial phases. This would reduce the computed radial speeds and voltage spike.

For the second mechanism, it would be correct to say that because the slug model assumes instantaneous signal communication [3] between the shock front and piston, this leads to the computed exceedingly large values. If we consider the communication delay due to the finite small disturbance speed between the piston and shock front (of the order of 0.3 mm/ μ s or in the nondimensionless units of these calculated 0.1 units of distance in 0.002 units of time), then because in the slug model the piston pressure drives the shock front and the motion of the shock front creates volume for the piston to move into, a communication delay of 0.002 or 0.003 in time between the piston and shock front would mean that the shock front would at any instant feel the considerably smaller pressure of the piston at an earlier time, and likewise the piston would feel the effect of the shock front at an earlier position. This delay effect, if incorporated into the model, would considerably slow down both the shock front and piston as they near the axis, and hence also reduce the voltage spike.

Operating the sequential focus in deuterium, a neutron pulse may be expected with each focus. It would be necessary to "float" the auxiliary anode in some manner so that the axial region beyond the auxiliary anode is unobstructed to the focus action. The presence of the target holder in all earlier target experiments obstructed the focus action so that multiple focus action from the targets was not observed [6]–[10]. It may also be necessary to use hollow auxiliary anodes; i.e., with a hole in the center in order not to disturb the deuteron beam-gas target mechanism responsible for a proportion of the fusion reaction in a plasma focus.

As mentioned in the introduction, such a sequential plasma focus may have applications in the production of sequenced bursts of neutrons and soft X-ray. For a greater number of pulses—i.e., a longer sequence—it may be advantageous to use a flat-top current pulse from an LC network discharge.

VII. CONCLUSION

Dividing a plasma focus event into three phases of which the first, the axial phase A , is followed by a radial phase R , which is then followed by an expanded column axial phase C , enables the plasma focus event to be computed with all the main features observed experimentally; in particular, the current, voltage, and speed characteristics during the axial phases A and C , and the voltage spike, current dip, and large radial collapse speed during the radial R phase. By the introduction of two auxiliary anodes, the model demonstrates that sequential or cascading plasma focus events may be achieved—each event exhibiting the three phases of A , R , and C , including all the dynamics and voltage and current characteristics of the two radial phases A and C and the radial R phase. Design parameters based on a 3-kJ focus such as the UNU/ICTP PFF [4] have also been suggested in these computations.

An inexpensive rotamak device

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The components of a typical rotamak device are described and the constructional details of an inexpensive version are given. The operating range of this particular version is described and, as an example, a detailed set of measurements made for one set of initial conditions are presented. Typically, steady toroidal currents of ~ 100 A are generated and maintained for the full 40 ms of operation by a ~ 1 -MHz rotating magnetic field of a few Gauss in amplitude. Plasmas having electron temperatures lying between 5–10 eV and number densities in the 10^{17}-m^{-3} range are routinely and very reproducibly produced.

I. INTRODUCTION

Plasma devices that generate significant volumes of quiescent plasma are of great use for basic studies in plasma physics. The so-called plasma box¹ that uses “magnetic walls” and contains a filament-created plasma is an excellent example of such an apparatus.

The purpose of this article is to describe another such apparatus that produces a highly reproducible current-carrying plasma for which the magnetic field generated by the plasma current plays a role in the confinement of the plasma. In addition to being an inexpensive source of plasma suited for basic research, such a device has a useful pedagogic role in demonstrating the principles of magnetic confinement. Although the workings of this device have been extensively studied, both theoretically and experimentally, for about a dozen years, its ease of construction, operation, and the reproducibility of its performance is not generally well known. The secondary purpose of this paper is to remedy this situation.

The device described in this article is a rotamak.² The rotamak is a compact torus device in which a rotating magnetic field (RMF) (rotating in planes normal to the z axis; see Fig. 1) is used to generate and maintain the toroidal plasma current. Equilibrium requires an additional, externally generated poloidal field (the “vertical” field of the tokamak) to counteract the natural tendency of the toroidal plasma ring to expand. The poloidal magnetic field that results from the addition of this “vertical” field to that due to the plasma current consists of the combination of closed and open field lines shown in Fig. 1.

A noteworthy feature of the rotamak discharge is its remarkable reproducibility. This feature alone points to the rotamak as a suitable piece of apparatus upon which to undertake basic plasma physics research.

In a typical rotamak, the applied RMF is generated by feeding two rf current pulses, of the same amplitude and frequency but dephased by 90° , through two orthogonally oriented coils located on the outside of the discharge vessel (Fig. 1). The power supplies that furnish these current pulses are the most important and, usually, the most expensive components of a rotamak apparatus. In the device

described here, this expense is circumvented by using supplies based on the use of metal-oxide-semiconductor field-effect transistors (MOSFETs). We estimate that, disregarding the price of the vacuum system, the cost of the rotamak was approximately \$4000.

The paper is organized in the following way. The apparatus and associated diagnostics are described in Sec. II. The operational range of the device is delineated in Sec. III and Sec. IV contains, as a typical example, detailed measurements made on a discharge having one particular set of initial conditions.

II. THE APPARATUS AND DIAGNOSTICS

The rotamak consists of the following components: a spherical Pyrex vessel fitted with side arms and a vacuum system; a double-channel MOSFET rf generator and two orthogonally oriented pairs of coils to provide the RMF; a low-voltage, high-current dc power supply and a pair of circular coils to produce the required equilibrium magnetic field; and a rf power amplifier and two coils wound on the pumping arms of the discharge vessel to provide preionization of the working gas. These essential components are shown in schematic form for a typical rotamak (not the version described in this paper) in Fig. 2.

A. The discharge vessel

The spherical rotamak discharge vessel is made of Pyrex with an inner diameter of 280 mm. In order to achieve symmetric pumping, two side arms are used to connect the spherical vessel to a pumping system.

The working gas (hydrogen) is let into the vessel through a glass tube located in the $z=0$ plane (see the coordinate system in Fig. 1). Its flow rate is controlled by the combination of a gate valve mounted in the pump line and a needle valve in the feed line.

Access for probes is provided by a machined ceramic (MACOR) block cemented over a slit cut in a poloidal (r, z) plane of the discharge vessel. A row of 21 holes (5.5 mm diam and 10 mm apart) was drilled through the ceramic block. These allowed glass probe guides to be inserted into the vessel one at a time. Each guide is vacuum sealed with an O-ring seated in the ceramic block. A

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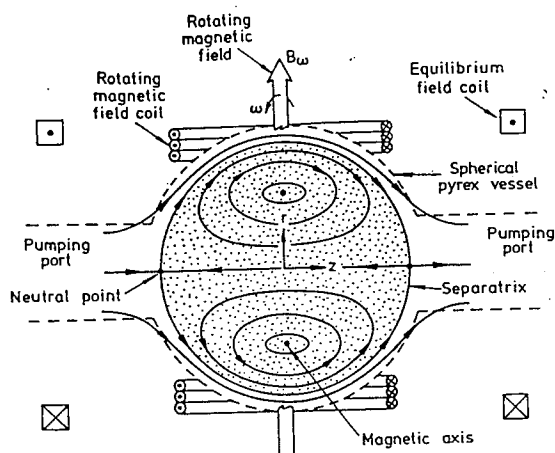


FIG. 1. The rotamak compact torus configuration.

Rogowski belt (used to measure the total driven toroidal plasma current) is mounted on the opposite poloidal plane by passing it over the outer surface of the vessel and back through an axial glass tube (8 mm diam) within the vessel. A second axial tube allowed a magnetic probe to be moved along the z axis. Figure 3 shows the disposition of the Rogowski coil and the probe ports; for clarity, a reduced number of probe guides have been shown.

B. Production of the applied rotating magnetic field

The RMF is generated by passing pulses of rf current of the same amplitude and frequency but dephased by 90° through two orthogonally oriented, rectangular coil systems located on the outside of the discharge vessel.

One of the rectangular coil systems consists of two coils connected in series. Each coil is composed of three turns of the inner conductor and dielectric of industrial RG-8 A/U coaxial cable supported within a perspex tubular frame, 340 mm in length and 280 mm wide. The two coils are separated by 120 mm.

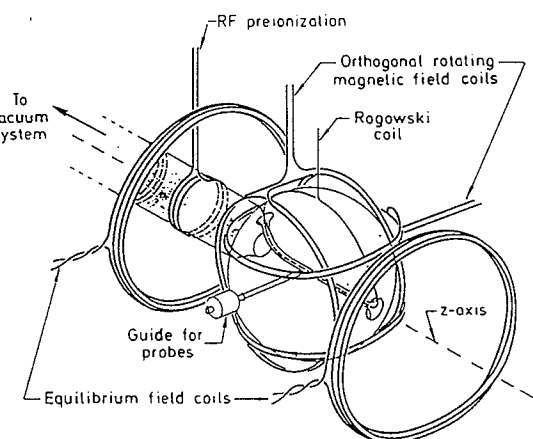


FIG. 2. Schematic diagram of a typical rotamak device.

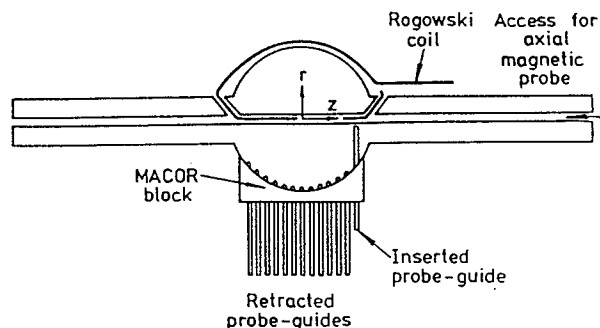


FIG. 3. Disposition of Rogowski coil and probe ports.

The second rectangular coil system is slightly longer than the first (400 mm) but is otherwise identical. It overlaps the first in an orthogonal manner. The inductances of these coils were measured to be 20 and $22 \mu\text{H}$, respectively.

When fed with the appropriate rf current pulses, this coil structure produces (in vacuum) the field lines shown in Fig. 4. They are calculated in the $z=0$ plane for a number of times during the rotation of the RMF. For the most part, the applied RMF is quite uniform within the discharge vessel. It should be understood that in a rotamak discharge, the imperfect penetration of the RMF results in a field that is considerably distorted in comparison to that shown in Fig. 4.

The rf supply that furnishes the two rf current pulses was designed and constructed at Flinders University. It is based on the use of MOSFET transistors and contains an oscillator, two driver stages, and two output stages. Each channel of the generator is capable of providing a pulsed (40-ms duration) rf output at frequencies lying between 300 and 990 kHz. The rf currents in the two pulsed outputs are dephased by 90° . A block diagram of the generator is presented in Fig. 5; a detailed description of the various stages follows.

A frequency-synthesized digital oscillator produces the small signals needed to switch the following driver stages. The circuit diagram of this oscillator is shown in Fig. 6. The frequency of the output signal of a 4-MHz crystal oscillator is divided to give a 40-kHz reference for the phase lock loop. The frequency of this reference signal is then multiplied by an integer N via a binary-coded-decimal thumbwheel. Finally, the frequency of this signal is divided by 4 and is gated to give the A and B signals which differ in phase by 90° and which have a frequency of $10 N \text{ kHz}$. If required, the A and B signals can be generated independently by disabling the appropriate gating pulse.

A schematic diagram of one of the two identical driver stages is shown in Fig. 7. Each driver stage has eight 10-turn trifilar-wound small toroidal ferrite transformers that are driven by a push-pull pair of IRF120 power MOSFETs. The $12\text{-}\Omega$ resistor determines the switching speed for the output stage.

The operation of the output stage and a detailed circuit diagram are shown in Figs. 8(a)–8(b). The bridge consists of parallel pairs of MOSFETs in each of the four arms.

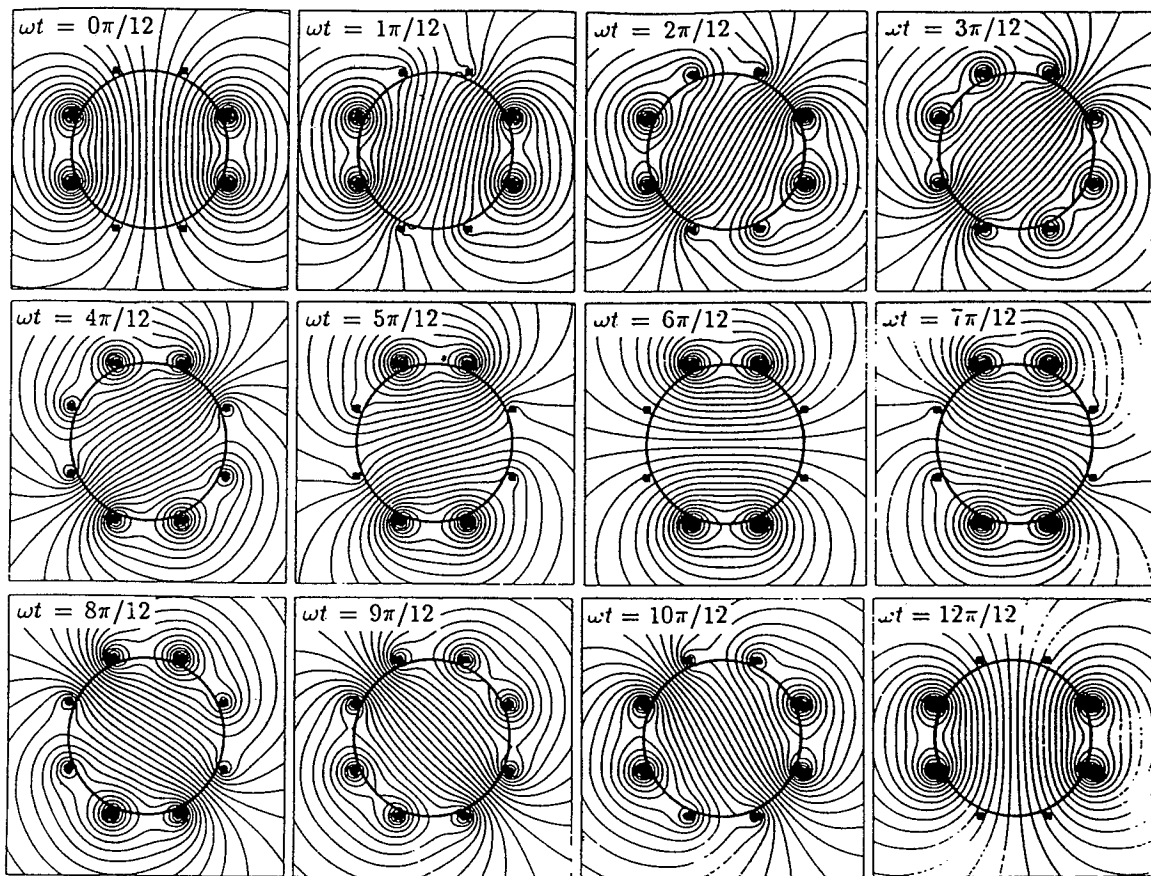


FIG. 4. Rotating magnetic-field lines generated *in vacuo* (in the $z=0$ plane) by the RMF coil structure. The solid circle indicates the position of the discharge vessel wall.

Alternate switching of the pairs of MOSEFTs in opposite arms of the bridge produces a square-wave voltage across the load. The power supply for the output stage consists of a charging unit and a 10 000- μF electrolytic capacitor bank. The bank can be charged to a maximum of 180 V.

Figure 9 is the equivalent circuit for both channels of the rf generator when it is actually being used to produce a rotating magnetic field. The generator impedance, plus the resistance of the coil that it feeds, is lumped into the quantity which we denote by R_g . The value of R_g was measured to be 5 Ω and the maximum available power from each channel of the generator at the maximum bank voltage of 180 V was measured to be 1.3 kW. L_A and L_B represent the inductances of the two RMF coil structures. These quan-

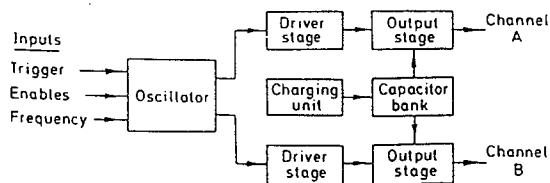


FIG. 5. A block diagram of the two-channel rf generator.

ties have different values for a vacuum shot and a plasma shot. The screening introduced by the presence of the plasma always has the effect of reducing the coil inductance.

Some mutual coupling between the two (nominally) orthogonal RMF coil structures is inevitable. Such a coupling is deleterious inasmuch as it introduces an asymmetry into the amount of power delivered by each channel of the generator. This effect is minimized by introducing two additional coils, of inductance M_A and M_B , into the circuits. The coupling between these coils is designed to be variable and, in practice, the coupling is chosen so that any mutual inductance that exists between the two main RMF coils is canceled out. In the absence of a plasma the mutual inductance between the two RMF coils was measured to be 0.24 μH . The mutual coupling coefficient was therefore 0.011. The mutual coupling coils M_A and M_B were constructed from 3.2-mm (o.d.) copper tubing covered with PVC sleeving for insulation. Each coil consisted of 6 turns, 8.6 cm in diameter and 4.3 cm in length; its inductance is 4.5 μH .

The capacitors C_A and C_B are introduced into the circuit for tuning purposes. If

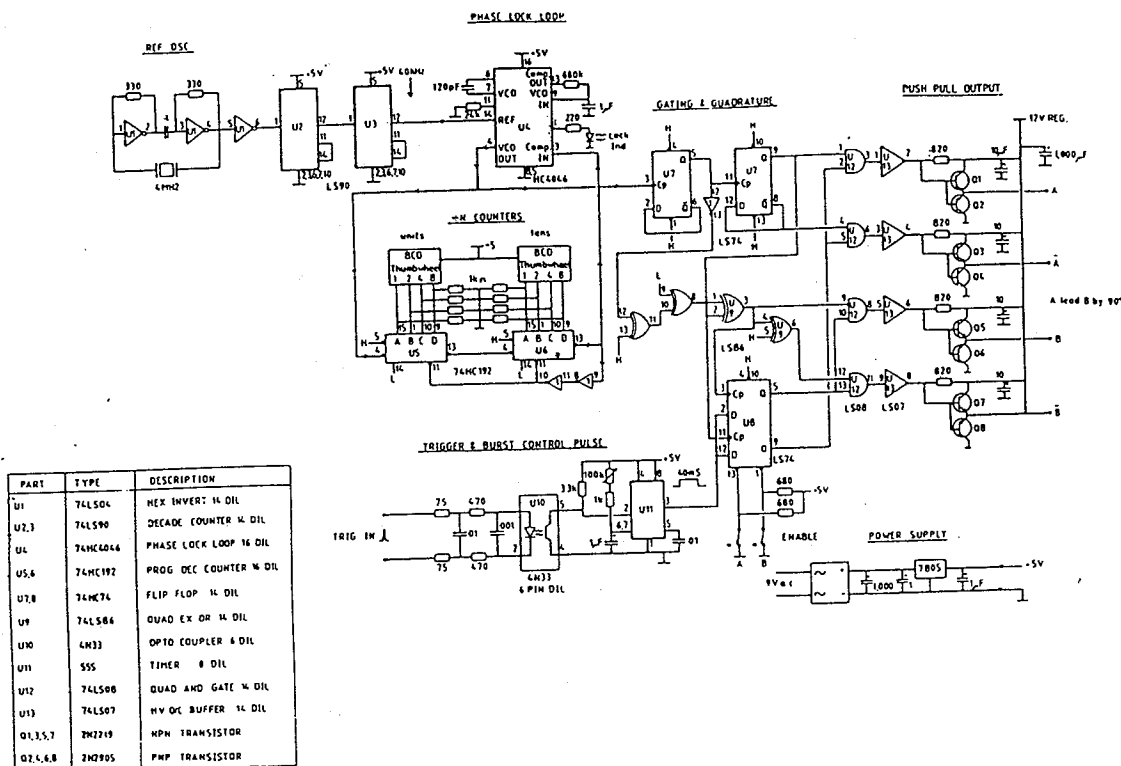


FIG. 6. Circuit diagram of the oscillator.

$1/\omega C_A = \omega(L_A + M_A)$ and $1/\omega C_B = \omega(L_B + M_B)$, (1)
 then the impedance presented to each channel of the generators is purely resistive. In practice, the capacitance C_A and C_B consisted of a combination of fixed ceramic capacitors and a vacuum-variable capacitor. R_A and R_B represent the load resistances that appear in the circuit due to the plasma load.

In the absence of plasma a maximum current is obtained when the capacitive reactance in the circuit is tuned to cancel out the inductive reactance due to the coils in the circuit. During a plasma discharge, however, the total inductance in the circuit decreases and it is necessary to increase the value of the capacitance in order to keep the circuit resonant. It is also necessary to adjust the coupling

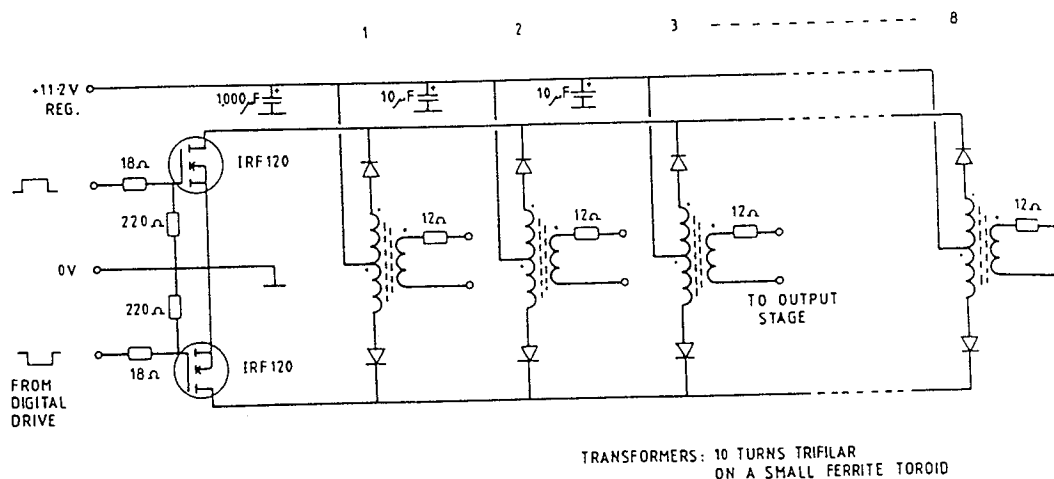


FIG. 7. Circuit diagram of one of the two identical driver stages.

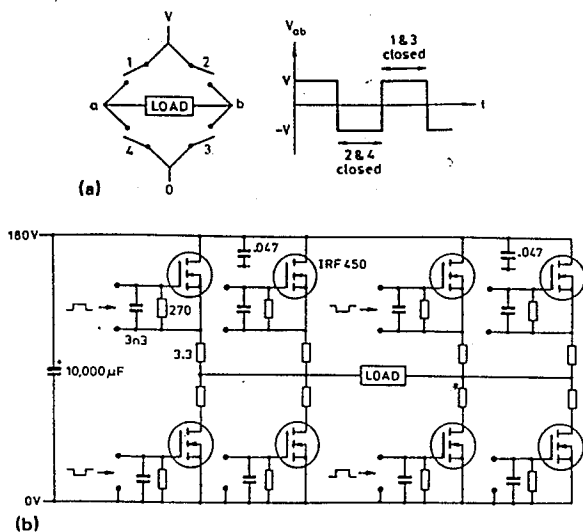


FIG. 8. (a) Operation of the output stage. (b) Circuit diagram of the output stage.

between the mutual inductance cancellation coils in these circumstances. Having made these adjustments, the rf currents passing through the RMF coils are approximately equal in amplitude and 90° apart in phase. The amplitude of the RMF at the center of the discharge vessel (in the absence of a plasma) lies, typically, in the range of 5–6 G.

C. Equilibrium magnetic field

An externally applied steady poloidal magnetic field is required in order to achieve toroidal equilibrium. This field interacts with the toroidal plasma current which is driven by the RMF to produce an inwardly directed force that contributes to the confinement of the plasma. In the rotamak device this equilibrium field is produced by a pair of coils centered on the z axis of the discharge vessel (see Fig. 1). For the apparatus described here, the coil diameter is

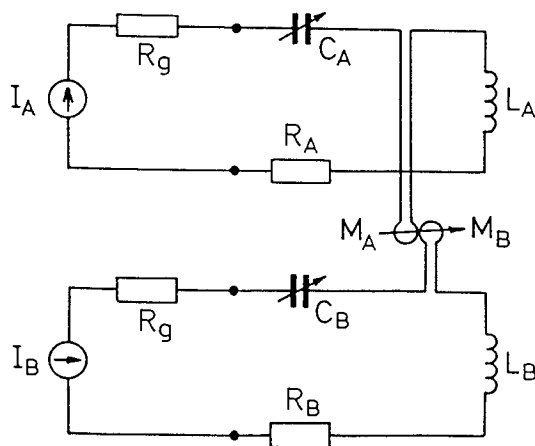


FIG. 9. Circuit diagram of the two output channels (A and B) connected to the RMF coil structure.

300 mm and the coil separation is 570 mm. The coils are fed with a pulse of constant current produced by a low-voltage high-current dc power supply. The duration of this current pulse is significantly longer than that of the RMF pulse which is triggered when the equilibrium field has reached a steady value.

D. Preionization

The rf electric field associated with the applied RMF was not capable of ionizing the hydrogen at low filling pressures (<4.5 mTorr). Preionization was essential for the formation of a seed plasma at low filling pressures. This was provided by passing rf current at a frequency of ~ 12 MHz through two multiturn coils wound on the pumping arms of the discharge vessel. The rf pulse was provided by a 300-W commercial ENI power amplifier; it had a duration of 12 ms and overlapped the start of the RMF pulse by 600 μ s.

E. Diagnostics

In order to investigate the plasma-field configuration produced in this rotamak device, the following physical quantities were measured using conventional techniques:

(i) The total driven plasma current, I_p . This was measured using the Rogowski coil described in Sec. II A.

(ii) The various components of the steady-state magnetic field B which is itself composed of the applied equilibrium field and the field produced by the driven plasma current I_p . Hall-effect magnetic probes which could be located in the probe guides described in Sec. II A were used to measure these components.

(iii) The various components of the time-varying magnetic field B associated with the RMF. Wire-wound magnetic probes were used to measure these components.

(iv) The spatial distribution of electron temperature and number density. A floating electric double probe which could fit into the array of feedthroughs used for the magnetic probes was used. The design of the probe and associated circuitry was similar to that used by Tendys.³ Calibration of the electric probe was carried out by comparing the probe measurements with a line-averaged number-density measurement made using an 8-mm microwave interferometer.

(v) The power transferred from the rf generator to the plasma.

III. THE OPERATING RANGE OF THE ROTAMAK DEVICE

The characteristics of the plasma-field configuration produced in the rotamak device are governed by the following externally controlled quantities: the nature and filling pressure of the working gas p_f ; the shape and the amplitude of the applied equilibrium magnetic field B_0 ; the frequency of the RMF; and the charging voltage on the capacitor bank of the rf generator (this sets the maximum available rf power).

In a typical rotamak discharge the vessel is first filled with hydrogen to a predetermined filling pressure. The cur-

rent pulse that produces the equilibrium field is then triggered. When the equilibrium field has attained the chosen steady value, and if the filling pressure is < 4.5 mTorr hydrogen, a preionization pulse is switched on. The preionization process overlaps the start of the RMF pulse (~ 40 ms) by $\sim 600 \mu\text{s}$. If the pressure of the hydrogen is > 4.5 mTorr, then the electric field associated with the RMF is sufficient to ionize the gas and the preionization is not required. The shot-to-shot time for the rotamak device described here is ~ 1 min.

A number (~ 20) of cleaning rotamak discharges are always made prior to any major experimental run. This has been found to be necessary in order to achieve highly reproducible discharges.

The operation of this device was not investigated over the full range of the externally controlled parameters. Neither were all of the characteristics of the resultant plasma-field configuration examined. We report here on the working of the device for the following values of the external variables: The working gas was hydrogen, the filling pressure p_f was 2.5–8.0 mTorr, the equilibrium field $B_v(0,0)$ was 0–4.5 G, the RMF frequency was 0.99 MHz, the capacitor bank charging voltage was 180 V, and the maximum available rf power was 1.3 kW per channel.

The plasma-field parameters that were measured were the maximum value of the total driven plasma current I_θ^M ; the radial position of the separatrix in the $z=0$ plane r_s , and the rf power dissipated in the plasma load P_p .

Figure 10 shows the time history of I_θ for a typical discharge having, as initial conditions, $p_f = 5.2$ mTorr hydrogen and $B_v = 1.3$ G. This 10-shot overlap oscillogram provides good testimony to the high reproducibility of the rotamak discharge. The amplitude of the driven current decreases progressively as time increases. This is due to the voltage drop on the capacitor bank of the generator during the course of a discharge. The slight distortion of the zero base line that occurs for ~ 10 ms both before and after the driven current pulse is an artifact of the measurement and should be ignored; it results from pickup on the Rogowski coil from the applied equilibrium field.

In Fig. 11 we present a set of oscillograms that shows the influence of the applied equilibrium field upon the steady driven current for a 4.7-mTorr hydrogen discharge. For the first five oscillograms of this set, the steady toroidal current is driven for the entire duration of the RMF pulse (40 ms) and its maximum value increases from ~ 50 to ~ 120 A as the applied vertical field is increased from 0 to 4.3 G. If the equilibrium field is set at too high a value, the driven current terminates before the end of the rf pulse due to a lack of available rf power (see the last oscillogram of the set).

The position of the separatrix was studied by using a Hall probe to measure the z component, B_z , of the steady poloidal magnetic field in the $z=0$ plane. For a particular discharge, $B_z(r,0)$ was recorded as a function of time at a series of positions (1.0 cm apart) along the r axis in the equatorial plane. Radial profiles of $B_z(r,0,t)$ could then be constructed at selected times throughout the discharge.

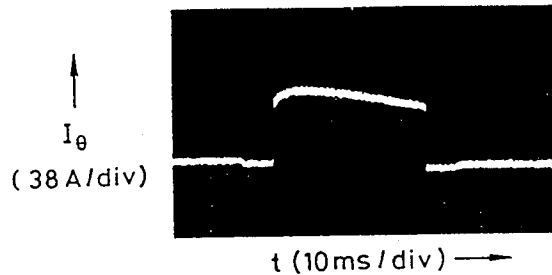


FIG. 10. Overlay of ten oscillograms of I_θ for a rotamak discharge having $p_f = 5.2$ mTorr hydrogen and $B_v = 1.3$ G.

The poloidal magnetic flux was computed using these profiles:

$$\psi(r,0,t) = 2\pi \int_0^r r' B_z(r',0,t) dr'. \quad (2)$$

The position of the separatrix in the $z=0$ plane, r_s , lies at the point where $\psi(r,0)=0$.

From a knowledge of R_g (generator impedance plus the resistance of the RMF coil) and measurements of the rf currents, both in the absence of a plasma and with a plasma present, it was possible to compute the rf power dissipated in the plasma, P_p .

Figure 12 shows the relationship between the externally controlled physical quantities B_v and p_f , and the measured quantities I_θ^M , r_s , and P_p . Each point in this diagram indicates one set of working conditions. For example, if the applied equilibrium field $B_v = 1.5$ G and the hydrogen filling pressure $p_f = 3.0$ mTorr were chosen, the diagram indicates that the total driven plasma current I_θ^M would be ~ 90 A, the position of the separatrix radius r_s would be ~ 12 cm, and the total rf power dissipated in the plasma load P_p would be ~ 2.2 kW. This diagram was constructed using the data from 42 different rotamak discharges. The contours are to be taken as indicative only.

VI. DETAILED MEASUREMENTS MADE ON A PARTICULAR HYDROGEN ROTAMAK DISCHARGE

In this section we present the results of detailed measurements made on one particular hydrogen discharge. The purpose of this exercise is to make clear the variety of measurements that are possible on this inexpensive rotamak device. A filling pressure of 5.2 mTorr and an externally applied equilibrium field of 1.3 G were chosen; this working point is shown in Fig. 12. The RMF frequency was 990 kHz and no preionization was used.

For these conditions, plasma current was driven for the full 40-ms duration of the rf pulse. The discharge was observed to be highly reproducible; the oscillograms of the driven current for 10 successive discharges have been overlaid and already shown in Fig. 10. A maximum driven current of ~ 73 A is attained in the discharge.

The steady poloidal magnetic field generated in the discharge is the resultant of two components: the applied equilibrium field and the field produced by the driven

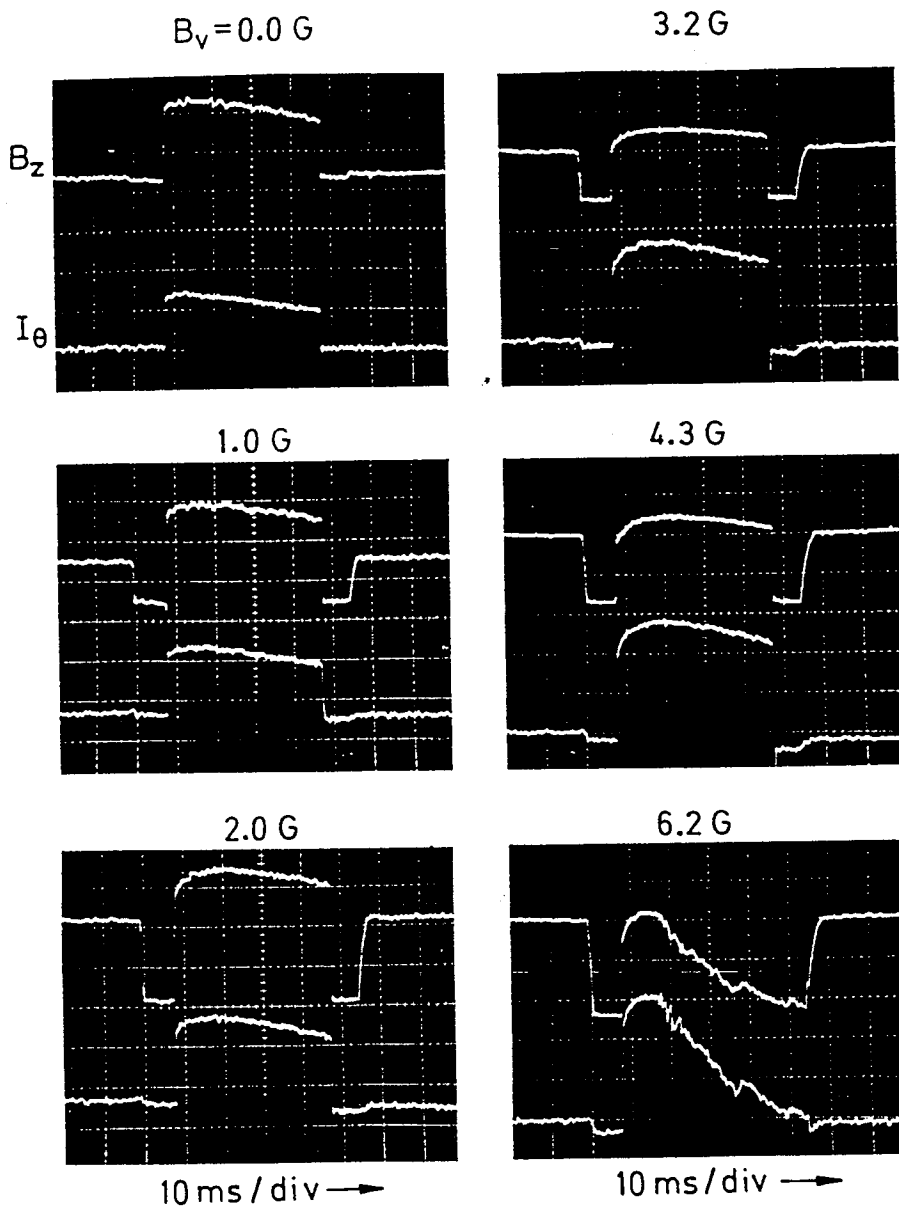


FIG. 11. The axial magnetic field at $r=0.8$ cm, $z=0$ (upper trace: 1.1 G/div left column; 2.6 G/div right column) and the driven toroidal plasma current (lower trace: 38 A/div) for different values of the equilibrium magnetic field B_e for a 4.7-mTorr hydrogen discharge.

plasma current. The z component of this resultant field $B_z(r, z)$ was measured as a function of time at a number of r positions for a given z position and then the procedure was repeated for a number of different z positions. In this way, data were collected over a matrix of 16×21 points in a r - z plane ($\Delta r = \Delta z = 1.0$ cm) at time intervals of $\Delta t = 63$ μ s.

The B_z data were analyzed by fitting a two-dimensional polynomial surface to the measurements. In the algorithm, the value of B_z at any point (r_i, z_j) was represented by a symmetric two-dimensional polynomial:

$$B_z(r_i, z_j) = \sum_{\alpha=0}^{N_1} \sum_{\beta=0}^{N_2} A_{\alpha\beta} r_i^{2\alpha} z_j^{2\beta}. \quad (3)$$

At any measurement point (r_i, z_j) , the error between the measured $B_z^m(r_i, z_j)$ value and the polynomial value $B_z(r_i, z_j)$ is given by

$$E_{ij} = B_z^m(r_i, z_j) - B_z(r_i, z_j). \quad (4)$$

By minimizing the square of the error over all 16×21 measurement points, the coefficients of the polynomial $A_{\alpha\beta}$ were obtained. It was found that the best fitting was achieved when the polynomial orders were $N_1 = 12$ and $N_2 = 4$. Figure 13(a) shows radial and 13(b) axial profiles of the raw measured B_z data together with the corresponding cuts in the fitted surface at the selected time of $t = 12$ ms. The fitting procedure smooths the raw data in both the radial and axial directions in an acceptable manner.

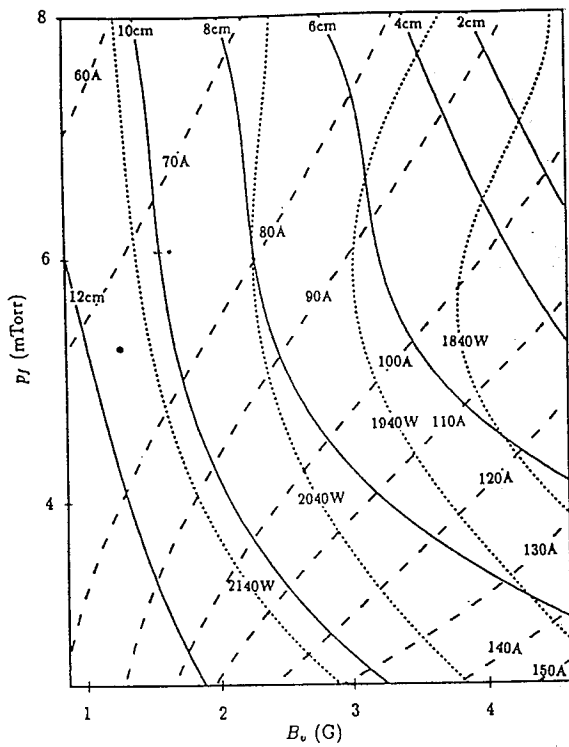


FIG. 12. The relationship between the externally controlled physical quantities B_v and p_f and the measured quantities I_θ^M , r_s and P_F .

The poloidal flux is obtained by integrating the polynomial expression for $B_z(r, z)$:

$$\psi(r, z, t) = 2\pi \int_0^r r' B_z(r', z, t) dr' \quad (5)$$

$$= 2\pi \sum_{\alpha=0}^{12} \sum_{\beta=0}^4 \frac{A_{\alpha\beta}(t)}{2\alpha+2} r^{2\alpha+2} z^{2\beta}. \quad (6)$$

Figure 14 shows a contour plot of the steady poloidal magnetic flux at the selected time of $t = 12$ ms together with the radial profile in the equatorial plane ($z = 0$). The dashed contour corresponds to $\psi(r, z) = 0$, i.e., it shows the location of the separatrix. The plasma-field configuration generated in this particular discharge is oblate with the separatrix surface lying entirely within the discharge vessel wall. The separatrix radius r_s , the magnetic axis r_m , and the neutral point z_X were measured to be 11, 7.5, and 8.7 cm, respectively.

In an axisymmetric toroidal system, the azimuthal (toroidal) current density j_θ is given by

$$j_\theta = -\frac{1}{\mu_0} \left(\frac{1}{2\pi r} \frac{\partial^2 \psi}{\partial z^2} + \frac{\partial B_z}{\partial r} \right). \quad (7)$$

Substitution of the analytic expressions for B_z and ψ into this equation yields

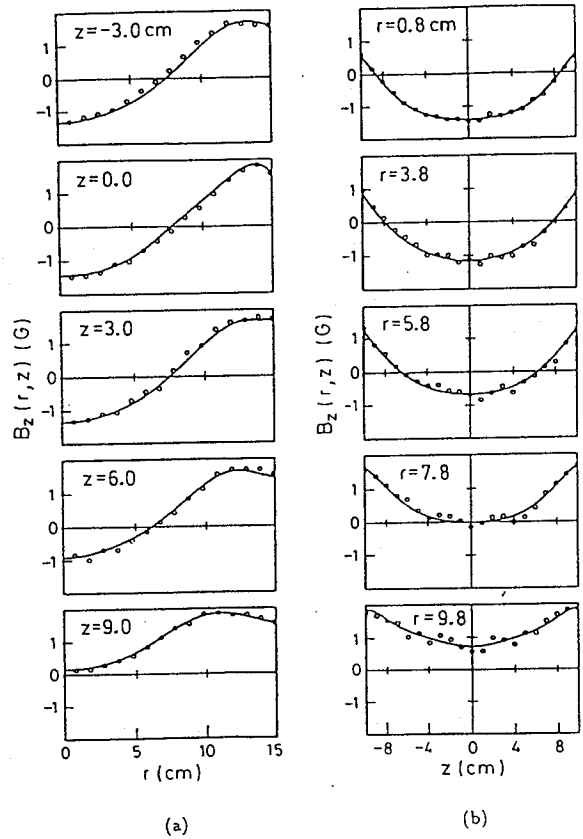


FIG. 13. Comparison of (a) the measured radial $B_z(r)$ profiles and (b) the measured axial $B_z(z)$ profiles with the corresponding cuts of the fitted polynomial surface.

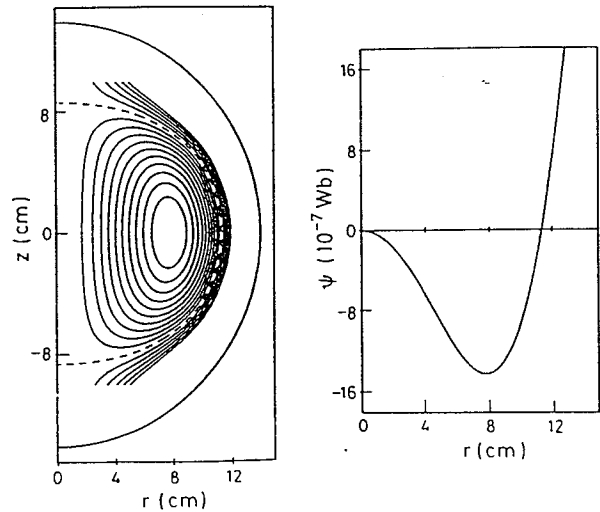


FIG. 14. Contours of the poloidal flux ψ . The positions of the separatrix (dashed curve) and the discharge vessel wall (thick curve) are shown. The contour spacing is $\Delta\psi = 1.35 \times 10^{-7}$ Wb. The radial profile of ψ in the $z = 0$ plane is shown on the right-hand side.

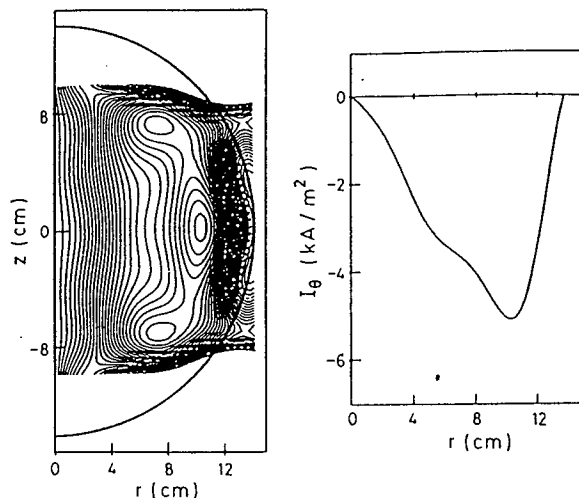


FIG. 15. Contours of toroidal current density j_θ . The contour spacing is $\Delta j_\theta = 200 \text{ A m}^{-2}$. The radial profile of j_θ in the $z=0$ plane is shown on the right-hand side.

$$j_\theta = -\frac{1}{\mu_0} \sum_{\alpha=0}^{12} \sum_{\beta=0}^4 A_{\alpha\beta} \left(\frac{2\beta(2\beta-1)}{2\alpha+2} r^{2\alpha+1} z^{2\beta-2} + 2\alpha r^{2\alpha-1} z^{2\beta} \right). \quad (8)$$

Figure 15 shows a contour diagram of j_θ ; the radial profile in the $z=0$ plane is also shown. Clearly, current cannot be driven outside the discharge vessel and the presence of contours in Fig. 15 that cut the vessel wall in a limited region is nonphysical and reflects an unsatisfactory fit of the experimental data in the region. In order to gauge the seriousness of this effect, the total toroidal driven current was calculated by integrating j_θ over the measured grid:

$$I_\theta = \int_{-z_0}^{z_0} \int_0^{\sqrt{R^2-z^2}} j_\theta(r,z) dr dz. \quad (9)$$

Here R is the radius of the discharge vessel and z_0 is the maximum extension of the measurement grid in the z direction. The total toroidal current calculated in this manner was $\sim 69 \text{ A}$ which compares favorably with the Rogowski coil measurement of $\sim 73 \text{ A}$.

Evidence of a triplet structure in the distribution of the toroidal current density is seen in Fig. 15. Such a distribution is predicted by the theory of RMF current drive in a spherical plasma.⁴

The electron temperature and number density were determined by means of an electric double probe at two positions: near the separatrix at $r=0.8 \text{ cm}$ and $z=0.0 \text{ cm}$,

and near the magnetic axis at $r=8.0 \text{ cm}$ and $z=0.0 \text{ cm}$. The results were: near the separatrix $n_e = 8.2 \times 10^{16} \text{ m}^{-3}$, $T_e = 6.3 \text{ eV}$, $p_e = 0.083 \text{ Pa}$; and near the magnetic axis $n_e = 1.1 \times 10^{17} \text{ m}^{-3}$, $T_e = 7.3 \text{ eV}$, $p_e = 0.129 \text{ Pa}$.

If the ion contribution to the total plasma pressure is ignored (and justification for this assumption can be found in Rotamak power-balance calculations undertaken by Donnelly, Rose, and Cook⁵), then the difference in plasma pressure between the magnetic axis and separatrix is 0.046 Pa .

Calculation shows that the steady magnetic structure shown in Fig. 14 can only support a difference in plasma pressure of 0.013 Pa between the magnetic axis and separatrix. The apparent paradox is resolved as follows.

Incomplete penetration of the applied RMF will always be accompanied by the presence of plasma screening currents and an associated radial ponderomotive force which arises from the self-interaction of the rf screening currents with the rotating magnetic field that produces them. This ponderomotive force acts in such a way as to confine the plasma and, in the discharge described here, it is about 2.5 times larger than the $\mathbf{J} \times \mathbf{B}$ force associated with the steady driven current. We stress that this is not a general circumstance. In more powerful rotamak discharges, the steady $\mathbf{J} \times \mathbf{B}$ force dominates the ponderomotive force as far as plasma confinement is concerned (see, for example, Knight and Jones⁶).

The plasma parameters reported here are modest. However, by increasing the rf power input to the discharge vessel, the discharge parameters can be significantly improved. For example, in a series of experiments to be described elsewhere, an injection of $\sim 450 \text{ kW}$ of rf power into a similarly sized vessel has led to the generation of $\sim 10 \text{ kA}$ of driven current and electron densities in the 10^{19} m^{-3} range.

ACKNOWLEDGMENTS

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MAGNETIC REYNOLD NUMBER AND CURRENT SHEET STRUCTURE

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Abstract

The dependence of the Magnetic Reynold number and the current sheet structure on the shock speed of an electromagnetic shock tube is being investigated in this paper.

Introduction

It is known that for electromagnetic drive in a pulsed plasma device to proceed efficiently a key indicator is the magnetic Reynold number $R_m = \mu \sigma v \ell$ where μ and σ are respectively the permeability and the electrical conductivity of the plasma, v its speed and ℓ is the characteristic length over which the driving magnetic field changes. Thus to operate a shock tube in the electromagnetic mode a minimum speed is needed to maintain the value of R_m at the sufficiently large value of $R_m \gg 1$. The dependence of R_m on plasma flow speed is greater than linear since the electrical conductivity σ also depends on the flow speed.

Theory

The predominant mode of energy deposition into a plasma flow, whether it is by the magnetic field-flow field coupled mechanism (B-v), designated as electromagnetic drive or by a diffusive magnetic field mechanism denoted as joule heating, may be examined from the following plasma induction equation:

$$\frac{\partial B}{\partial t} = \nabla \times v \times B + \frac{1}{\mu \sigma} \nabla^2 B \quad (1)$$

In this equation the first term on the RHS is recognised as the B-v term whilst the second term on the RHS with its diffusion coefficient of $(\frac{1}{\mu \sigma})$ is recognised as the magnetic field dif-

fusion term responsible for joule heating. By a dimensional comparison of these two terms¹ the conditions for electromagnetic drive $R_m \gg 1$ may be obtained as:

$$\mu \sigma v \ell \gg 1 \quad (2)$$

For electromagnetic shock tube operation a major parameter is the shock speed. It is useful to note the dependence of R_m on the shock speed q_1 . This may be obtained as follows. Following Spitzer² we may write an expression for the plasma electrical conductivity:

$$\sigma = \frac{1}{65.3 \ln(\Lambda) Z} T_e^{\frac{3}{2}} \quad (3)$$

where $\Lambda = (\text{Debye length } \lambda_D) / (90^\circ \text{ impact parameter } b_0)$ and Z is the charge number of the plasma having electron temperature T_e .

From strong shock wave jump equations³ we have:

$$T_e = 2.4 \times 10^{-4} M \frac{(\gamma - 1)}{(\gamma + 1)^2} \frac{q_1^2}{D} \quad (4)$$

where γ is the specific heat ratio, M the molecular weight of the plasma and D its departure coefficient. For an atomic gas like argon we may write $D = (1 + Z)$ where Z is the charge number.

Thus we may write:

$$R_m = C \frac{(\gamma - 1)^{\frac{3}{2}}}{(\gamma + 1)^3} \frac{\ell}{\ln(\Lambda) Z (Z + 1)^{3/2}} q_1^4 \quad (5)$$

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where $C = 0.72 \times 10^{-13} \text{ M}^{3/2}$ if we take q_1 as the plasma flow speed. This is a reasonable approximation.

Equation (5) indicates a rapid increase of R_m with q_1 ($R_m \propto q_1^4$) for a given ℓ if the thermodynamic function γ and Z are constant, as is for perfect gas. For real gases however, γ and Z have a big influence on the function of R_m with q_1 .

The thermodynamic function γ may be taken to be an indicator of the degree of freedom f . We may write $\gamma = (2 + f)/f$ so that $\gamma \rightarrow 1$ in the case where $f \rightarrow \infty$. This is a gas with a large heat capacity, difficult to heat up as can be seen from Equation (4) where as $\gamma \rightarrow 1$, $T \rightarrow 0$. As a typical example it is known that for a gas such as argon in its freely ionising regime⁴ (i.e. not approaching any ionisation limits) $\gamma \sim 1.15$ with $f \sim 16$. This compares with the perfect gas case with $\gamma = 5/3$ and $f = 3$.

Thus as a gas gets heated sufficiently to begin ionising, the reduction of the value of γ

below $5/3$ towards 1 tends to decrease the rapid increase of R_m with q_1 as evident from Equation (5).

Further, as the plasma gets heated to higher temperatures the value of Z will increase due to increasing ionisation and continue to increase, with increasing temperatures to a limit of 18 at several million K. This increase of Z with temperature tends to further reduce the rapidity of the increase of R_m with shock speed.

To demonstrate the dependence of R_m on q_1 and the real gas effects on this dependence, Z and γ have been computed^{5,6} as a function of T for argon. The value of R_m is then computed over a range of temperatures (or over a range of q_1) to adequately contrast regimes where the gases are real with regimes where the gases are near perfect.

The resultant value of R_m for argon are plotted in Fig. 1 as a function of shock speed q_1 , using a reference value of $\ell = 1 \text{ cm}$, these values of R_m being denoted as R_m^* (value of

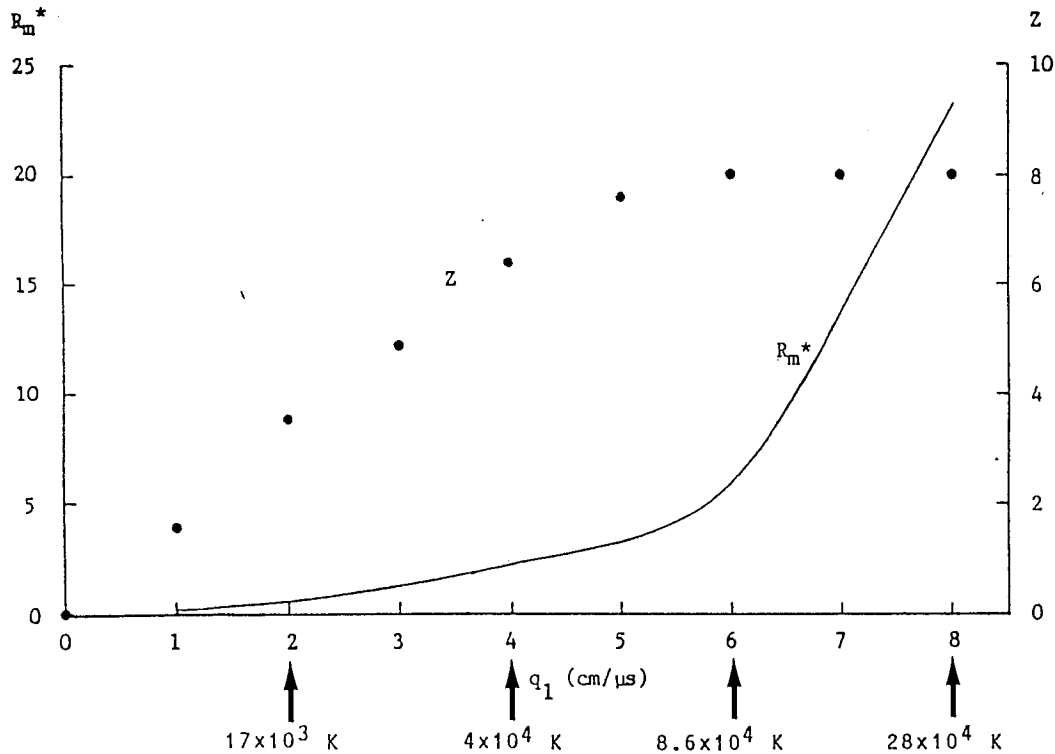


Fig. 1 Reference magnetic Reynold number R_m^* and plasma charge Z versus shock speed q_1 for argon.

R_m referenced to $\ell = 1$ cm).

From Fig. 1 it is seen that between 1 cm/ μ s and 4 cm/ μ s R_m^* goes from 0.18 to 2.21 so that R_m^* increases slower than q_1^2 . Between 4 cm/ μ s and 8 cm/ μ s however R_m^* goes from 2.21 to 23.2, increasing faster than q_1^3 . In fact between 6 cm/ μ s and 8 cm/ μ s, the increase of R_m^* is almost as fast as q_1^4 . The reason for this is evident when one correlates to the graph of Z vs q_1 where Z is seen to increase rapidly from 1.55 at 1 cm/ μ s to 6.4 up to 4 cm/ μ s and then begins to turn to an asymptotic value of 8, remaining at 8 between 5.5 cm/ μ s and 8 cm/ μ s as the argon ionises to a close shell configuration which gives it, thermodynamically, a near perfect gas behavior over a range of temperature from 1.2×10^5 K to 4×10^5 K.

Experiments

An electromagnetic shock tube⁷ was operated at 8 kV in a range of filling pressures varying from 0.1 torr to 10 torr. The shock tube was powered by a 60 μ F capacitor bank, had inner electrode radius, a , 2 cm, outer electrode radius, b , 3.75 cm and electrode length of 20 cm. The trajectory of the magnetic piston was obtained with a movable magnetic probe.

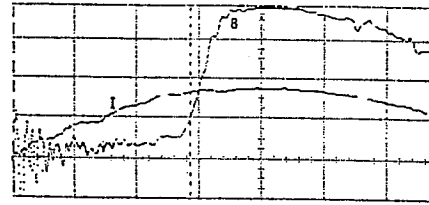
Using a snow plow model, the shock tube assuming an electromagnetic drive mode has a speed given by:

$$q_1 = \left[\frac{4\pi^2 (b^2 - a^2)}{\mu_0 \ln(b/a)} \right] \left[\frac{I_0}{a} \right] / [\sigma_0^{1/2}] \quad (6)$$

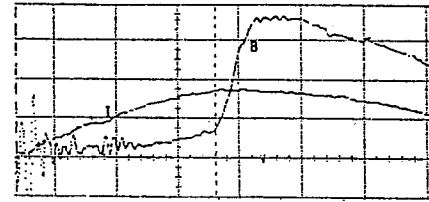
so that a change of pressure range of 100 would produce a speed range of 10, if the electromagnetic mode of drive prevailed over the whole pressure range.

At 0.1 torr, typical magnetic probe signals are shown in Fig. 2. These show a z - t trajectory as indicated in Fig. 3 with a near constant speed region of 6.6 cm/ μ s between $z > 4$ cm and $z = 14$ cm.

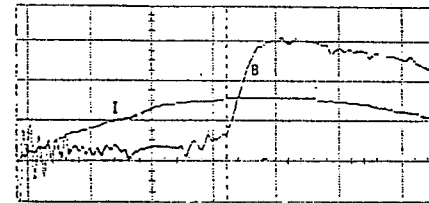
The rise time of the magnetic field as the current sheath sweeps past the probe at each z position (Fig. 2) is converted into current sheath thickness using the speed information obtained from Fig. 3. This gives a picture consistent with a current sheet having a steady structure of constant thickness between 2 and 2.5 cm for z



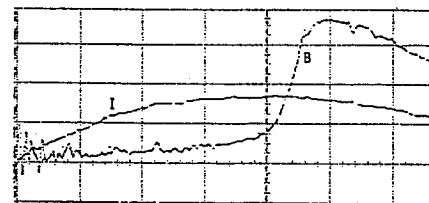
(a) $Z = 4$ cm



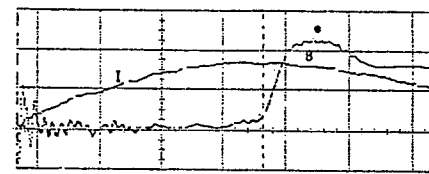
(b) $Z = 6$ cm



(c) $Z = 8$ cm



(d) $Z = 10$ cm



(e) $Z = 12$ cm

Fig. 2 Magnetic field B and plasma current I signals of the electromagnetic shock tube for various z -positions at $P = 0.1$ torr argon. (Timebase: 1 μ s/div).

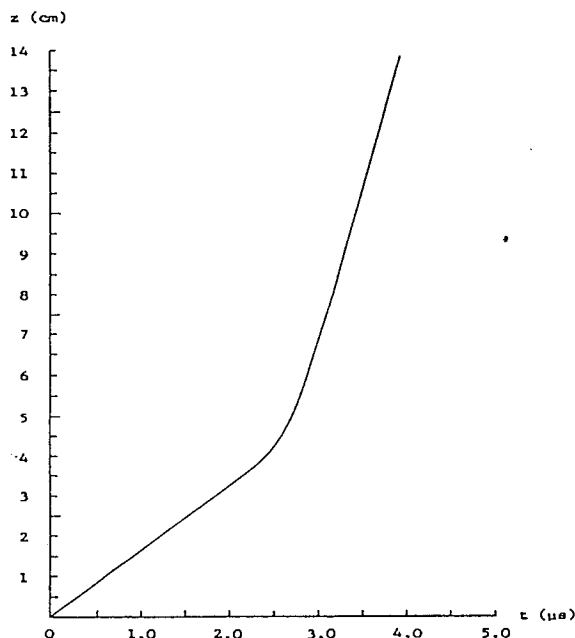


Fig. 3 The z - t trajectory of the electromagnetic shock tube at $P = 0.1$ torr argon.

> 4 cm to $z = 14$ cm. The overall evidence is consistent with non-diffusive good electromagnetic drive with $R_m \gg 1$. Using the value of $\ell = 2.5$ cm and the computed reference magnetic Reynold number R_m^* of Fig. 1, R_m at the observed speed is found to be 27.

Several sets of data taken between 0.1 torr and 0.6 torr show similar features of steady structure indicative of good electromagnetic drive. At 0.6 torr between $z = 3$ cm and $z = 15$ cm, there is a near constant speed region of 3.2 cm/ μ s with a current sheath thickness of 2 to 3 cm. The reference magnetic Reynolds number from Fig. 1 is 1.5 and the value of R_m using the experimentally measured value of $\ell = 2.5$ cm is 4. Although with a value of $R_m = 4$ we may consider that the drive is only 80% electromagnetic and is already 20% diffusive, the experimental results indicate that the snow-plow model and its Equation (6) is still applicable and that the propagating current sheath may still be treated as an essentially non-diffusive structure.

As the pressure is increased further the evolution of the current sheath structure begins to show significant signs of diffusion. For example at 1 torr, the magnetic field signals at several

positions from $z = 1.5$ cm to $z = 6$ cm indicate that the sheath thickness has diffused from 2.5 cm at $z = 1.5$ cm to 3.5 cm at $z = 6$ cm. The diffusive characteristic steadily becomes predominant as the pressure is raised and observations are taken up to 10 torr. For example, at 5 torr and 7 torr the magnetic signals from $z = 1$ cm to $z = 3$ cm are shown in Fig. 4 and Fig. 5 respectively.

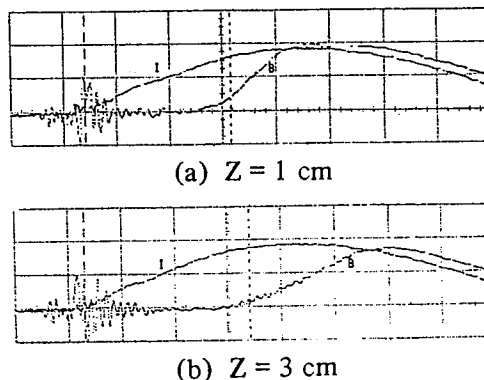


Fig. 4 Magnetic field B and current I signals of the electromagnetic shock tube for $z = 1$ cm to $z = 3$ cm at $P = 5$ torr argon. (Timebase: $1 \mu\text{s}/\text{div}$).

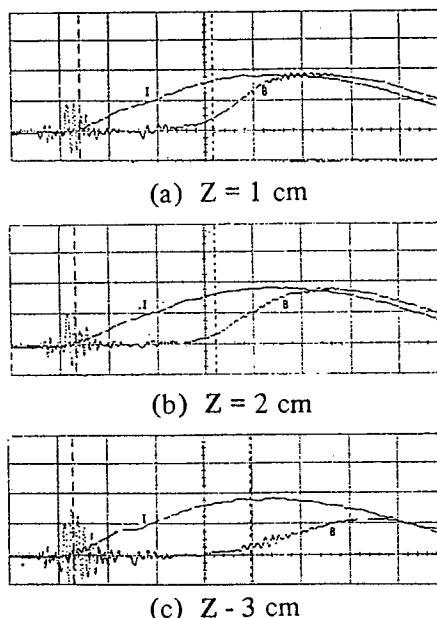


Fig. 5 Magnetic field B and current I signals of the electromagnetic shock tube for $z = 1$ cm to $z = 3$ cm at $P = 7$ torr argon. (Timebase: $1 \mu\text{s}/\text{div}$).

From Fig. 4b (5 torr) the magnetic sheath sweeping past the probe at $z = 3$ cm is estimated to have a thickness of 3.6 cm as compared with the structure at $z = 1$ cm which has a thickness of 1.8 cm.

The corresponding value of R_m , using the experimentally estimated ℓ are 0.9 (at $z = 1$ cm) and 1.8 (at $z = 3$ cm). It must be recognised that because of the obvious diffusive nature of the sheath, the estimation of speed is not very meaningful so that the above quoted values of R_m represent at best very gross estimates. Fig. 5 or 7 torr operation shows similar clear features that the current sheath propagation is diffusive in nature.

Conclusion

In this paper it is shown that in driving a strong shock the reference magnetic Reynold number is dependent on shock speed to the 4th power for a plasma which may be considered as a perfect gas, e.g. for fully ionised hydrogen and for argon in a temperature range characterised by ionisation to a close-shell configuration. In other ranges where the gas is freely ionising the magnetic Reynold number is approximately dependent on the shock speed to the 2nd power.

For argon between 1 cm/ μ s and 4 cm/ μ s may be identified a freely ionising range during which the reference magnetic Reynold number increases as q_1^2 . With higher shock speeds e.g. from 6 cm/ μ s to 8 cm/ μ s the reference magnetic Reynolds number increases more rapidly approximately as q_1^4 .

The computation further predicts that with the magnetic characteristic length of $\ell = 1$ cm, we require shock speed above 6 cm/ μ s to have

$R_m^* \gg 4$. (R_m^* being the magnetic Reynold Number referenced to $\ell = 1$ cm).

Experimentally we measure ℓ to be 2 cm for steady drive structures driven at pressures between 0.1 torr and 0.6 torr for argon and corresponding speeds of 6.6 cm/ μ s and 3.2 cm/ μ s giving magnetic Reynold number of 27 and 4 respectively. In this regime of operation the magnetic signals at varying drive distances up to $z = 16$ cm show clearly a steady, non-diffusive, predominant electromagnetic drive mechanism. In this regime the electromagnetic drive model such as the snow plow model may be used.

At pressures ranging from 1 torr to 10 torr, the magnetic field structures are clearly diffusive corresponding to magnetic Reynold number about 1. In this regime it is clear that the snow plow equation may not be applicable. The structure moves more by diffusion than as a steady or thin structure.

These results are consistent with the theory and are important for delineating the regimes of operation of electromagnetic shock tubes and for the design of electromagnetic devices.

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X-ray emission in a small plasma focus operating with H₂-Ar mixtures

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Abstract. The temporal and spatial characteristics of the x-ray emission in a 3 kJ plasma focus are investigated when operating in H₂ with an Ar admixture. The experiments are performed in a UNU/ICTP PFF device. The x-ray emission is detected with a multichannel system of PIN-Si diodes with different filtering looking axially and radially into the focusing region. Two main periods are observed in the x-ray emission, corresponding to two successive compressions in the focus. X-ray emission arising from electron beam activity and dense plasmas is identified. On the basis of the x-ray emission characteristics several features of the plasma focus dynamics are discussed.

1. Introduction

Soft x-ray emission in transient high-temperature plasmas has attracted renewed interest in view of potential applications as a high-brightness source for lithography and soft x-ray microscopy. The plasma focus (PF) is a highly reproducible source of high-temperature pulsed plasmas (temperature typically 1 keV, density typically 10^{19} cm^{-3}) which does not require sophisticated high-voltage techniques or expensive facilities. This feature is an important advantage when compared with other pulsed x-ray sources such as laser-produced plasmas [1], vacuum spark [2, 3], gas-puff Z-pinch [4] or X-pinch [5]. Although PF devices are usually optimized for neutron production with operation in pure deuterium, it is known that if the device is operated in a mixture of hydrogen and noble gases the x-ray yield is strongly enhanced [6, 7]. The increase in soft x-ray emission depends on the particular gas used and the volumetric ratio of noble gas to hydrogen with the maximum x-ray yield being obtained at a volumetric ratio of 40% argon to 60% hydrogen [8]. The exact mechanism for high-intensity x-ray emission in PF is still controversial and more experimental work is required in order to optimize the x-ray production for practical applications. Moreover, the effect of heavy atom impurities on the focus dynamics has not yet been studied in detail. In this work we present

relative spectral response of the detectors with the different types of filters used in the experiment is shown in figure 2. The detectors are located at two different x-ray measurements. The result shows contributions to the x-ray spectrum arising from electron beam target interaction and hot high-density plasma. The time evolution of the x-ray emission is characterized by two main periods associated with two successive compressions of the focused plasma.

2. Experimental apparatus

The experiments have been conducted in a UNU/ICTP plasma focus [9], as illustrated schematically in figure 1. The PF gun is of the Mather type with 16 cm long electrodes of inner and outer diameter 1.9 and 6.4 cm respectively. The inner electrode is hollow and the outer electrode is a geometric arrangement of six cylindrical rods. The electrodes are made of copper. The energy storage is a single 30 μF capacitor and the design is optimized for operation at 15 kV (3.3 kJ bank energy) in deuterium at 4 Torr. Under these optimal conditions the maximum discharge current is 170 kA. The time of maximum compression is determined from the derivative of the discharge current, which is monitored with a small coil. The x-ray emission is observed with PIN-Si diodes of the BPX 65 type, polarized at 44 V. Different thin filters are used in front of detectors to block out visible light and to provide broad band spectral resolution. Filter thicknesses and materials are selected to provide different spectral windows in the 0.05–4.5 nm range. The

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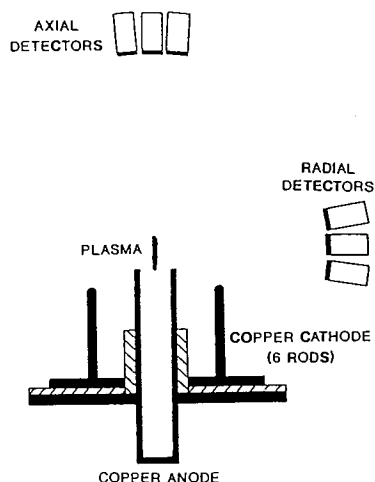


Figure 1. Schematic diagram of the focus electrode system and the experimental layout of the detectors.

observations of x-ray emission in a small PF operating with mixtures of hydrogen and argon. The main diagnostics are based on broad band time-resolved multichannel positions: firstly, looking radially at the focusing region at a distance of 16 cm and, secondly, looking axially at the focus at a distance of 62 cm (see figure 1). This arrangement allows any emission originating from the inside of the anode to be discriminated. With this geometrical arrangement for a point source at the focus position the expected signal at the axial position should be 7% of the signal at the radial location if the same filter is used in both detectors. The electric signals are registered with a four-channel digitizing oscilloscope with an effective bandwidth of 100 MHz.

3. Experimental results

The characteristic time evolution of the x-ray emission at three different H_2/Ar ratios is shown in figure 3. The signal was obtained with Mylar filtered detectors (see figure 2) located at the radial position. Two main periods of x-ray activity are observed. The beginning of each

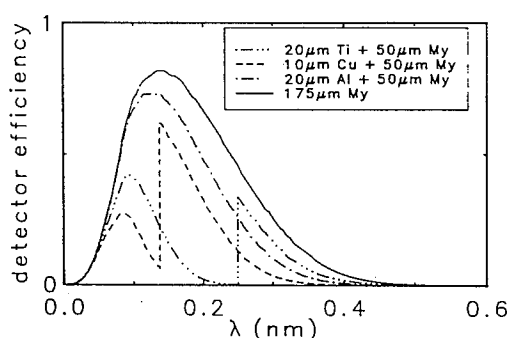


Figure 2. Detector efficiency of PIN diodes folded with filter transmission. Different curves correspond to the filter combinations used in the experiment.

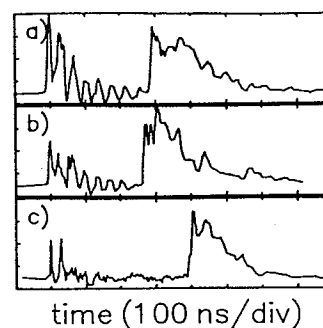


Figure 3. Characteristic evolution of the x-ray emission at three different H_2/Ar volumetric ratios: (a) 50% $H_2/50\%$ Ar at 1.1 Torr; (b) 70% $H_2/30\%$ Ar at 1.5 Torr; (c) 80% $H_2/20\%$ Ar at 1.5 Torr. Vertical axis is 4 V per division.

period coincides with a strong compression of the plasma at the focus, as it is inferred from the dI/dt signal (see figure 4(d)). The first period is characterized by one or more short pulses and separated by more than 200 ns from the second period as seen in figure 3. In the second period the emission lasts for longer than 100 ns with a narrow peak at the beginning. The single-shot x-ray signal obtained with different filters is shown in figure 4. Figures 4(a) and 4(b) correspond to radial detectors with copper and Mylar filters respectively. In figure 4(c) the detector was located at the axial position and used a copper filter of the same thickness as in figure 4(a). Figure 4(d) corresponds to the dI/dt signal. The time correlation between the x-ray periods and plasma compression (indicated by arrows on dI/dt signals, figure 4(d)) is seen clearly. Several important features of the x-ray emission can be noted. First, the signal corresponding to the radial

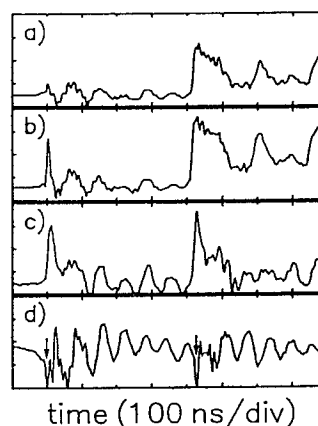


Figure 4. Single shot x-ray emission observed with different filtering. The volumetric mixing ratio is 92% $H_2/8\%$ Ar at a pressure of 1.5 Torr. (a) Radial detector with copper filter, (b) radial detector with pure Mylar filter, (c) axial detector with copper filter, (d) time derivative of the discharge current. The two arrows indicate times of large dI/dt , corresponding to times of plasma compressions. The vertical axis in the x-ray signals is 4 V per division. dI/dt is shown in arbitrary units.

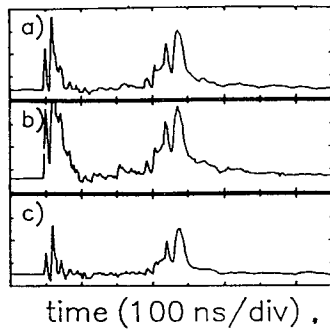


Figure 5. Single shot x-ray emission observed with radial detectors. The volumetric ratio is 50% H_2 /50% Ar at a pressure of 1.1 Torr. (a) Aluminium filter, (b) Mylar filter, (c) copper filter. Vertical axis is 4 V per division.

detector with the copper filter does not show the strong peak at the first compression seen in the axial detector with the same filtering and in the radial detector with the Mylar filter. Second, due to the geometrical arrangement, the signal in the axial detector (at a distance of 16 cm from the focus) at each plasma compression corresponds to an x-ray flux 14 times higher than that in the radial direction (at a distance of 62 cm from the focus) for an equivalent signal level. Thus, comparing the axial detector (figure 4(c)) and the radial detector (4(a)), both with identical copper filters, it is noted that the x-ray is detected axially about 100 times during the first period and about 20 times during the second period when compared with the x-ray detected radially. Third, the strong peak at the first compression seen in the axial detector is delayed by ~ 20 ns with respect to the equivalent peak in the radial detector with the Mylar filter. The nearly 30 ns period signal superimposed in all traces is due to noise induced by electrical oscillations in the PF circuit. The x-ray emission is shown with different filtering in figures 5 and 6. In all cases the detectors are located at the radial position. The emission peak at first compression is present in signals obtained with Mylar, aluminium and titanium filters and it is very weak or

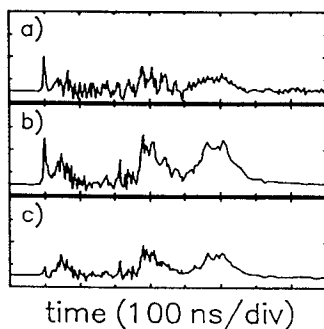


Figure 6. Single shot x-ray emission observed with radial detectors. The volumetric ratio is 80% H_2 /20% Ar at a pressure 1.5 Torr. (a) Titanium filter, (b) Mylar filter, (c) copper filter. Vertical axis is 4 V per division.

nearly absent in the signal corresponding to the copper filter. The sequence with copper, aluminium and Mylar filters shows a second peak in this period with the lower intensity corresponding to the copper filter. In the second period the stronger signal is obtained with the Mylar filter in all cases. The signal obtained with the copper filter is less intense than with aluminium but stronger than with titanium. In this second period the temporal features of x-ray emission are roughly the same with all filters.

4. Discussion

Hirano *et al* [10] have studied the x-ray emission in a 65 kV, 9 kJ PF operating in pure deuterium. Soft x-rays were found to be emitted within a time span of ~ 50 ns in a characteristic series of successive peaks, corresponding to the maximum compression, the disruption and the decay of the plasma column. Detailed studies of the spatial and temporal evolution of the x-ray emission in PF operating with a hydrogen-argon mixture have been reported by Choi *et al* [11] in a 60 kV machine. A first period in the x-ray emission was found to be associated with the formation of hot, dense plasma regions which evolve in a timescale of less than 100 ns. The formation of a second dense plasma region is linked with the onset of a high-energy electron beam. A significant fraction of the x-ray emission is attributed to H- and He-like argon lines in the 0.3 to 0.4 nm region. The observation of two successive compressions when operating with hydrogen-argon mixtures has been previously reported by Volobuev *et al* [7] in 30 kV, 50 kJ and 20 kV, 20 kJ PF machines. In these cases the second collapse is ascribed to the break-up of plasma filaments into hot spots. The previous results show that x-ray emission is highly complex and some particular features appear to be machine dependent. In our experiments we observe a similar temporal behaviour as Volobuev *et al* [7], with two successive compressions of the focused plasma. In the first compression the x-ray emission starts with a narrow peak which coincides with the first dip in dI/dt . This is clearly seen in the Mylar filtered x-ray signal observed in the radial direction shown in figure 4(b). At this time the copper filtered detector at the same radial position (see figure 4(a)) does not show a significant excursion, whereas the axial detector with the same filtering (figure 4(c)) shows a large peak, whose maximum is delayed by ~ 20 ns with respect to the signal in figure 4(b). The absence of an equivalent emission peak in the copper filtered radial detector indicates that the emission seen along the axis around maximum compression time originates inside the inner rim of the hollow anode. The x-ray signal in the radial detector at this time can be attributed to emission from the hot dense plasma formed at maximum compression in the focusing region. Characteristic duration of this first x-ray pulse is about 10 ns. The emission shows an important contribution of H- and He-like argon lines in the 0.3–0.4 nm band. This can be seen in figures 5 and 6, where the scaling of the signal

level in the first peak corresponds exactly to the relative detector efficiency shown in figure 2. The fact that the titanium filter gives a signal several times higher than with the copper filter indicates that at this time the emission does not contain characteristic copper lines. A comparison of signal level with different filters indicates that the strong peak along the axial direction is due to electron beam bombardment of the inner rim of the hollow anode. In this case the emission is dominated by copper K_α lines and is consistent with the emission of a 30 ns axial electron beam which reaches maximum intensity about 20 ns after peak compression. The second period of x-ray emission starts at the time of a second compression in the focus, as can be seen in figure 4. Again, a comparison of relative signal level between the radial and axial detectors shows that the first peak of the axial emission in this period is an order of magnitude more intense than that measured in the radial detectors. Maximum x-ray signal in the axial detector is also delayed by ~ 20 ns with respect to the radial detectors as in the first period. The axial emission is characterized by a narrow peak, indicating that it is most probably due to a second axial electron beam hitting the anode rim. The radial emission shows a fast rise which is then followed by a slow quasi-linear decay. This time the radial detector with the copper filter shows a strong signal with a time evolution identical to that seen with the Mylar filtered detector at the same position. The bulk of the x-ray emission is strongly dominated by copper lines, as can be inferred from the relative signal level in figures 4, 5 and 6.

The temporal evolution of the x-ray emission in these experiments is in general agreement with results obtained in larger machines, as reported by Volobuev *et al* [7] and Choi *et al* [11]. In particular, the electron beam following the first plasma compression is discussed in detail by Hirano *et al* [10]. The second period, associated with a second dip in dI/dt observed 200 to 300 ns after the first compression, is briefly discussed by Volobuev *et al* [7]. The large extent of the copper line emission is ascribed to a decompression of vaporized anode material. The exact relation between hot plasma formation and electron beam emission is not yet fully understood and more experimental work should be conducted to clarify the physical mechanism involved. This is also valid in relation to the dynamic phenomena responsible for the second compression observed in the experiments. Our

results show that even at fairly modest levels of operational voltage and stored energy, the x-ray emission is highly complex, although the shot-to-shot reproducibility of the main features under each condition was found to be good. Potential applications usually require soft x-rays which exclude energetic K_α lines. From this work the strong emission with a large content of copper lines seen in the second period appears to be inconvenient. The elimination of these copper lines by redesigning the focus electrodes needs further experimentation. New electrode materials may also need to be considered.

Acknowledgments

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Bench-Marking the 3 kJ Plasma Focus*

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A study of the body of experimental results as well as modelling indicates that all plasma focus machines big and small operate with the same energy density both in the axial and radial phases related to an almost constant current per unit radius for all machines. This results in operational speeds and compressed plasma temperatures which are the same for all machines. It is proposed that the existing network of 3 kJ machines may be the most efficient and effective way to produce a comprehensive experimental picture of the plasma focus. Operational bench-marks are established for these 3 kJ machines.

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I. Introduction

The small plasma focus (1–10 kJ) is the most cost-effective device to produce a high temperature (1 keV) and high density (10^{19} cm^{-3}) plasma. When operated with argon or xenon it produces large quantities of soft x-ray whilst with deuterium it produces a fusion plasma. Typical operation in a 3 kJ device in 3 torr deuterium produces a burst of 10^8 neutrons of 10^{-7} s duration giving peak emission rates in excess of 10^{15} n/s. The scaling law that neutron yield is proportional to the square of device energy ($Y \sim E^2$) has been experimentally established.

A careful comparison of data¹ produced by large (above 100 kJ), medium-sized (10–100 kJ) and small plasma focus machines all over the world indicates that irrespective of size all installations produce plasmas of the same temperature within a small range of densities. This is a remarkable and useful characteristic for design purposes. This characteristic is closely related to a simple conventional design criterion that the current amplitude per cm of anode (I_0/a) is almost constant at about 300 kA/cm. This ensures for all machines the same value of drive magnetic field in the axial phase and the same compressed energy density in the focus phase leading to the same high temperature in all devices, large or small. On the other hand this energy density limit corresponding to an axial drive speed limit of about 10 cm/ μs is also suspected of limiting the neutron yield scaling law to $Y \sim I^4$ instead of a better scaling law of $Y \sim I^n$ where n could be as high as 8 if advantage is taken of the rapid increase of D-D fusion cross-section with temperature (power greater than 4) at the operating temperature of existing plasma focus machines.

The larger machines produce more neutrons. This increased neutron yield appears to be due only to a combination of the larger volume of focussed plasma with the consequent increase in lifetime of the focussed region. Any realistic modelling of the

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plasma focus will show that each linear dimension of the approximately cylindrical focus or pinch region is proportional to the anode radius. And since all plasma focus are designed conventionally with a constant I_0/a it follows that the volume of the focussed or pinched plasma is proportional to I_0^3 . The period of plasma confinement is limited by the magnetohydrodynamic transit time, a function only of the smallest linear pinch dimension, and hence of I_0 since the energy densities which control the relevant magnetohydrodynamic speeds are practically identical as discussed above. Combining these scalings of volume and confinement time gives immediately the experimentally observed scaling law of $Y \sim I^4$.

II. The phases of plasma development

Breakdown phase: The device consists of an inner electrode and a coaxial outer electrode separated by a refractory insulator at the launching end. Capacitor C_0 charged to voltage V_0 is switched onto the inner electrode by switch S (Fig. 1) so that a discharge occurs across the surface of the insulator between the electrodes. The $\mathbf{J} \times \mathbf{B}$ force on this axially symmetric surface current lifts the current off the insulator in an inverse pinch phase.

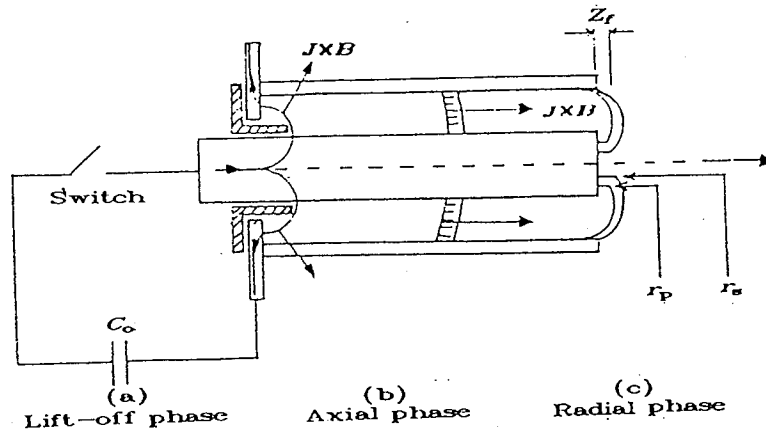


Fig. 1: Modelling the plasma focus: (a) breakdown and lift-off phase (b) axial acceleration phase, (c) radial implosion focus phase; the $\mathbf{J} \times \mathbf{B}$ force during this phase implodes the plasma layer radially inwards, at the same time elongating the pinching column.

Axial acceleration phase: The current then flows radially outwards between the electrodes in a radially symmetric sheet canted in the forward direction at the inner electrode. The current sheet scooping up all the gas it encounters is accelerated down the tube. Detailed experimental work has shown that for a 1-D representation it is necessary to assume that the drive current is a fraction (typically 0.8) of the external circuit current whilst the mass sweptup is a fraction (typically 0.2) of the total mass encountered by the current sheet. This may be referred to as a current shedding and a mass shedding effect.

Radial implosion phase: When the current sheet reaches the end of the anode the

end of the sheet which has been sliding along the anode in the axial direction begins to slide across the face of the centre electrode in the radially inward direction. The other end which has been sliding along the outer electrode in the axial direction continues in its motion. Because of the increasing drive magnetic force (inversely proportional to the square of radius) the current sheet or magnetic piston accelerates inwards driving an imploding shock wave ahead of it. The configuration is that of an elongating pinching layer of shock heated plasma (of length Z_f) lying between the radially converging shock front at r_s and the radially driving piston at r_p .

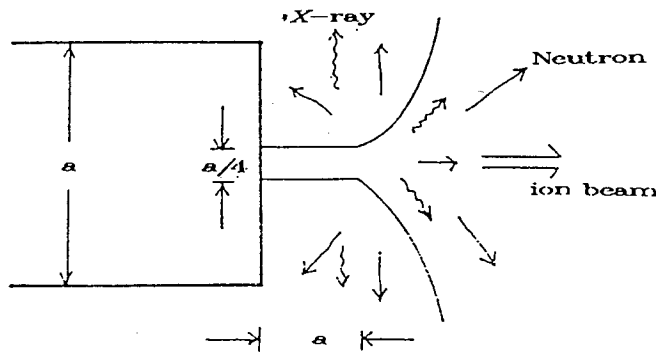


Fig. 2: Dimensions of the dense plasma focus column, at the end of the implosion phase.

When the shock front has imploded on-axis the magnetic piston continues converging on-axis driving the shock which reflects off-axis. The reflected shock soon hits the piston ending the dense phase. Whilst it lasts a dense plasma column sits on the axis of the focus tube just off the face of the anode. As a rule-of-thumb the radius and length of this dense plasma

focus column (Fig. 2) may be taken as $1/8a$ and a respectively when operating in deuterium, and has a significantly smaller radius less than a when operating in argon or xenon due to thermodynamic effects.² Towards the end of this dense plasma phase instabilities mainly of the $m=0$ type set in. The dense column seems to explode in a manner more rapid and certainly more spectacularly chaotic than the relatively very well-behaved implosion phase. A large diameter turbulent plasma is rapidly formed.

The sequence of events from the implosion to the formation of the large diameter plasma has been presented in sequences of time-resolved Schlieren photographs correlated to the measured tube voltage, and x -ray and neutron signals (Fig. 3).³ There is consistent evidence to show that the soft x -ray from the plasma is associated mainly with the dense plasma phase, the hard x -ray is more to be associated with the instability phase whilst the neutron emission peaks between the instability and the explosion phase.

III. Design parameters of the plasma focus

The electro-dynamical behaviour of the plasma focus may be described in each of the major phases by writing down the equations of motion coupled to an appropriate circuit equation.

In the axial phase adopting a snow-plow or thin-layer model results in a two-equation system⁴ which on appropriate normalisation yields two scaling parameters determining the behaviour during this phase. These two parameters take the form of an impedance matching parameter, $\beta = L_{z0}/L_0$ defining the matching of L_{z0} the maximum tube

inductance of the axial phase to the stray inductance L_0 of the circuit and a time matching parameter, $\alpha = t_0/t_a$ defining the matching of t_0 the characteristic electrical time of discharge to the characteristic axial transit time t_a where $t_a = K z_0 p_0^{1/2} / (I_0/a)$. K is a geometrical constant also incorporating the current shedding and mass shedding factors and p_0 is the ambient density. This yields a characteristic axial speed of $u_a = z_0/t_a$ which assumes the form: $u_a \sim (I_0/a)/p_0^{1/2}$.

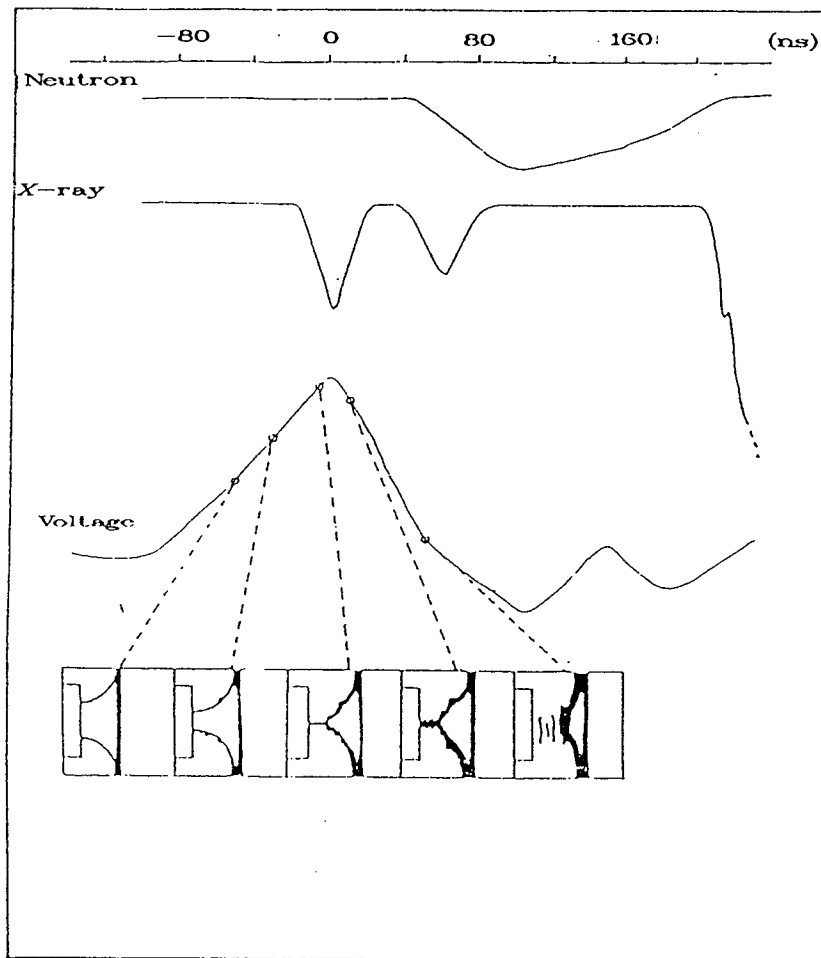


Fig. 3: Summary of the temporal development of the radial implosion process.

Moreover¹⁸ in both the axial and radial phases the characteristic speeds scale as (I_0/a) and inversely as $(p_0^{1/2})$.

There are three design criteria⁵ arising out of the consideration of the axial phase. First, the value of α should be designed to be in the range 1–1.5. Second, β should not be too much less than 1. Third, all conventional machines seem to need to be adjusted to operate in a narrow range of axial speeds (just before radial collapse) of 8–12 cm/ μ s, in order to achieve optimum neutron yield.

The 3kJ plasma focus known as the UNU/ICTP PFF (United Nations University/International Centre for Theoretical Physics Plasma Fusion Facility)⁵ has been designed

with $C_0=30\ \mu\text{F}$, $V_0=15\ \text{kV}$ and $L_0=110\ \text{nH}$. This defines a current amplitude $I_0=250\ \text{kA}$ fixing a as $1\ \text{cm}$, t_0 at $1.8\ \mu\text{s}$ so that risetime to peak current takes $2.8\ \mu\text{s}$ hence $z_0=16\ \text{cm}$ giving an average axial transit speed of $5.5\ \text{cm}/\mu\text{s}$ corresponding to a peak speed at the end of the axial phase of $9\ \text{cm}/\mu\text{s}$. Taking $\alpha=1.2$, a current factor of 0.85 and a mass factor of 0.2 enables us to fix an operating pressure of $3\ \text{torr}$ in deuterium. Computation of a typical model¹⁴ yields current, voltage variation and also gives trajectories in the axial and radial phases.

IV. Studies on the 3 kJ plasma focus

Typical behavior of the 3 kJ plasma focus may be observed from the signature current dip and voltage spike and by shadowgraphs of the current sheet in the axial and radial phases (Fig. 4). These results establish that the electro-dynamical behavior of the small plasma focus is no different from the larger plasma focus devices.

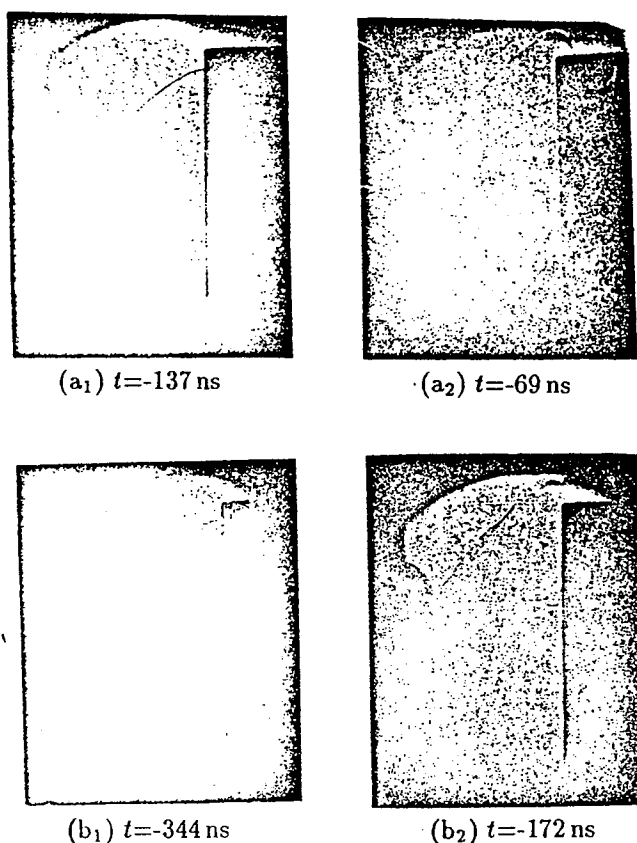


Fig. 4: Shadowgraphs comparing axial phase and start of radial phase for normal positive polarity vs. negative polarity focus:

- (a₁) positive polarity end of axial phase
- (a₂) positive polarity start of radial phase
- (b₁) negative polarity end of axial phase
- (b₂) negative polarity start of radial phase

In each shadowgraph, the anode is on the right and the cathode is on the left. Axial motion is upwards.

The 3 kJ plasma focus has been used to study ion beams⁶ from the focussed plasma using a metal obstacle and deuterated target enabling the neutron emitting regions of the device to be mapped (Fig. 5). Such experiments confirm the importance of the deuteron beams in the neutron production of the small plasma focus, no different from the case in bigger plasma focus devices.

X-ray emission characteristics in the 3 kJ plasma focus operating with $\text{H}_2\text{-Ar}$ mix-

tures have also been reported.⁷ Two main periods are observed in the x-ray emission corresponding to two successive compressions. X-ray emission arising from electron beam activity and dense plasma regions is identified and correlated to detailed features of the dynamics. Figure 6 shows temperature (T_e) evolution deduced from ratio of filtered signals.

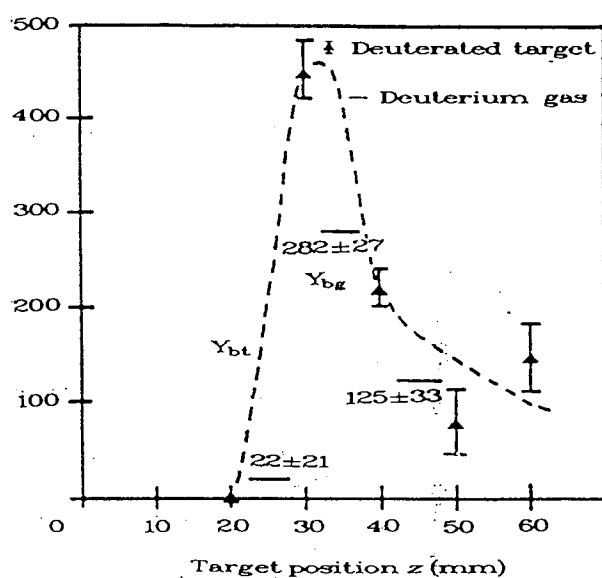


Fig. 5: Variation with position of the neutron counts (single shot) due to deuterated target alone (Y_{bt}) and due to the per cm of deuterium gas in the chamber (Y_{bg}).

Other studies using the 3 kJ plasma focus emphasize on neutron emission,⁸ influence of back-wall insulator dielectric constant on neutron yield,⁹ instabilities as elaborated by shadowgraphy, materials modification¹⁰ using ion beams from the focus, studies of the plasma focus as a source of high pressure,¹¹ negative polarity plasma focus (Fig. 4(b)) and focus implosion onto a axial

wire target,¹² studies of a cascading plasma focus system¹³ with possibility of sequenced bursts of x-ray and neutrons¹⁴ for cinematographic purposes and studies of chaos mechanisms and deterministic dynamics.¹⁵

V. Network of 3 kJ plasma focus installations

There exists a large variety of phenomena occurring in sub-microsecond phases in the focus, including highly nonlinear and chaotic behaviour, hence each existing plasma focus facility only manages to study some aspects of the total behavior. The collation of the total behaviour meets with a major difficulty in that each plasma focus is designed differently because of different emphasis. Thus the behaviour of each machine may be differently coloured by different machine effects or boundary conditions peculiar to that machine. Another approach for a comprehensive experimental picture may be to set up a network of identical machines on an international basis. This is not possible for big machines because of the question of cost.

On the other hand much of the physics that may be studied in large plasma focus installations can be carried out much more cost-effectively on small plasma focus devices. There is considerable savings also in experimental turn-around time. More

scientific manpower resources may be harnessed in a network including also small laboratories in small nations. Furthermore a network of 15 identical machines already exists in countries including Sierra Leone, Nigeria, Egypt, Italy, Pakistan, India, Thailand, Malaysia, Singapore, Indonesia and China. The research using this 3 kJ machine designated as the UNU/ICTP PFF^{5,17} is very diversified as already mentioned earlier. For example the machine in Pakistan is being used to look into a variety of problems⁹ including 2-D modelling, dielectric effects and instabilities; one of the two in India is being used for materials modification;¹⁰ that at the ICTP^{15,16} in Trieste has been used for studies on chaos and deterministic dynamics, to bench-mark the performance of the device and to provide international training as have the ones in Malaysia which are also being used for neutron,⁶ x-ray⁷ and basic studies, the one in Singapore for device development, cascading focus studies¹⁴ and thermodynamic effects,² the ones in Indonesia for neutrons⁸ and aerospace applications¹¹ and the one in Shanghai is being planned for laser- focus interaction. Gradual upgrading of the scientific expertise and diagnostic systems will enable the diverse results of the network of identical machines to have an impact when collated and compared perhaps under the coordination of the Asian African Association for Plasma Training (AAAPT) which has taken a leading role in the establishment of this network of devices¹⁷ as a network of the ICTP.

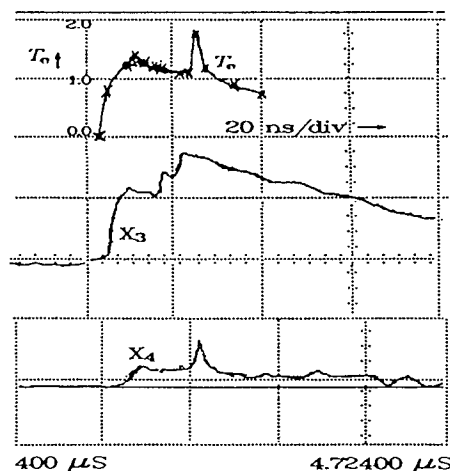


Fig.6: Single shot x-ray emission in 0.6 torr Ar.

X_3 : aluminised mylar filter ($24 \mu\text{m}$)
 X_4 : aluminised mylar filter ($24 \mu\text{m}$)
 + $10 \mu\text{m}$ copper filter
 (X_4 trace has been displaced 4 ns to compensate for difference in cable lengths)

T_e : electron temperature T_e in keV as a function of time deduced from the ratio of the signal amplitudes of X_3/X_4 .

VI. Bench-marking the 3 kJ Plasma Focus

In order for the results of the network of 3 kJ plasma focus machines to be collated to form a comprehensive total body of evidence on the experimental behaviour of the plasma focus in all its aspects, identical design alone is not enough. The devices have to be compared at identical conditions of operation. With reference to the discussions

of Section III above the axial phase dynamics is governed by the scaling parameters α and β . In identical machines (identical C_0 , L_0 , V_0 , a , z_0) these scaling parameters are made identical when the ambient pressure is set to be identical for each gas used. A more detailed discussion¹⁸ shows that even when the radial phase dynamical equations are considered the additional scaling parameters introduced remain identical for identical gas species and pressure. Thus bench-marking becomes a straight-forward procedure. Considering the large number of studies that have been carried out in the 3 kJ plasma focus⁵⁻¹⁶ we propose the following bench-marks to ensure that the 3 kJ plasma focus is operated at optimum consistency with good production of neutrons (deuterium operation) and soft x-rays:

Deuterium	:	5.5 mbar
Air	:	0.9 mbar
Argon	:	0.6 mbar

giving with better than 95% consistency the following:

Axial Transit time measured from start of current		
to time of voltage spike	:	3.0 μ s
Peak axial speed before focus	:	9.0 cm/ μ s

The proposal is that every set of experiments carried out on each of the network of 15 identical 3 kJ plasma focus machines should comprise at least some discharges with the above bench-mark operating conditions. The results of these bench-mark shots should be carefully kept. This enables standardization and interpolation, when necessary, of results for meaningful comparison.

VII. Complementing international cooperation in plasma focus research

The scientific activity of this network can complement the envisaged role of the proposed ICDMP (International Centre for Dense Magnetized Plasma) which plans to build within one centre a range of devices including one large (MJ) device, several medium energy devices and several small devices with two main objectives; firstly the consolidation and exchange of the scientific and technological expertise in pulse power technology and plasma focus technology on a world-wide basis and secondly the further development of scientific manpower in these areas by the provision of essential and integrated training combined with follow-up equipment. The Working Group of the ICDMP formed in Moscow in December 1990 has since met another six times in Warsaw, Paris, Stuttgart, San Diego, Ferrara and Beijing. It will meet again in April in London. In the meantime the training and international exchange aspects of plasma focus research is already being carried out, made possible by the versatility, simplicity and richness in physical phenomena of the 3 kJ plasma focus. Moreover with proper bench-marked experiments results from the network of 3 kJ machines may produce a more comprehensive picture of plasma focus physics than otherwise possible.

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Pulse charging of capacitors for reduction of voltage stress

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The advantages of on-demand pulse charging of high-voltage (HV) capacitors are discussed, highlighted by use of the technique to reduce the pulse width of a nitrogen laser to subnanosecond. Pulse charging reduces the HV stress on the capacitor dielectric resulting in a more compact laser reducing the discharge time of the laser strip-line capacitor. The HV pulse for charging is produced by switching a low-voltage capacitor via a step-up coil into the HV strip-line capacitor which is then immediately discharged. The system reduces the on-charge duty cycle to below 0.001.

The engineering of capacitor discharge is a major field of study in itself.¹ For repetitive operation the capacitor is charged by connecting to a dc source over a period of time t_c , holds the full voltage for t_h , and is then discharged over t_d , after which the power source immediately begins charging it, giving a voltage rest period t_r which is practically zero. For example for a nitrogen (N) laser firing at 1 pulse per second (pps) we have $t_c=10$ ms, $t_h=990$ ms, $t_d=0.1$ μ s, $t_r=0$. We define an on-charge duty cycle (OCDC) as the fraction of (the period HV is fully on across the capacitor)/(the period of the cycle), thus approximately: $OCDC = (t_h + [1/2]t_c + [1/2]t_d)/(t_h + t_c + t_d + t_r)$. For the example of the N laser we have an OCDC of 1, corresponding to continuous HV (high voltage) stress, or the maximum voltage stress situation. This high value of the OCDC is undesirable. A dielectric will withstand a much higher voltage for brief periods,¹ and will have a longer lifetime if subjected to the high voltage only when necessary.

We now design a system so that charging is triggered just before the laser pulse is required and the laser capacitor is discharged (firing the laser) as soon as it is charged. We then have $t_c=1$ ms, $t_h=0$, $t_d=1$ μ s, $t_r=999$ ms with the OCDC becoming 0.0005. With such a pulse-charging system the voltage stress time on the system accumulates to 1 s for every 2000 pulses, instead of 1 s for every pulse. In practical terms this is an enormous reduction of high-voltage stress. Very much thinner dielectric will suffice and the system may be made much more compact.

Pulse charging has been used in the charging of HV capacitors using water as dielectric,² to reduce charge leakage. On the other hand relief of high voltage stress may itself become a critical design consideration. As an example we pursue the case of the N laser further. The N laser produces a pulse typically of one to several ns.³ The laser channel sits astride two capacitors, one for voltage swinging⁴ and the other powering the laser by a ns pulse of electrical current. These capacitors are of strip-line (parallel plate) geometry giving the lowest inductance. Typically the N laser is operated with stored energy of 1 J (5 nF at 15–20 kV), laser output of 0.3 mJ, and laser power of 100 kW over the pulse width of nanoseconds. For applications such as visualization of high speed events⁵ or fluorescent studies of environmental samples⁶ it is desirable to get the pulse width down to below a ns without reduction in pulse intensity. This has turned out to be difficult due to the size of the strip-line capacitors.

Using mylar (relative permittivity $\epsilon_r=3$) as insulation we have the capacitance C given by: $C=0.0266 (A/d)$ nF, where A is the area of the capacitor plates and d the thickness of the insulating mylar. To get 5 nF we require $(A/d)=188$ m. Using $d=0.2$ mm (four layers of 50 μ m mylar film) we require $A=376$ cm². A literature survey shows that the length of the laser channel is between 10 and 20 cm. Thus the strip-line capacitor powering the laser needs to be no less than 20 cm in length, fixing the electric current discharge time and hence the laser pulse width to no less than 2 ns. We have used a lumped circuit model^{4,7} to show that conventional N laser design has maximized circuit discharge speed to approach the limit discussed above.

Of course the pulse width may be reduced by reducing the length of the strip line to 10 cm or less, but this is accompanied by a reduction in capacitance (hence laser energy) unless we compensate by a reduction in d . However it is found that two layers of 50 μ m mylar totaling $d=0.1$ mm puncture often (even three layers puncture, though less frequently). Thus d cannot be reduced. In this situation pulse charging provides a breakthrough. With pulse charging, the OCDC and hence the HV stress, is enormously reduced. With an OCDC of 0.001, adequate insulation is provided by $d=0.1$ mm, and even $d=0.05$ mm, for 16 kV, enabling the reduction of the strip-line length to 10 cm. Further by halving the pulse width we double the laser intensity. We may thus further reduce the strip-line length to 5 cm using $d=0.1$ mm, indeed with an increase in power when compared with the original typical configuration. The lumped circuit model⁴ shows that our improved strip line produces a FWHM pulse width that is reduced to less than 1 ns. The situation is improved further if $d=0.05$ mm is used, leading to further improvement of compactness and pulse width.

A simple circuit (Fig. 1) has been developed to implement the on-demand pulse charging of the N laser. The pulse charging (electrolytic 0.1 mF) capacitor C is charged continuously at 340 V. A silicon-controlled rectifier (SCR) is used for the pulse charging switch. On switching the discharge of C is transformed to 16 kV by a motor cycle ignition coil. To keep the OCDC small the N laser is triggered via the laser spark gap soon after the strip-line capacitors are fully charged, using a delay circuit set at 350 μ s. The inductor (mains choke) is to provide resonant charging mode for C . With this mode, parameters may be more easily adjusted to ensure that the SCR switches off after the discharge

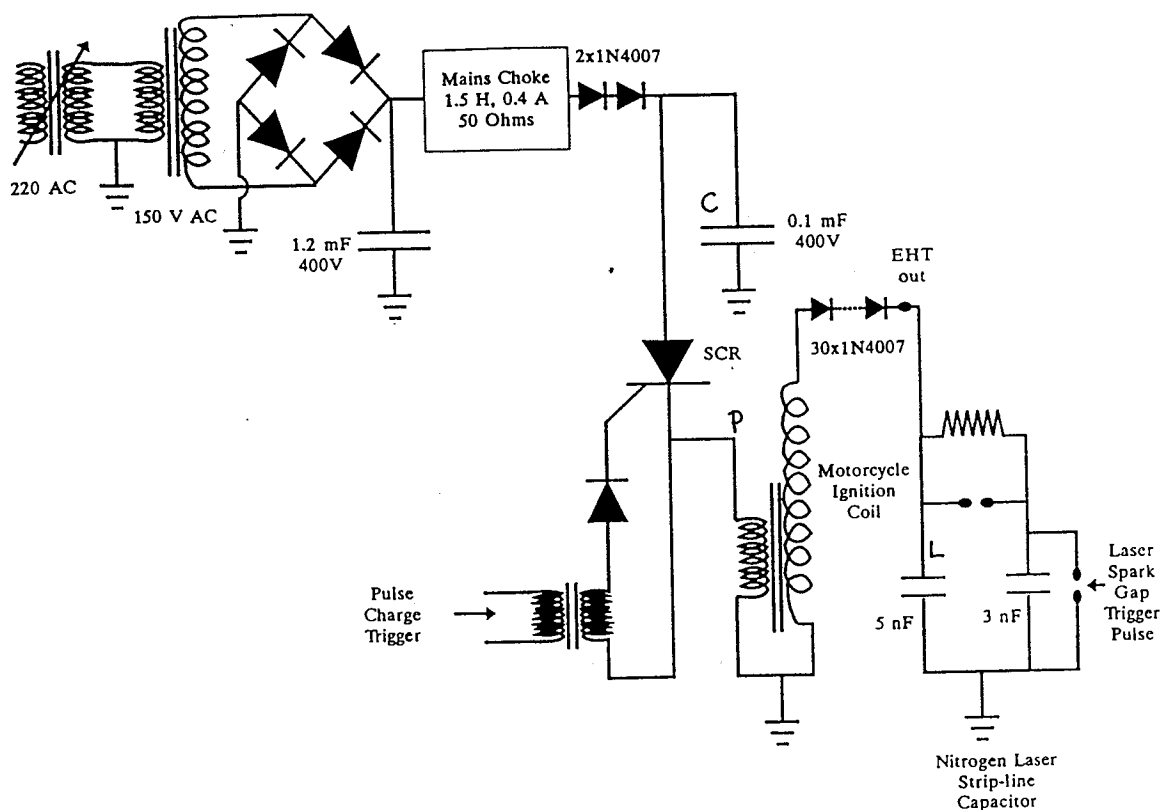


FIG. 1. Circuit diagram of the pulse charge system.

of C . At the same time the resonant mode gives rise to voltage enhancement (up to 2). The HV terminal after the ignition coil is taken to an HV rectifier chain of 1N4007 diodes, to isolate the HV strip-line capacitors, once charged, from the grounded secondary coil.

Test pulses at various points of the circuit are obtained with a 1 Gsa/s (Gigasample per second) DSO and these are shown in Fig. 2 for the voltages at C and L . On triggering the SCR the voltage at C drops from 340 V to 0 in 800 μ s while voltage at L rises to 16 kV in 250 μ s. For this shot the

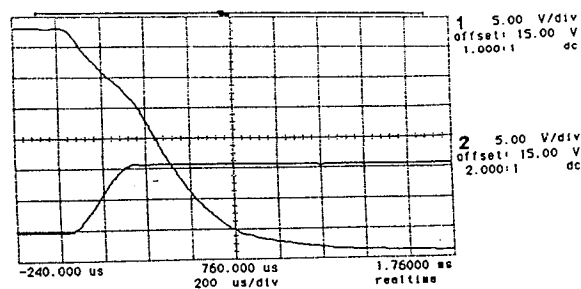


FIG. 2. Voltages at points C (trace starting at the top) and L (bottom trace) on triggering of SCR. Laser HV capacitors not triggered. Time (horizontal) scale is 200 μ s/div. Top trace: 50 V/div. Bottom trace: 7 kV/div. (For points C and L , refer Fig. 1.)

laser capacitors are not triggered. Hence the voltage at L remains on, holding at 16 kV. Typically we trigger the laser strip-line capacitors within 100 μ s of reaching 16 kV thus reducing the OCDC to no more than 0.000 35 for 1 pps.

Besides N laser systems the pulse charge system could also be used to advantage in high-voltage pulse generators, pulse systems, and impulse testers.¹ The range of parameters discussed is only an example, not to be taken as limitations. The range of voltage and charging capacity can be extended. The use of pulse charging could change the design concept and economics of HV capacitor systems.

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SAREC DOCUMENTATION

THE INTERNATIONAL
**SCIENCE
PROGRAMS**
OF UPPSALA UNIVERSITY

AN EVALUATION REPORT

BY OLLE EDQVIST, BERHANU ABEGAZ,
LEE SING AND BARRY NOLLER

EVALUATIONS 1994:2

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Acknowledgements

The task of evaluating the International Science Programs (ISP) at Uppsala University was given by SAREC in October 1992 to an evaluation team consisting of Dr Olle Edqvist, Stockholm (team leader), Dr Berhanu Abegaz, Addis Ababa, Ethiopia, Prof Lee Sing, Singapore and Dr Barry Noller, Darwin, Australia.

The work was finished in February 1992. The evaluation team met the ISP staff and a number of Swedish host institutions in November 1992. In December the evaluation team members visited some 40 institutions in Africa, Asia and Latin America and met and discussed with several hundred scientists who in one way or another are involved in the work of ISP. The International Centre for Theoretical Physics (ICTP) and the Third World Academy of Sciences (TWAS) at Trieste, Italy, and the International Science Foundation (IFS) have also been visited. The final report was delivered in February 1993.

The team is grateful to SAREC for the opportunity to evaluate ISP. ISP is a fascinating organisation with a long history and great experience. It has been very rewarding work. The visits we have made to institutions all over the world have brought us into contact with enthusiastic, hard-working and highly competent scientists, young and senior. We have learned a lot from them. We have been extremely well received everywhere and met with warm hospitality. We would like first and foremost to thank all who have taken time to discuss with us, to describe their work, their aspirations and their problems. Undoubtedly this reception is due to the importance the researchers both in the groups supported by ISP and in the host groups attach to ISP's work.

The Rector of Uppsala University, Stig Strömholm, received the team with great hospitality at its first visit to the university. The Directors of ISP, Lennart Hasselgren and Rune Liminga, the Head of Administration, Åsa Bergengren, and the staff of ISP, have given us all possible help and in various ways supported our work. We thank them warmly.

The practical – and decisive – matters involved with this enterprise have been handled with efficiency by Maija Lindroos at CITEC. When work must be done in such a short timespan, travel arrangements are of vital importance. To get four busy people to meet in faraway Sweden, to put them flying in different directions to three continents and to get them together again

without mishaps is an achievement. We wish to thank her for all support. Finally we would like to thank Eve Johansson for checking the language of the report.

1. Executive summary

Basic sciences and development aid

Our point of departure is that research in the basic sciences, including fundamental research, is an important part of development in poor countries. We think that basic sciences should be supported on three grounds: their contribution to applied sciences, their role in university training and education and their role for technological development. The development of good and inspiring teachers in the sciences and the formation of *a new generation of young scientists* with a solid scientific training are seen as an important output of basic research. In addition we stress the importance of transferring *instrument technology* and scientific methodologies between the sciences and from fundamental research to development work and production.

Observations

The salient features of the ISP work have been its long term commitment to good research groups and its determination to phase out projects when the work has been successfully concluded or when the quality of the work is not satisfactory. This readiness of ISP to make uncomfortable decisions has been very important for the long-term results of the programme.

The results from the ISP support have been excellent with a minimum of financial input. The Asian research projects visited by the team and supported by ISP have (over a 10-year period) in total produced 20 PhD theses, 134 MSc theses and more than 200 scientific papers in refereed journals. The average annual funding per project has been 100-130 kSEK. The Latin American projects have resulted in 5 PhD theses and 13 MSc's, which also can be judged as a good result. Considering that most of the African projects are more recent, satisfactory results have also been achieved in Africa where 3 PhD theses and 11 MSc theses have been completed with ISP support.

That this has been possible with such small means depends on the mode of work of ISP, where the responsibility for progress rests with the research group supported. The ISP support is a critically important input, but also an encouragement and a strong incentive to do good work. ISP has in this way helped the supported groups to help themselves.

Other beneficial aspects of the ISP support have been identified, including pressure and help to get research results into print, help in building up instrumentation and in improving laboratory environments. Continued support to give the research groups access to library services and scientific journals is essential.

The work of ISP is to a very great extent dependent on the directors. They play a decisive role in leading the work, in visiting research groups, in choosing researchers for training, in judging proposals, in phasing out projects and in keeping in touch with the host institutions. Their good judgement is fundamental for the performance of ISP. The results of ISP, as we see it, speak well for the way the directors have managed their respective tasks. We have met unanimous praise for their work.

The work of ISP is in practice split into two separate programmes, IPPS and IPICS, with separate identities under the ISP umbrella. The lack of coordination between the branches has led to a greater spread over countries and universities than is desirable. The benefits of working within a common organisational frame are not fully utilised.

The administration services are very good. It seems that the sharing of the practical burdens of these tasks between the ISP secretariat, the programme directors and the assistant director on the one hand and the Swedish host institutions on the other, is handled very well and without frictions.

Recommendations

The main component of the present ISP work is the promotion of and support to long-lasting *south-north* links between research groups in developing countries and in Sweden. ISP should continue to train researchers from selected research groups in developing countries in a "sandwich" model with repeated shorter visits to Swedish institutions. That support should be complemented with support on a project basis to the research group for equipment, travel, spare parts, other follow-up, courses etc. Training of researchers for PhD or MSc degrees should be done with the base in the home country and aiming for the awarding of degrees in the home university as far as possible.

However, there is another pattern of support emerging from the present programme practices – the *South-South-North triangle*, i.e. regional collaboration between two or more research groups in the Third World supported by north-south

links. Regional research collaboration enables scientists in a region to share scarce resources, to help each other with practical matters and to overcome shortages in knowledge and resources. Such triangular arrangements of a South-South-North character where regional collaboration is supported both scientifically and financially from Sweden offer a pattern with promise for the future.

It is recommended that ISP concentrate on providing support to *university departments*. Some projects may be partly situated in institutes outside the university (geological surveys, specialised research institutes etc.), but the centre of every project should still be situated within a university department. Scientific quality should be the main criterion for choice of new projects for support. In all work the main concern should be to make advances in the research projects through postgraduate training and publications.

New branches for biology and geosciences should be set up. The *biology branch* may include disciplines such as ecology, environmental biology, systematic botany, zoology, limnology, molecular biology and genetics. It should have a bearing and an emphasis on research problems of relevance for the tropical environment and ecosystems.

The new branch for *geosciences* may include support to research within earth sciences such as seismology, geology, hydrology, coastal marine research, climatology, atmospheric sciences, solar radiation etc. The focus should be on university research as a basis for the development of services such as regular measurements and interpretations of various geoscientific data.

If new branches are set up the existing branches of ISP for physical and chemical sciences will be able to concentrate their work on these sciences.

It is recommended that ISP give increased support to *instrument construction, adaptation and development*, as well as help with procurement advice. Particular emphasis should be given to the development of the competence of the research groups to adapt and build their own equipment. Training of technicians in instrument repair and handling as well as in workshop techniques (electronic, mechanical, glass-blowing etc.) may be supported as part of a major project.

In the light of the excellent results achieved, and in order to enable ISP to carry out the increased tasks spelled out above – to respond to the higher ambitions in terms of scientific scope, follow-up support and instrumentation support – increased financial resources are both justified and needed.

The team therefore recommends that SAREC continue to support ISP and *increase its core funding in stages up to 28 MSEK in 1995/96*. It is important that the contribution be given as a block grant and that commitments are given on a three-year basis.

We believe that there are good possibilities for seeking *additional funding from other Nordic countries* if ISP includes new host institutions from other Nordic countries and increases the scientific scope of work. When setting up the new branches and choosing areas of work, ISP should give attention to the funding preferences of other potential donors.

In order to strengthen the Board of ISP and to give it a proper leading role in the organisation a restructuring of its composition is proposed. For the same reason it is further proposed that a system of programme reviewers be set up.

Finally, we recommend that SAREC consider the possibilities of using the ISP model for the administration of bilateral research support in other subject areas.

A simple optical fiber axial speed detector

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An optical fiber detector is developed to measure simply and accurately the axial speed of the plasma sheath in a plasma focus device. Using a suitable model, self-consistent information on the distribution of ionized mass and current inside the structure of the plasma sheath may also be inferred. The thickness of the sheath is also obtained. © 1995 American Institute of Physics.

Calculations on plasma focus dynamics show¹ that over the last 10% of the length of the anode the plasma sheath attains an almost constant speed, the peak axial sheath velocity, which for all plasma focus devices appears to be constrained by design to a value of 10 cm/μs or a little less. However, our recent experiments with a 3 kJ device operated at axial speeds higher than 10 cm/μs show² an enhanced radiation (of neutrons and x rays). It becomes important to measure accurately and simply this peak axial speed.

We present an optical method based on the plasma emissivity with the following advantages when compared for example to streak photography: (i) accuracy and simplicity, and (ii) thickness of the sheath is determined.

The moving plasma structure during the axial phase consists basically of shock front, shock layer, and the current

sheath (magnetic piston). There are no clear demarcations of these due to the diffusive character of current flow and mass distribution in both radial and longitudinal directions. Also, the sheath is canted.

We propose a simple model in which the intensity of emitted light is approximated by a three region profile (Fig. 1) of lengths l_i , $i=1,2,3$, respectively. The sheath moves with constant velocity v along the z axis in front of an optical detector with aperture d and an instantaneous, linear response $J(t)$ which is proportional to $\int_0^d J(z)dz$, corresponding to the shaded area (Fig. 1). The absolute value of $J(t)$ depends on the absolute maximum light intensity ($J_{\max}$), efficiency of the optical detector, and the aperture d . As the plasma sheath passes by the detector, $J(t)$ may be written as follows:

$$J(t) \propto \begin{cases} v^2 t^2; & 0 \leq t < \frac{d}{v} \\ 2dvt - d^2; & \frac{d}{v} \leq t < \frac{l_1}{v} \\ -(d+l_1-vt)^2 + 2dl_1; & \frac{l_1}{v} \leq t < \frac{d+l_1}{v} \\ 2dl_1; & \frac{d+l_1}{v} \leq t < \frac{l_1+l_2}{v} \\ -\frac{l_1}{l_3} (l_1+l_2+l_3-vt)^2 + 2l_1(l_1+l_2+d-vt) + l_1l_3; & \frac{l_1+l_2}{v} \leq t < \frac{l_1+l_2+d}{v} \\ \frac{l_1}{l_3} [-2dvt + 2d(l_1+l_2+l_3) + d^2]; & \frac{l_1+l_2+d}{v} \leq t < \frac{l_1+l_2+l_3}{v} \\ \frac{l_1}{l_3} (l_1+l_2+l_3-vt)^2; & \frac{l_1+l_2+l_3}{v} \leq t \leq \frac{l_1+l_2+l_3+d}{v} \end{cases} \quad (1)$$

where $t=0$ is the time when the light of the plasma's leading edge touches the detector's edge. Thus the five parameters l_1 , l_2 , l_3 , v , and d may be derived from the output signal $J(t)$. For fast data processing, two identical channels are coupled to one photodetector. By placing the second channel parallel to the first at distance D we simulate the output signal of the detector (J_s) by adding to the signal $J(t)$ from the first channel [Eq. (1)] the function $J(t-D/v)$, corresponding to the signal from the second:

$$J_s(t) = \begin{cases} J(t); & 0 \leq t \leq \frac{D}{v} \\ J(t) + J\left(t - \frac{D}{v}\right); & \frac{D}{v} < t \leq \frac{l_1+l_2+l_3+d+D}{v} \end{cases} \quad (2)$$

As the analytical expression of the resulting signal $J_s(t)$ becomes complicated, numerical simulation is preferred. An example of the simulated profiles of the signals from each

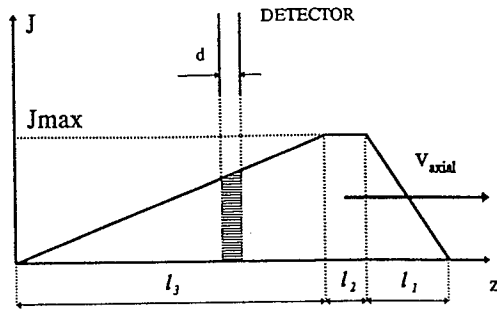


FIG. 1. Simulation of light intensity distribution J inside the plasma sheath. The plasma is moving along the z axis with a constant velocity v_{axial} in front of the optical detector which has an aperture d .

channel and the speed detector output signal is given in Fig. 2 for $l_1=3$ mm, $l_2=1.5$ mm, $l_3=30$ mm, $d=0.7$ mm, $D=14.2$ mm, and $v=10$ cm/ μ s. It is compared with an experimental result (Fig. 3) showing that (i) the leading edges of the two pulses are parallel to one another, (ii) the first peak exhibits a plateau whereas (iii) the second peak shows a sharper feature. These indicate that the simulated light intensity profile is close to the experimental profile.

For easy interpretation one chooses experimental conditions so that: (i) $d < l_2$ (small aperture), (ii) $D > l_1 + l_2 + d$ ($J(t-D/v)$ of second channel peaks on linear region of trailing edge of first channel), and (iii) $D < l_3$ (high accuracy). These conditions are easily fulfilled since l_1 and l_2 are mm thick whereas l_3 is cm thick.

The ratio of the two peak values is written

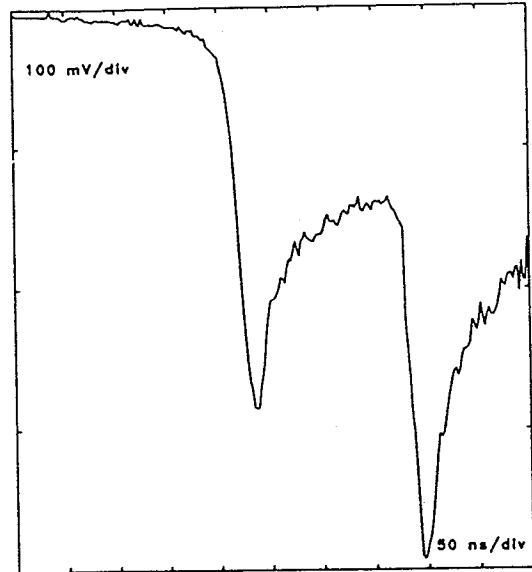


FIG. 3. Characteristic signal of the peak axial sheath velocity detector.

$$R = 2 - \frac{D}{l_3} + \frac{l_2 - d}{l_3}. \quad (3)$$

The last term (~ 0.03) is negligible. Hence l_3 and then the plasma sheath thickness $l = l_1 + l_2 + l_3$ is estimated

$$l_3 \approx \frac{D}{2 - R} \approx l. \quad (4)$$

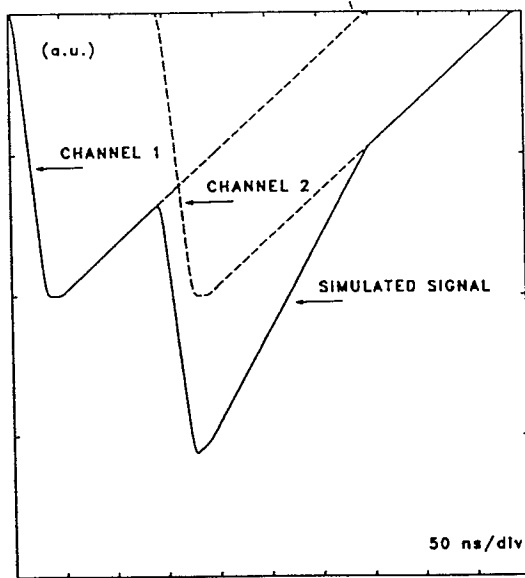


FIG. 2. Simulated signals for the peak axial sheath velocity detector. Parameters: $l_1=3$ mm, $l_2=1.5$ mm, $l_3=30$ mm, $v=v_{\text{axial}}=10$ cm/ μ s, $d=0.7$ mm, and $D=14.2$ mm.

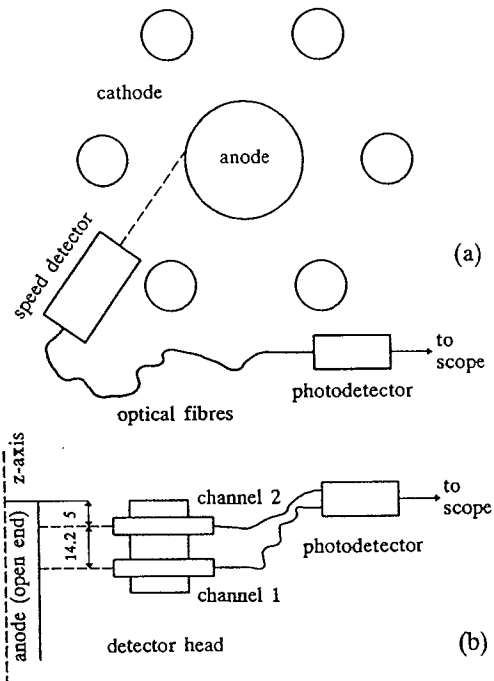


FIG. 4. Optical fiber axial speed detector; (a) top view, (b) lateral view.

For $D=14.2$ mm and R in the range of 1.4–1.6, the plasma sheath thickness, is estimated at 25–35 mm.

The peak axial velocity is calculated from the time interval (τ) between the two peaks: $v=D/\tau$. The error is determined by the errors of D and τ . Using the value for v , l_1 is determined for the known value d from the risetime of the first pulse: $(l_1-d)/v$ [second definition, Eq. (1)]. We then determine l_2 from the time interval of the plateau of the first pulse: $(l_2-d)/v$ [fourth definition, Eq. (1)].

The device, optical fiber axial speed detector (OFASD) consists of (i) detector head, (ii) optical transmission lines, and (iii) photodetector. A schematic top view of OFASD inside the chamber is shown in Fig. 4(a) with lateral view in Fig. 4(b) to measure the peak axial velocity. The detector head consists of two parallel identical collimating channels (cross section, Fig. 5) used to pick up light emitted by the plasma. The acceptance angle of each channel is 2° . The distance between the two channels is 14.2 mm. The detector head is placed 25 mm from the anode surface. The optical transmission lines each 5 m long consist of $300\text{ }\mu\text{m}$ optical fibers coupled to an EMI 9813B photomultiplier. Inside the discharge chamber the optical fibers are shielded from stray light by black rubber tubing covered with aluminum foil.

The time response of the photodetector affects the profile of the signal convoluting the real signal with the apparatus function. For example, using a photomultiplier with 4–5 ns

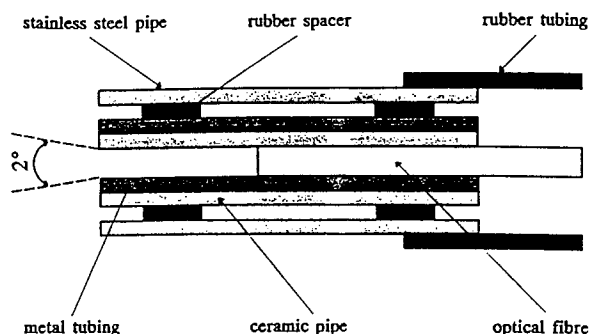


FIG. 5. Schematic cross section of a channel (collimator) of OFASD.

risetime, the signal shows a rise period of about 15 ns for the first part of the signal in the interval $[0, d/v]$ which usually is less than 10 ns. This aspect is clearly seen in Fig. 3 (beginning of the leading edge). Since the current sheath is canted, it is important to correctly position the speed detector head. Otherwise the sheath thickness cannot be determined.

¹ S. Lee, "Plasma Focus Experiments," in *Laser and Plasma Technology*, edited by S. Lee *et al.* (World Scientific, Singapore, 1985), pp. 37–62.

² A. Serban, Ph.D. thesis, Nanyang Technological University, Singapore (1995).

RESEARCH TRANSFER AS AN EDUCATIONAL PROCESS A MODEL AND SOME EXPERIENCE

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Introduction

Physics research in a country always takes place against the background of physics education in the country. Sustained progress in research often cannot be made until the general level of education has attained a certain level. Since the 1980's international agencies like the UNESCO and the International Centre for Theoretical Physics (ICTP) have taken the initiative on a global basis to increase awareness and action in curriculum organisation and reform, laboratory aids, teaching methods, books and manpower requirements. These problems are being successfully faced and gradually improved upon in even poor developing countries although progress is often not as widespread and comprehensive as one would have liked.

Against this background of a relatively progressive scene of physics education may be viewed the much more laborious progress being made in research in physics areas such as the following: solid state physics and materials, geophysics, atmospheric physics, non-conventional energy, laser physics, optics, plasma physics, high energy physics, instrumentation and other areas in theoretical, computational and mathematical physics and in experimental and applied physics. In each of these subject areas progress is very slow when averaged over the developing countries. But in several subject areas individual institutions may be identified where satisfactory progress has been made and continuing effort is being sustained on the basis of individual groups. Such groups form the key to any plan to accelerate the progress of physics research in developing countries.

Traditionally, developing countries have their highest level physics manpower trained in advanced countries: the U.K., the U.S.A., Russia, Germany, France, Italy, Australia for example. At postgraduate level typical training consists of a research programme drawn up to fit the student into the ongoing work at the advanced host institution. The student learns how to carry out the research program using the equipment and technical resources available at the institution. On completing his Masters or Doctorate the student returns to his home institution where he then faces the problem of having no environment, no technical resources to carry on any worthwhile research.

There is a problem of mismatch. To attempt to transfer a research programme from a flourishing laboratory in an advanced country into a laboratory in a poor developing country without special comprehensive preparation is akin to attempting to transfer a blooming plant from a well-nurtured garden into an arid desert environment. The plant shrivels and dies.

Various proposals have been suggested to alleviate these problems:— from proposals to choose 'relevant' topics for postgraduate training, so that presumably more official funding then becomes available, to networks of regional centres and travelling scientists schemes. The most remarkable in these efforts to encourage third world physicists is the ICTP itself, set up to alleviate the isolation of scientists from developing countries; and succeeding marvellously — especially for theoretical physicists and mathematicians. Success to the same degree has probably not been achieved for experimental physicists (although some good programmes have been implemented e.g. by the International Science Program of Uppsala University). The experimental physicist benefits enormously from the contacts, stimulating atmosphere and fresh ideas of the ICTP, but unlike the theoretical physicist is unable to continue working with mere ideas back in his home institute. He needs equipment and technical support.

What the fresh, young enthusiastic Ph.D. in experimental physics needs is the opportunity and the ability to transfer from somewhere a self-contained infrastructure of technology for a specific research area: choice of a feasible and worthwhile facility, design and construction concepts, the control, power and measuring techniques, modelling, optimisation and computational principles and techniques, all adaptable to the resources of his home institute. The technology has to be simplified so that he can firstly become the technical expert, and then train his technicians on the job. The technology has to have been evolved or have been modified to be at once effective and suitable for implementation in the atmosphere of the developing country. The technology has to have a basic structure that is self-contained, self-sustainable and low cost. Having chosen and learned the technology, the young physicist should then build this facility himself to gain the vital self-confidence and to have the technical expertise to adapt the facility as his research horizons expand. How may we help the young physicist do this, in a reasonable period of time and at reasonable cost?

There are in existence in developing countries research groups which have built up slowly but steadily a self-contained environment for research incorporating all the technical and physics elements required for a sustained research effort. Some of these groups have the capacity and willingness to take the initiative in research initiation and transfer.

Regional Centres for Research Transfer

In 1984 the following proposal¹ was made to several international agencies. Use the facilities and resources of an existing group in a developing country to prepare a program to transfer its total research technology in a specific topic to another group in the region having an interest and commitment in the subject area offered. Designate the group as a Centre for Research Transfer.

Identification of a Regional Centre for Research Transfer

The Centre shall have:

1. specific and specialised research activity in the area of physics it is offering
2. sufficient experience and productivity in that area of physics including: development of undergraduate courses, production of postgraduate theses (preferably to doctoral level) and research papers
3. a self-contained technical infrastructure for the research
4. evolved the technical infrastructure at the centre itself so that the technical infrastructure may be adapted to another developing country without excessive cost in equipment and funding
5. a willingness (enthusiasm) to take the initiative to prepare a comprehensive program to teach, in one package, all the technology required to carry out research in the designated subject area.

Identification of Program Participants

A participant for this program must have a strong physics background, must be young and willing to, after the program, spend several years on the building and research of the selected project. The participant must come from an institution willing to build up the project. The home institution should have some minimum mechanical and electronic workshop facilities and some specified basic equipment.

Role of the Centre

The Centre should on its own initiative:

1. Identify a facility (modelled on its own experience) that may be built and on which research may be carried out fruitfully.
2. Plan a breakdown of the facility into its basic technical sub-systems.
3. Define the major technical requirements (related to the working principle) of each component so that its design and building may be adapted to suit local technical capabilities and individual needs.

4. Plan the basic theory and model needed to optimise the parameters of the facility, and on which the behaviour of the facility may be studied fruitfully and with possibility of extension.

5. Plan for computation and numerical modelling to be done with modest computing facilities like microcomputers.

6. Plan the building of the power and control systems and basic diagnostics so that these may be built in simple (preferably modular) form in the local environment.

7. Plan a comprehensive series of experiments and lectures to demonstrate all the above in modular as well as in assembled working form.

8. Identify the basic equipment that may not profitably be home-built within the framework of the particular program, such as, for example, vacuum pumps, oscilloscopes, electronics and power components.

9. Select the participants (bearing in mind the suitability also of the environment of the home institutions).

10. Conduct a course (from 3-6 months as necessary) based on the above for a group of 2-8 participants.

11. Provide facilities for construction of the system to be transferred.

12. Oversee the design, construction and testing of the facilities by the participants.

13. Arrange air freighting of facility.

14. Provide follow-up.

Role of International Agencies

When a Regional Centre for Research Transfer has prepared its program, and ready participants are identified, the question of funding will require the assistance of international agencies. Travel and living expenses need to be provided for the participants. Follow-up grants to promising participants selected at the end of the course need to be provided for those basic components not available at the home institutions. Some follow-up travel expenses may need to be budgetted. The question of follow-up grants will necessarily limit the possible projects to those which require special component costing less than some pre-set limit.

The inter-relationship among the three parties concerned is illustrated in the following Figure.

SOUTH
 Centre for Training Programme
 for Research Transfer of
 specific technology/facility

SOUTH
 Recipient Group
 building up specific
 technology/facility

Contribution

1. Manpower and infrastructure.
2. Planning and organisation.
3. Design of specific facility.
4. Detailed course content.
5. Teaching - Open Box approach.
6. Construction of facility.
7. Follow-Up equipment and expertise.

Contribution

1. Manpower and commitment.
2. Basic mechanical and electronic workshop facilities.
3. Basic laboratory equipment and space.

NORTH
 International Organisations

Contribution

1. Living and travel expenses for recipient participants.
2. Cost of parts and labour and freight for follow-up equipment.
3. Cost of follow-up visit and scientific exchange.
4. Coordination and technical expertise.

Cost and Benefit

As seen in the Figure, the implementation of this program would represent a cooperative effort between two developing countries aided by an appropriate international agency. No capital cost is required to establish the Regional Centre, since it is already in existence and only needs to be identified and designated. In terms of operating cost the Regional Centre in the developing country would bear the greatest proportion in terms of man-power, facilities, planning, teaching, demonstrating and follow-up work. The success of a research transfer project would bring great benefit to both the existing Centre and the recipient group. To the existing Centre, the intense teaching would bring deeper understanding to the technical and research problems and

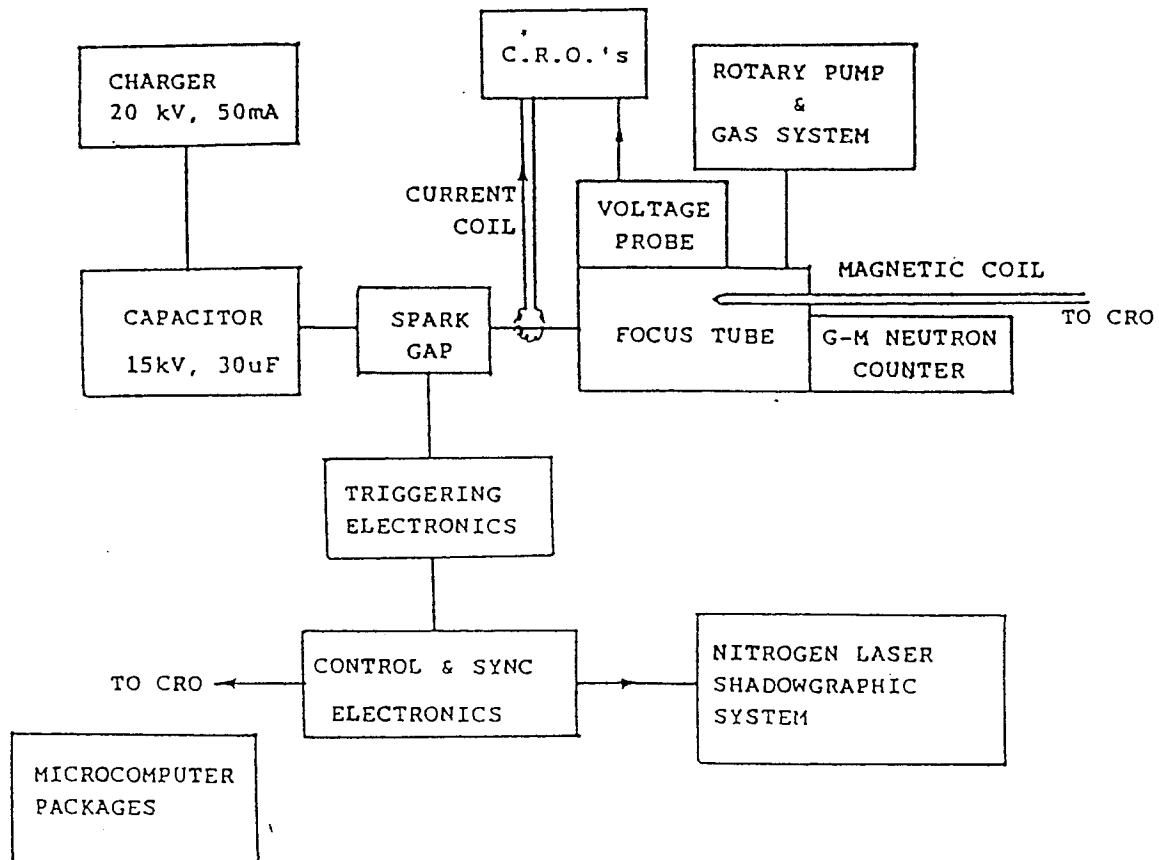


Fig.1. Sub-system for the UNU/ICTP PLASMA FUSION FACILITY

the gain in confidence and self-esteem would lead to greater maturity in its continuing research effort. To the recipient group, a successful project could cut away 5-10 years of development time resulting in the early establishment of the research facility with all the attendant uplifting effects on research and teaching morale.

Research Transfer Programmes in Plasma and Laser Technology

An opportunity to collaborate in the above ideas with the United Nations University and the International Centre for Theoretical Physics presented itself in the period 1985-1990. This challenge was seized upon by the University of Malaya Plasma and Laser Research Groups which took on the role of a Regional Centre for Research Transfer. Programmes were run with the following aim and method.

Aim: To Initiate/Strengthen experimental research in a **specific** field in several developing countries.

Method : By transfer of an integrated package of expertise, components and equipment.

Several programmes were run in the period 1985-1990.

Central to these programmes were facilities which were partially developed by the trainees themselves as part of their training. These facilities were then transferred back to the trainees' home institutions so that experimental research may be initiated based on these facilities.

Facilities for transfer

These were carefully packaged. Each package is made up of carefully designed sub-systems. Two of the packages the plasma focus and the nitrogen laser are shown in Fig.1 and Fig.2. One may ask the question— why use the plasma focus as a facility for research transfer? This is in fact a crucial question. The facility chosen for transfer must be relevant, interesting and rich in physics phenomena, yet have attributes that allow it to be cost-effectively produced and maintained. The following was the rationale leading to the choice of the plasma focus as a key element in this venture.

Why the Plasma Focus?

Plasma physics has attained considerable importance in its present applications and also with its potential associated with radiation and fusion energy. Considerable effort, for example the Plasma Physics Colleges organised by the ICTP in Trieste, has been expended to provide plasma physics education at an international level aimed

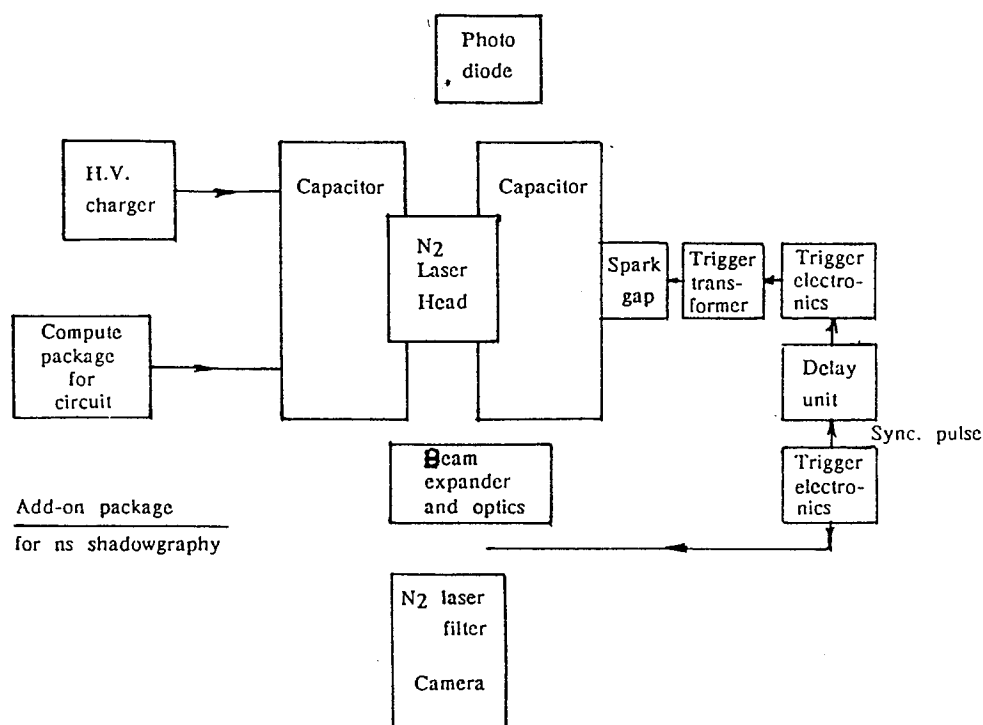


Fig.2. Nitrogen laser package and add-on Shadowgraphy package

towards stimulating the study of plasma physics even in developing countries. This worthwhile educational effort encounters considerable difficulties at the experimental level particularly from the equipment point of view. Many scientists from smaller developing countries have been trained in postgraduate plasma physics programmes in developed countries in experimental facilities. On their return to their home institution they face the daunting challenge of building up some simple, yet effective research facilities to provide continuity in their experimental research experience and also to train their students.

In the early stages of the discussion there was not even a clear idea which experiment could be usefully developed although low cost, cost effectiveness, simplicity and good educational value combined with a large variety of plasma phenomena, amenable to study by simple diagnostics should be among the factors to be considered in relation to devices for developing countries². Thus, the glow discharge has often been

suggested as a suitable plasma for study in a developing country. The glow discharge has several applications, for example deposition and sputtering of thin films, and can also be used as a medium for the experimental study of plasma waves. It serves as a good starting point to develop plasma jets and arcs which may be used as plasma torches or heaters for industrial and metallurgical applications or for applications in MHD power generation.

To move upwards in temperature so that one may aspire to study intense and fusion aspects of plasma physics one may consider building an electromagnetic shock tube to study shock heating or a linear z-pinch for the study of imploding shocks and magnetic compressions. These are 'classical' devices with well-known technology. The z-pinch even in the low cost scaled-down form necessary for this educational exercise could produce a plasma of sufficient density and temperature to be of interest even though no measurable nuclear fusion may be expected.

The plasma focus goes one stage better. It is an excellent device for teaching plasma dynamics and thermodynamics besides being a rich source for a variety of plasma phenomena including soft x-rays and plasma nuclear fusion. The plasma focus is superior to both the electromagnetic shock tube and the linear z-pinch in its range of plasma parameters, combining as it does the essential mechanisms of the devices in such a properly sequenced manner that all the features of both devices, and many more, are produced in one single simple low cost device, when properly designed.

As a result of informal discussions among participants from developing countries at the 1983 Plasma Physics College at the ICTP it was decided to include the plasma focus as one of the educational devices for the initiation of experimental plasma and fusion research in the smaller developing countries as an effort to develop and share fusion related technology among ourselves. This project received support from the United Nations University (UNU) whose Rector Dr. Soedjatmoko added a further dimension when he stated in a communication: "We at the (UNU) have strong reasons to believe that plasma physics will be one of the major technologies of the future in developing as well as industrialised countries. We find great merit in the argument that developing countries should begin now to experiment with and develop modest plasma systems in order to acquire practical knowledge and skills to better employ technologies based on plasma physics once major breakthroughs permit the utilization for the production of energy as well as for other applications."

Cost effective physics

In order to implement a project whereby a developing country may produce a suitable package for sharing technology with other developing countries with the aim of initiating experimental plasma research it is necessary to consider the cost effectiveness of the device to be chosen. Does it produce a rich variety of plasma phenomena? Does it require an expensive vacuum system? Can its power supplies, control electronics and basic diagnostics be packaged at reasonable cost? What physical mechanisms operate to make the chosen device perform better at lower packaging cost than other devices? Can we understand and model the design and performance of the device so that we may effectively do research on it? What are the areas of research and potential applications of the device?

From the point of view of the production of a plasma with conditions of density and temperature sufficient for plasma fusion studies at an affordable cost there is little doubt that the class of fast magnetic compression devices known generally as the pinch, including the linear Z -pinch, the superfast pinch, the gas-puff pinch and the plasma focus offers the best potential. We have considered this class of device and found that the plasma focus is most cost effective having the same power supply, control electronics and basic diagnostic requirements as the simple z-pinch and a much cheaper vacuum system with only rotary pump requirement, yet producing more intense plasma phenomena including copious x-rays, relativistic electron beam (REB) and fusion neutrons, all in one small easily packaged facility. What is the physics behind this cost effectiveness?

Ultra high power pinches have been operated with pulse forming lines to reduce current risetimes so that the pinch may be operated at smaller radius, hence higher density. This high power approach requires the use of complex and expensive technology.

On the other hand the plasma focus uses a very simple principle. Essentially it allows a conventional (slow risetime of 3 μ sec or more) capacitor bank to drive a very fast pinch (typically 1 cm radius in 50 ns) at a sufficiently high density and a large current during the time of pinch.

The plasma focus has two sections: the first section is a coaxial electromagnetic shock tube whose length is matched to the capacitor risetime. The rising capacitor current drives a shock wave axially down the shock tube at a suitable speed until the

shock wave reaches the end of the tube at peak current. Then by the geometry of the device (see Fig. 3) the axial drive phase is simply converted to a radial compression or pinch phase.

The pinch phase is very intense because it starts at a very large current (typically 500 kA) and at a relatively small radius (typically 1 cm). Thus the operating pressure may be relatively high (5 torr in D, for a plasma focus against 0.1 torr or less for a pinch). The increased density and temperature more than compensates for the reduced volume in terms of radiation and neutron yield.

Having seen from the basic physics mechanism that the plasma focus is capable of high levels of performance without special technological development the next step in the development of an educational package was to consider the modelling and design of a practical device.

Cost Effective Design of a Plasma Focus

Using these simple ideas a dynamic model ^{2,20} (see Fig. 3) was developed. This considers the focus dynamics in two separate phases - the axial run-down (shock tube) phase which crucially delays the radial focus, or pinch phase until the plasma current has reached its peak value. The model couples the electric circuit to the plasma dynamics and is written to facilitate the design, on any microcomputer, of an optimum plasma focus in terms of a parameter which enables the matching of the electrical risetime to the axial run-down time, a second parameter which adjusts the ratio of the axial run-down time to the radial pinch time so that this factor may be thought of as a power enhancement factor, and a third parameter which adjusts the ratio of the device inductance to the external circuit inductance. Other parameters in the model include the ratio of outer to inner radii, the aspect ratio and the specific heat ratio. This latter ratio is a thermodynamic function of temperature and affects the radial pinch structure and dynamics.

The Experimental Facility and Results

The design of a plasma focus² may take as a starting point the availability, or choice of a capacitor bank. For the training programmes from the point of view of

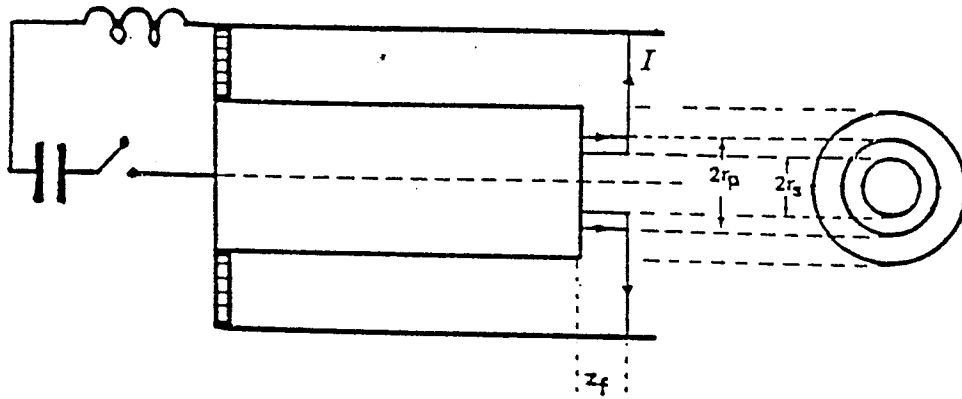


Fig. 3a. Phase 1: axial acceleration phase

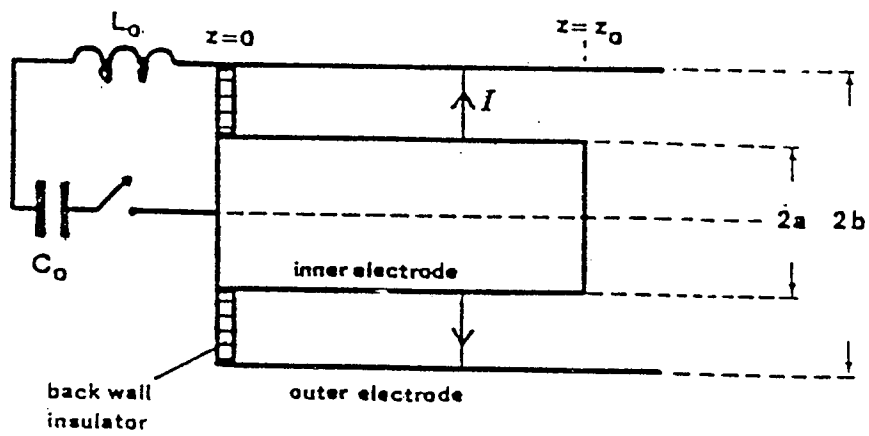


Fig. 3b. Phase 2: radial compression phase

economy and cost-effectiveness a single Maxwell capacitor rated at $C=30\text{ }\mu\text{F}$, $V=15\text{ kV}$ of inductance less than 40 nH was selected.

The experimental facility designed from the above physical model is shown in Figs. 4, 5 and 6. Fig. 4 shows the plasma focus circuit using a swinging-cascade spark gap switch triggered via a TV transformer. Fig. 5 shows the parallel plate spark gap arranged in a low-inductance configuration on top of the capacitor with 16 output coaxial cables (No. 18 in Figs. 5 and 6) which connect the spark gap output to the plasma focus input flange as shown in Fig. 6. The plasma chamber (No. 32) consists of a 30 cm length of 6.5 inch mild steel tubing and the required vacuum is provided by a small single stage rotary pump with ultimate base pressure of 0.01 torr. The design of the focus tube electrodes has several important features particularly regarding the mounting of the backwall glass insulator (No. 30). Diagnostics are also indicated in Fig 6.

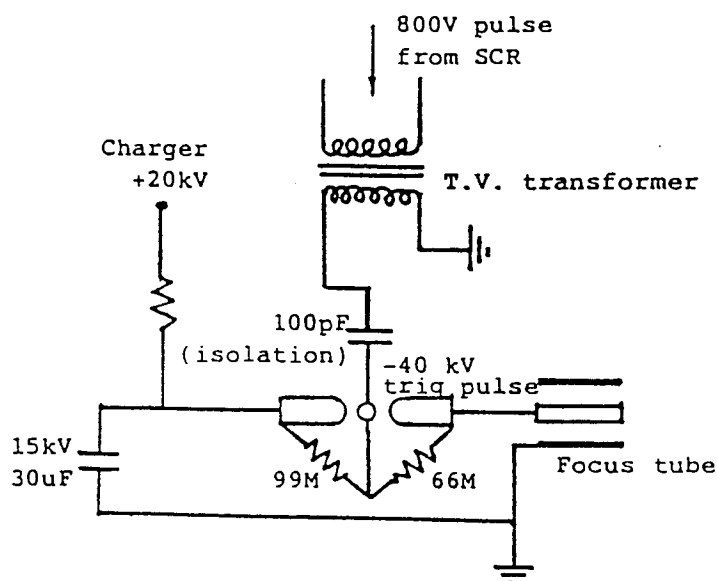


Fig 4a Circuit for the swinging-cascade spark gap and focus tube

The system was tested between 13-15 kV in various gases including air, argon, hydrogen and deuterium. The strength of the focussing action is gauged from the current dip and voltage spike. (Current is measured using a Rogowski coil and voltage using a voltage divider.)

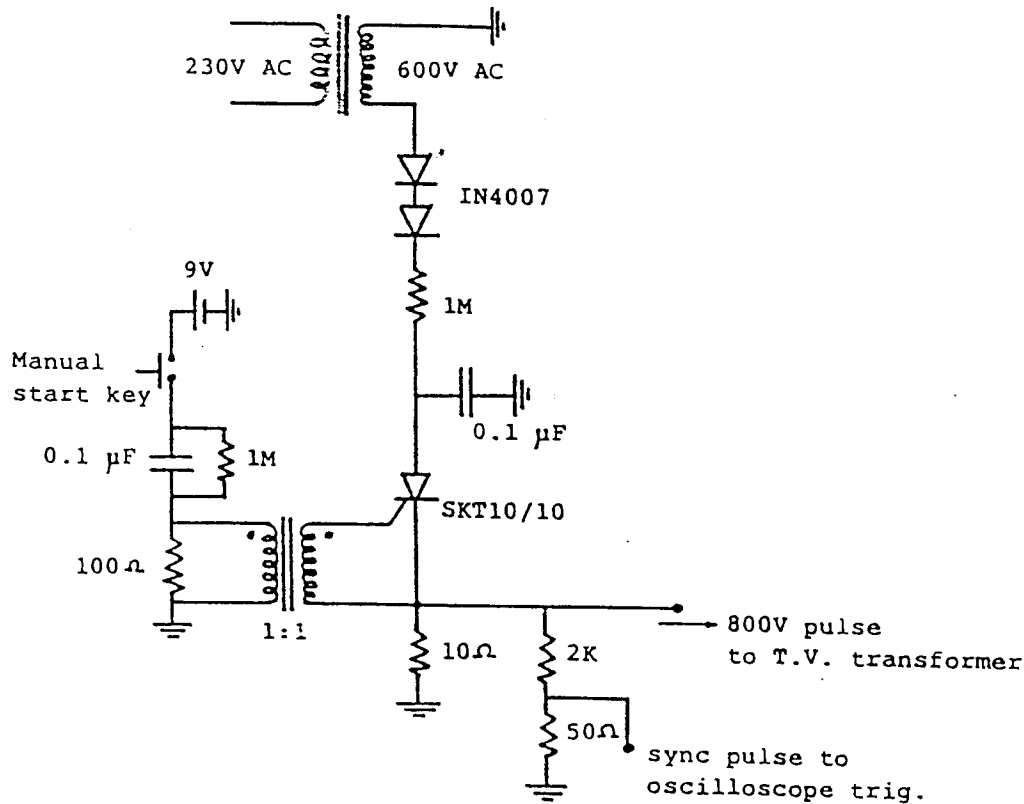


Fig. 4b. Trigger and synchronizing electronics.

Figure 7a shows an oscillogram of the current and voltage waveforms of the plasma focus in 0.5 torr of air, with focussing action about $1 \mu\text{sec}$ after peak current. Figure 7b shows a deuterium focus, at 13 kV, 2.5 torr with focussing action occurring at peak current.

These oscillograms show a terminal axial speed of $10 \text{ cm}/\mu\text{sec}$ corresponding to a deuterium plasma temperature at the end of the axial phase of $2 \times 10^5 \text{ K}$. The observed current sheath is well-formed with a thickness of 2 cm at the end of the axial phase as estimated from the oscillogram. The current dip and voltage spike are indicative of a good pinching action during the radial phase, in agreement with the model.

In deuterium when operated at 15 kV and optimum pressure conditions of 3 torr consistent counts of 1000-2000 are obtained using a PM-scintillator counter, corresponding to $0.5\text{-}1 \times 10^8$ neutrons per shot.

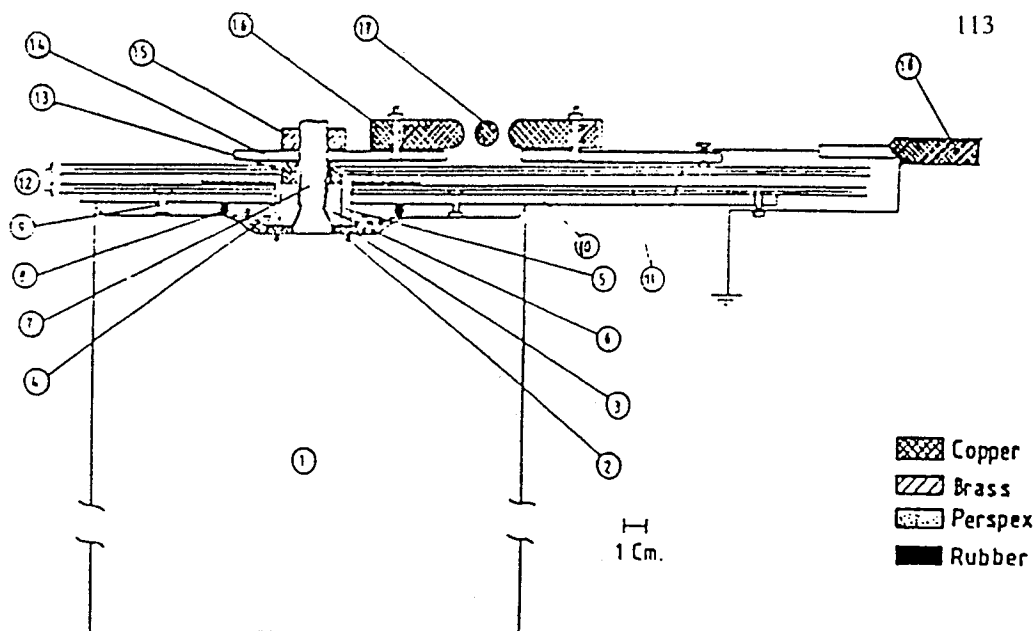


Fig. 5. The capacitor connecting plates, the spark gap and output cables.
 1- 15 kV, 30 μ F capacitor; 2- capacitor O-ring seal; 3- washer; 4- oil; 5- nylon cap; 6- steel nut; 7- capacitor output seal; 8- O-ring seal; 9- earth stud; 10- earth plate; 11- 5-mil mylar film; 12- polyethylene film; 13- copper ring HV connector; 14- capacitor high voltage (HV) output plates; 15- lock nut for HV plate; 16- HV electrode for swiging cascade spark gap; 17- trigger electrode; 18 - output coaxial cables (16 in parallel).

The system shows remarkably consistent and reproducible operation. For the purpose of one of the a training programmes sponsored by the UNU, six systems were assembled one after the other and tested over a period of two months. Each system (designated as the UNU/ICTP PFF) was assembled and tested over a period of one week averaging between 100-200 shots in the various gases. Once a system has been established to be operating normally, that is without undue leakage and after an initial period of out-gassing involving some three to five discharges, proper focussing is achieved for better than 95% of the discharges, apart from those discharges deliberately operated outside the established suitable pressure range for the gas used.

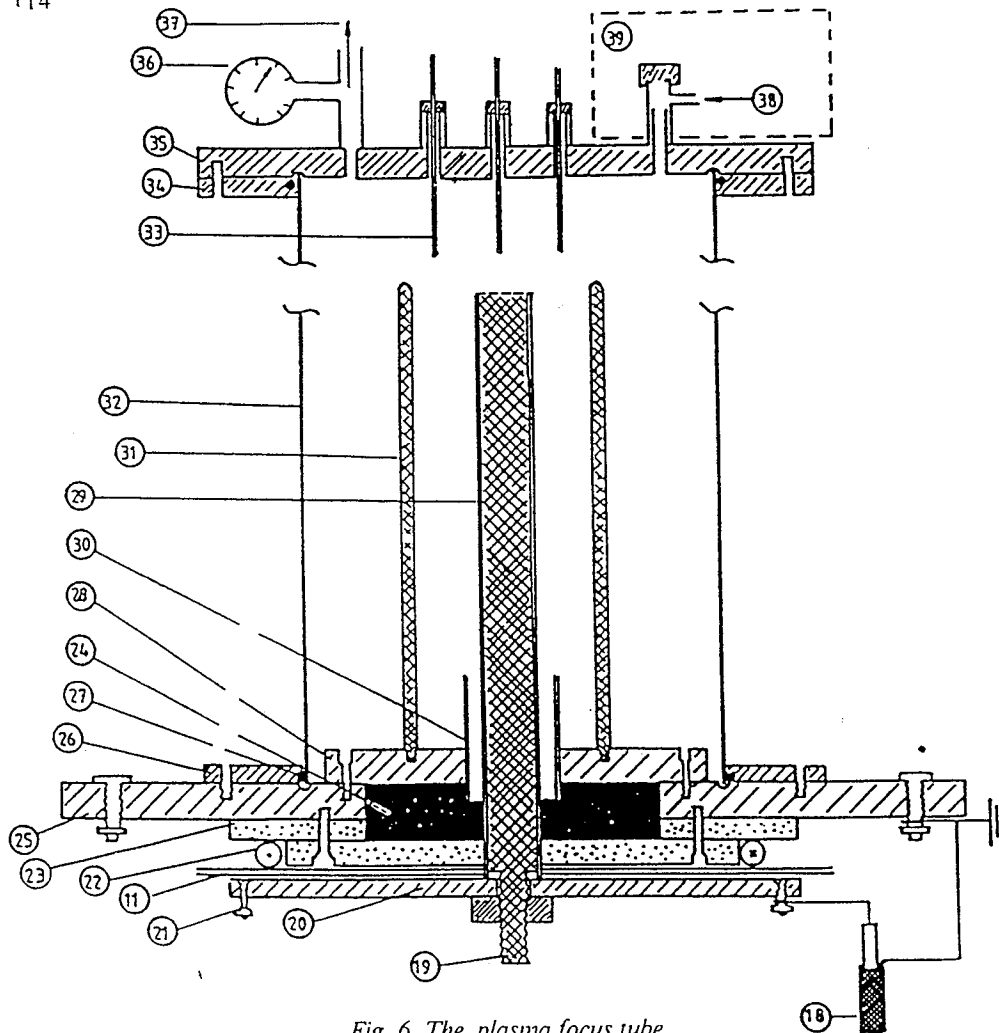


Fig. 6. The plasma focus tube.

18- input coaxial cables (16 in parallel); 19- stud of anode; 20- anode collector plate; 21- connecting points for coaxial cable HV lead; 22- Rogowski coil; 23- perspex spacer; 24- rubber holder; 25- cathode collector plate; 26- mild steel flange; 27 - O-ring-seal; 28- focus cathode support plates; 29- focus anode; 30- glass insulator; 31- focus cathode (6 rods); 32- mild steel focus chamber; 33- movable magnetic probe in glass jacket; 34- flange; 35- back flange; 36- diaphragm gauge; 37- outlet to vacuum pump; 38- inlet for test gas; 39- wax container with indium foil and PM-scintillator activation counter.

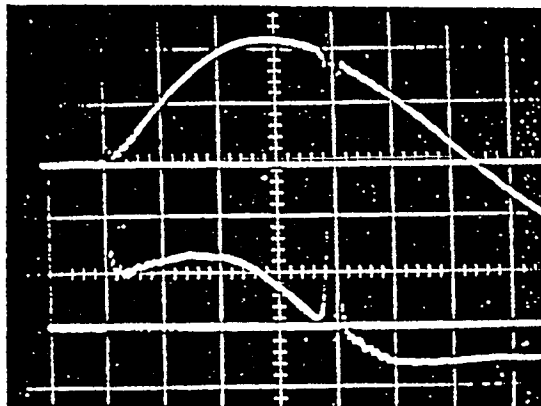


Fig. 7a. Current (upper trace) and voltage (lower trace) of plasma focus in air.

13 kV, 0,5 torr

Top trace: 73 kA/cm

Bottom trace: 2 kV/cm

Time scale (horizontal): $1 \mu\text{s/cm}$

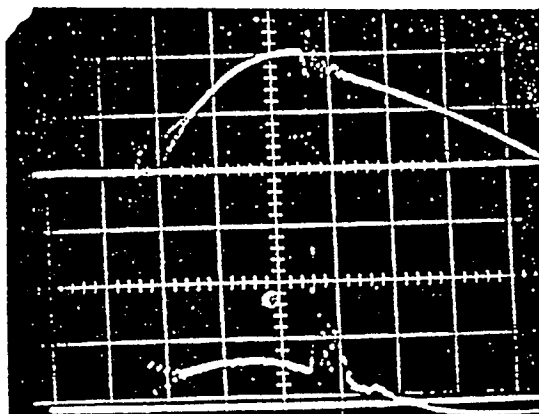


Fig. 7b. Current and voltage trace of plasma focus in deuterium.

13 kV, 2,5 torr

Top trace: 75 kA/cm

Bottom trace: 4 kV/cm

Time scale (horizontal): $1 \mu\text{s/cm}$

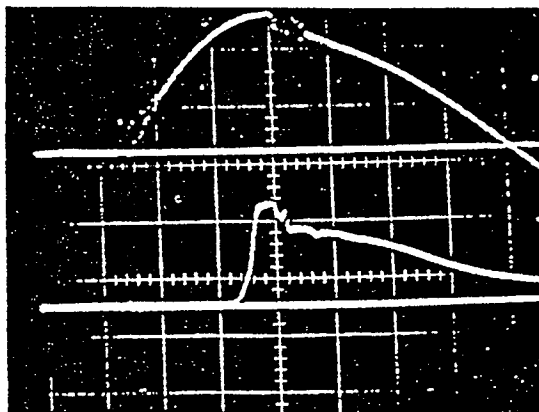


Fig. 7c. Current and magnetic trace of plasma focus in deuterium.

15 kV, 3,5 torr

Magnetic probe placed at $z = 10,2 \text{ cm}$

Top trace: 73 kV/cm

Bottom trace: 0,6 T/cm

Package for transfer:

The equipment packages transferred include electrodes, vacuum chamber, pulsed control switching electronics, power supplies, high power discharge systems, diagnostic systems, design, testing and research procedures and computational packages for microcomputer modelling of circuit and plasma dynamics.

Schedule of a typical training programme:

A typical programme is designed for 6 months and may have the following typical structure:

October to December 1985 - Lectures and experiments on existing devices in the University of Malaya laboratories including pulsed electronic modules, power supplies glow discharge, electromagnetic shock tubes (EMST), plasma focus, computation packages on circuit and plasma dynamics; and various lasers; system planning, design, construction and development of all sub-systems for each facility chosen by the individual Fellow (see Table I).

December 1985 - February 1986 - development, assembly and testing of each set of facility; research work on the various devices. March 1986 - reports and further planning; preparation for shipment of equipment; writing of research papers and presentation of some research results to the Second Tropical College.

Results of the Training Programmes

I. Facilities transferred

Experimental plasma/fusion/laser research has been initiated in 8 Third World countries. Facilities transferred include those in the following Table I:

II. Progress at home institutions

Good progress has been achieved back at the home institutions as a result of the training programmes and the follow-up equipment and assistance. Plasma Focus facilities are now fully operational at Quaid-I-Azam University, University of Delhi, Rivers State University of Science and Technology, Al Azhar University, Prince of Songkla University and Yogyakarta Nuclear Research Centre. Other facilities have been established at Njala University College, University of Rajasthan, Shanghai Institute of Optics and Fine Mechanics, National Space and Aeronautics Board of Indonesia and a training facility at the ICTP. Strong postgraduate programmes have been established at Quaid-I-Azam University, University of New Delhi and Yogyakarta. At least 11

Table 1

	UNU/ICTP PFF	EMST Flow Simulator	Nitrogen Laser System	Laser Shadowgraph System	Glow Discharge
Cairo, Al Azhar U.	x		x	x	
Jaipur, Rajasthan U.	x		x		
Delhi, Delhi U.	x*		x*	x*	
Srinaga, SP College			x		
Jakarta, LAPAN (Space research)		x*			
Yogyakarta, PPNY (Nuclear research)	x*		x*	x*	x
Islamabad, QAU	x*		x*	x*	
Port Harcourt, US&T	x*		x*	x*	
Sierra Leone, NUC	x*				
Songkla, PSU	x		x		
Liberia			x*	x*	

* Have produced Ph.D./M.Sc. theses from these facilities.

postgraduate theses including Ph. D. theses³⁻⁵ have been successfully completed at Quaid-I-Azam, New Delhi, Yogyakarta, Bandung Institute of Technology, Rivers State University of Science and Technology and in Sierra Leone. Research publications^{2,6-11} have resulted from these training programmes and work back at the home institutions.

III. Consequent Development of Organisations

(i) ICAC-UM

As a result of our involvement in the implementation of the concept of Training Programmes for Research Initiation the Physics Department, University of Malaya was invited to be an Affiliated Centre of the International Centre for Theoretical Physics

(ICAC-UM). This Centre has continued to innovate activities as a training centre for research transfer.

(ii) Asian African Association for Plasma Training (AAAPT)

In order to widen the scope for technology and research transfer among Third World countries the AAAPT was formed in 1988 as a network of the ICTP with the following objectives:

- Plasma Physics training programmes in Asia and Africa.
- Development of research packages for transfer.
- Exchange of scientists.
- Newsletter.

Activites (and associated activities):

- Formation on 7.6.1988 (during Third Tropical College on Applied Physics), Kuala Lumpur, Malaysia.
- 2nd (UNU)ICTP Training Programme, Kuala Lumpur, Malaysia, June-Oct 1988.
- Beijing College on Plasma Diagnostics, Beijing, P.R. China, Oct-Nov 1989.
- 3rd ICTP-UM Training Programme, Kuala Lumpur, Malaysia, Dec 89 - May 1990.
- Regional College on Plasma Applications, Songkla, Thailand, January 1990.
- 4th Tropical College on Applied Physics, Kuala Lumpur, Malaysia, May-June 1990.
- Third Summer School on Plasma Physics, Tsingdao, P.R. China, 15—22 August, 1990.
- Basic Course on Plasma Physics Theory, Islamabad, Pakistan, September-December 1990.
- Nitrogen Laser Training Programme, Kuala Lumpur (October - November 1990)

- Fifth Training Programme on Plasma Laboratory Techniques, Beijing, China (April-May 1991).
- Sixth ICTP-UM Training Programmes on Plasma & Pulse Technology, Kuala Lumpur (March-April 1992).
- A series of AAAPT Council Meetings and scientific visits to various major institutions in Egypt (May 1992); these form a series of continuing Council Meetings which previously had been held in conjunction with associated meetings in Kuala Lumpur, Beijing, Songkla, ICTP Trieste, Delhi, Islamabad.
- 5th APP Conference (SAPPC) post-conference Workshop on Plasma Sources & Applications, Kuala Lumpur (Aug 1992).
- International Symposium of Laser-Plasma Interactions, Shanghai (November 1992); co-sponsored.
- Sixth ICDMP Meeting of Working Group, Beijing (Oct 1992); co-sponsored.
- Fourth AAAPT College on Plasma Technology - Training on Plasma Diagnostics, Cairo (April-May 1993).
- International Conference on Plasma Physics, Changsa, China, together with Fourth APSC Summer School on Plasma Physics of Nonlinear Phenomena and the First APSC Workshop on Plasma Science & Technology (May 1993).
- Regional attachment centres and scientific exchange programmes, University of Delhi, Quaid-I-Azam University and Association of Plasma Studies of China (since 1991).
- Joint PSU-UM Plasma Physics Seminar, Prince of Songkla University, Hatyai, Thailand (March 1994).
- AAAPT African Network attachment programme in connection with Regional Course on Plasma Physics, Quaid-I-Azam University, Pakistan (Nov 30 1994 - Feb 1995).

— Training Programme on Plasma Focus and AAAPT African Network attachment, University of Malaya, Kuala Lumpur, Malaysia (17 April - 20 May 1995).

— AAAPT Council Meetings and Inauguration of AAAPT Research and Training Centre in Institute of Physics, Chinese Academy of Sciences, Beijing, P.R.China (22-25 May 1995).

In connection with the training programmes there has been a parallel programme for the development of Plasma Training & Applications Packages to be used as follow-up equipment. The following were developed:

1. Nitrogen Laser teaching & applications package.
2. Optical Fibre Monochromator System.
3. Plasma Focus Fusion Facility, ICTP-UM PFF.
4. 5-Channel diode x-ray spectrometer.
5. Nanosecond Laser Shadowgraph demonstration & application package.
6. Multi-purpose Plasma Device.
7. Linear Theta Pinch Package.

More than 32 packages of the above equipment have been transferred to 16 institutions in 11 South countries. The total value of the equipment has been estimated to be worth USD500,000, including the equipment now placed at the ICTP in an attempt to start a Plasma and Laser Resource Network.

The emphasis of activities from 1991 has been shifted to regional attachment centres, a special focus being attachment programmes for African scientists. With this in mind an AAAPT Research and Training Center has been established at the Institute of Physics, Chinese Academy of Sciences (CAS) to be funded by the CAS under its South-South Fellowship agreement with the Third World Academy of Sciences, the ICTP Office of External Activities, the Institute of Physics, CAS, Beijing and AAAPT. Facilities at this Center include a theta pinch, a plasma source for ion implantation and a tokamak. Experimental and theoretical studies are offered. A sandwich PhD programme is being

planned in which PhD candidates registered at their home institutions may be trained at the Center with attachments of 3 months every year over a period of 3 years.

The ICAC-UM and the AAAPT have also taken the initiative to propose the formation of a Plasma and Laser Technology Resource Network.

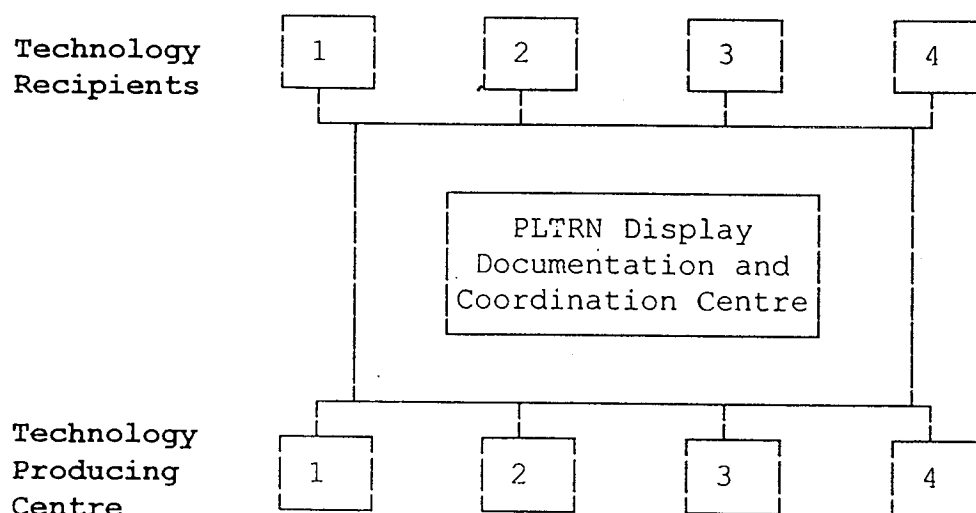
(iii) Plasma and Laser Technology Resource Network (PLTRN)-

a proposal

Aim: To assist development of equipment packages.

To assist distribution of equipment packages.

Concept:



Structure of Technology Resource Network.

Proposal:

PLTRN be established to benefit as many Third World scientists as possible.

Actions taken:

Nitrogen Laser Education and Application package already installed at ICTP (contributed by ICAC-UM).

Optical Fibre Monochromator (OFMS) package already completed and sent to ICTP (contributed by AAAPT, Project of Chinese Academy of Sciences, Beijing).

Multi-purpose plasma devices, pinch and glow discharge device completed and donated to University of Cairo (contributed by AAAPT, project of Egypt Atomic Energy Authority, Plasma and Nuclear Fusion Division).

Other packages being planned include:

Laser Shadowgraphy System

Plasma Fusion Facility

Multi-channel X-ray Spectrometer

(The above have also been placed at the ICTP)

Theta Pinch

Transistorised Rotamak FRC System

YAG Laser package Hologram System

IV. Network of 3 kJ plasma focus installations

There exists a large variety of phenomena occurring in sub-microsecond phases in the focus, including highly nonlinear and chaotic behaviour, hence each existing plasma focus facility only manages to study some aspects of the total behaviour. The collation of the total behaviour meets with a major difficulty in that each plasma focus is designed differently because of different emphasis. Thus the behaviour of each machine may be differently coloured by different machine effects or boundary conditions peculiar to that machine. An approach for a comprehensive experimental picture may be to set up a network of identical machines on an international basis. This is not possible for big machines because of the question of cost.

On the other hand much of the physics that may be studied in large plasma focus installations can be carried out much more cost-effectively on small plasma focus devices. There is considerable savings also in experimental turn-around time. More scientific manpower resources may be harnessed in a network including also small laboratories in small nations. Furthermore a network of 15 identical machines already exists in countries including Sierra Leone, Nigeria, Egypt, Italy, Pakistan, India, Thailand, Malaysia, Singapore, Indonesia and China. The research using this 3 kJ machine designated as the UNU/ICTP PFF (United Nations University/International Centre for Theoretical Physics Plasma Fusion Facility) is very diversified. For example the machine in Pakistan⁶ is being used to look into a variety of problems including 2-D modelling, dielectric effects and

instabilities; one of the two in India^{10,11} is being used for materials modification; that at the ICTP in Trieste has been used for studies on chaos and deterministic dynamics¹², to benchmark the performance¹³ of the device and to provide international training as have the ones in Malaysia which are also being used for neutron, x-ray and basic studies^{14,15}, the one in Singapore for device development, thermodynamic effects, radiation enhancement and x-ray lithography¹⁶⁻¹⁸, the ones in Indonesia for neutrons and aerospace applications³ and the one in Shanghai had been planned for laser-focus interaction. Gradual upgrading of the scientific expertise and diagnostic systems will enable the diverse results of the network of identical machines to have an impact when collated and compared perhaps under the coordination of the Asian African Association for Plasma Training (AAAPT) which has taken a leading role in the establishment of this network of devices as a network of the ICTP.

V. Complementing International Cooperation in Plasma Focus Research

The scientific activity of this network can complement the envisaged role of the proposed International Centre for Dense Magnetised Plasma¹⁹ (ICDMP) which plans to build within one centre a range of devices including one large (MJ) device, several medium energy devices and several small devices with two main objectives; firstly the consolidation and exchange of the scientific and technological expertise in pulse power technology and plasma focus technology on a world-wide basis and secondly the further development of scientific manpower in these areas by the provision of essential and integrated training combined with follow-up equipment. The Working Group of the ICDMP formed in Moscow in December 1990 has since met another 9 times in Warsaw, Paris, Stuttgart, San Diego, Ferrara, Beijing, Buenos Aires, and in Bucharest and Kuala Lumpur as the Steering Committee. In the meantime the training and international exchange aspects of plasma focus research is already being carried out, made possible by the versatility, simplicity and richness in physical phenomena of the 3 kJ machines.

A tangible product of the above concept of research transfer has been the AAAPT. The training philosophy and experience of this organisation has already been incorporated into the proposal document of the ICDMP. Furthermore there is now an effort initiated by the Institute of Atomic Physics in Bucharest to extend the scope of such training and collaborative activities to other interested developing and developed countries of Europe, America and Asia and especially Central and East European Countries by the

establishment of a more comprehensive network within the framework such as the UNITWIN/UNESCO programme. Such a network is intended to operate at three advanced levels starting at training for research initiation and extending further to scientist exchange at the highest level.

Conclusion

The initiation/strengthening of experimental research as an educational process in developing countries is discussed. A model had been proposed to implement research transfer amongst developing countries, selecting a laboratory with expertise in a particular area and working out a procedure to transfer the expertise particularly to small laboratories. The transfer involves an intensive and individually tailored training programme complemented by follow-up open-box equipment. The experience of the training and transfer activities is discussed. The model is found to be effective with tangible results including establishment of a number of laboratories with postgraduate programmes up to Ph D level and the production of high quality research papers. More than 11 postgraduate theses including Ph D's and effectively sandwich Ph D's have already been produced. Furthermore these training activities have resulted in the formation of the Asian African Association for Plasma Training which now has several regional research attachment centres and a Research and Training Center with plans for a formal sandwich Ph D programme. International collaboration includes an effective network of 3 kJ plasma focus installations, and contributions to the training sections in the proposals of the International Centre for Magnetised Plasmas.

Acknowledgement

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support and assistance to the above programmes have been responsible for demonstrating the success of the research transfer model.

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Effect of three-wave-phase development on the stimulated Raman scattering in an electron plasma

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Abstract. The effects of the development of the three-wave phase on the amplitude of the pumping laser light, the scattered light, and the electron plasma wave are studied. Analytical solutions are obtained to describe a pumping laser light decreasing with time and the development of the electron plasma wave and scattered wave from an initial increasing state to saturation and finally to a decaying state which is closely related to the three-wave phase.

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In studying laser plasma Inertial Confinement Fusion (ICF), laser scattering has been a concern as a potential cause of decreased laser–target coupling efficiency. The instabilities also continue to be of interest in a scientific sense because the seeding and saturation mechanisms are not well understood [1–4].

Stimulated Raman Scattering (SRS) is a parameter instability in a plasma in which an electromagnetic wave interacts with an electron plasma wave to produce a scattered electromagnetic wave. SRS in laser–plasma interaction has been studied via back and forward scattering [5, 6], and an estimate of the intensity level of SRS from the instability growth has also been reported earlier [7, 8]. Furthermore, the growth of SRS in an inhomogeneous plasma and the development of SRS with time has been analyzed extensively [1, 9].

Generally, most of the works presented numerous results with the approximation of slowly varying amplitudes of the electron response velocities. Furthermore, the effects of three wave phase is usually neglected in the calculation.

In this work, without assuming slow variation of the electron response velocities, we analyze and calculate the effects of the development of the three-wave phase on the amplitudes of the three waves and present a simple analytical solution to describe the evolution of the laser light, the electron plasma wave and the SRS light.

Consider an infinite medium. The electromagnetic fields and plasma parameters are described by the following MHD equations [1, 10]:

$$m \left(\frac{\partial}{\partial t} + \bar{\mathbf{u}} \cdot \nabla \right) \bar{\mathbf{u}} = -e\bar{\mathbf{E}} - \frac{e}{c}(\bar{\mathbf{u}} \times \bar{\mathbf{B}}) - 3T_e \frac{\nabla n}{n} - \nu m \bar{\mathbf{u}}, \quad (1)$$

$$\nabla \cdot \bar{\mathbf{E}} = 4\pi e(n_0 - n), \quad (2)$$

$$\frac{\partial}{\partial t} n + \nabla \cdot (n\bar{\mathbf{u}}) = 0, \quad (3)$$

$$\nabla \times \bar{\mathbf{E}} = -\frac{1}{c} \frac{\partial}{\partial t} \bar{\mathbf{B}}, \quad (4)$$

$$\nabla \times \bar{\mathbf{B}} = \frac{1}{c} \frac{\partial}{\partial t} \bar{\mathbf{E}} - \frac{4\pi e}{c} n \bar{\mathbf{u}}, \quad (5)$$

where n_0 is the plasma density, $\bar{\mathbf{u}}$ is the velocity vector of the electron, n is the electron density; e, m, T_e are the electron charge, the electron mass, and the electron temperature, respectively; $\bar{\mathbf{E}}$ and $\bar{\mathbf{B}}$ are the electric field vector and the magnetic field vector, and ν is a damping coefficient. In the SRS, the fields of the pumping laser $\bar{\mathbf{E}}_i(x, t)$, the scattered light $\bar{\mathbf{E}}_s(x, t)$, and the electron plasma wave $\bar{\mathbf{E}}_L(x, t)$ propagate in a parallel direction, and three fields can be expressed as [1]

$$\bar{\mathbf{E}}_i(x, t) = \frac{1}{2} \{ E_i(t) \exp[-i(\omega_i t - k_i x)] \hat{\mathbf{X}} + \text{c.c.} \}, \quad (6)$$

$$\bar{\mathbf{E}}_s(x, t) = \frac{1}{2} \{ E_s(t) \exp[-i(\omega_s t \pm k_s x)] \hat{\mathbf{Y}} + \text{c.c.} \}, \quad (7)$$

$$\bar{\mathbf{E}}_L(x, t) = \frac{1}{2} \{ E_L(t) \exp[-i(\omega_L t - k_L x)] \hat{\mathbf{X}} + \text{c.c.} \}. \quad (8)$$

Here the symbol $\pm$ in (7) corresponds to forward- and back-scattered light, E_i, E_s , and E_L are the amplitudes of the pumping laser light, the SRS light, and electron plasma wave. The frequencies of the three waves and their transmitted modes satisfy the phase-matching condition

$$\omega_i - \omega_s = \omega_L, \quad k_i \pm k_s = k_L. \quad (9)$$

Substituting (6–9) into (1–5) we obtain for the incident pumping light:

$$\left(\frac{\partial}{\partial t} - i\omega_i\right)mu_i = -eE_i \pm \frac{1}{2}imu_s k_s u_L + \frac{1}{2c}eu_L B_s - v_{ei}mu_i, \quad (10)$$

$$-ick_i B_i = \left(\frac{\partial}{\partial t} - i\omega_i\right)E_i - 4\pi en_0 u_i - 2\pi en_L u_s, \quad (11)$$

$$-ick_i E_i = \left(\frac{\partial}{\partial t} - i\omega_i\right)B_i, \quad (12)$$

for the SRS light:

$$\left(\frac{\partial}{\partial t} - i\omega_s\right)mu_s = -eE_s - \frac{1}{2}iu_L^* k_i mu_i + \frac{1}{2c}eu_L^* B_i - v_{ei}mu_s, \quad (13)$$

$$\pm ick_s B_s = \left(\frac{\partial}{\partial t} - i\omega_s\right)E_s - 4\pi en_0 u_s - 2\pi en_L^* u_i, \quad (14)$$

$$\pm ick_s E_s = \left(\frac{\partial}{\partial t} - i\omega_s\right)B_s, \quad (15)$$

and for the electron plasma wave:

$$\left(\frac{\partial}{\partial t} - i\omega_L\right)mu_L = -eE_L - \frac{1}{2c}e(u_i B_s^* - u_s^* B_i) - 3T_e \frac{\partial n_L}{\partial x} / n_0 - v_L mu_L, \quad (16)$$

$$\left(\frac{\partial}{\partial t} - i\omega_L\right)n_L + ik_L n_0 u_L = 0, \quad (17)$$

$$ik_L E_L = -4\pi en_L. \quad (18)$$

Here u_i, u_s, u_L are the electron response velocities to the incident light, the scattered light, and the electron plasma wave, respectively. The damping coefficient v for the laser wave mainly results from collision damping v_{ei} of electrons with ions. For the electron plasma wave, its damping coefficient $v = v_L$ will still include effects of the Landau damping and the collision damping v_{ei} . Considering only the forward scattering, (13–21) yield the following wave equations for the pumping laser light, the scattered light, and the electron plasma wave:

$$\frac{\partial^2 u_i}{\partial t^2} + \left(c^2 k_i^2 + \omega_{pe}^2 - iv_{ei}\omega_i - 2i\omega_i \frac{\partial}{\partial t} - \omega_i^2\right)u_i = -\frac{\omega_{pe}^2}{2}(n_L/n_0)u_s, \quad (19)$$

$$\frac{\partial^2 u_s}{\partial t^2} + \left(c^2 k_s^2 + \omega_{pe}^2 - iv_{ei}\omega_s - 2i\omega_s \frac{\partial}{\partial t} - \omega_s^2\right)u_s = -\omega_{pe}^2(n_L^*/n_0)u_i/2, \quad (20)$$

$$\frac{\partial^2 u_L}{\partial t^2} + \left(3v_e^2 k_L^2 + \omega_{pe}^2 - iv_L\omega_L - 2i\omega_L \frac{\partial}{\partial t} - \omega_L^2\right)u_L \times (n_L/n_0) = -k_L^2 u_s^* u_i. \quad (21)$$

Here, $u_{i,s}(t)$ and n_L in the medium can be expressed as [1]

$$u_{i,s}(t) = |u_{i,s}^0(t)|\exp[i\varphi_{i,s}(t)], \quad n_L = n_L^0(t)\exp[i\varphi_L(t)]. \quad (22)$$

Assuming that $\varphi_{i,s}$ and φ_L are slowly varying quantities and substituting (22) into (19–21), the following relations between amplitude and phase are obtained:

$$\frac{\partial^2}{\partial t^2} U_i + (c^2 k_i^2 + \omega_{pe}^2 - \omega_i^2)U_i = -\frac{1}{2}\omega_{pe}^2 U_s N_L \cos\delta(t), \quad (23)$$

$$\frac{\partial^2}{\partial t^2} U_s + (c^2 k_s^2 + \omega_{pe}^2 - \omega_s^2)U_s = -\frac{1}{2}\omega_{pe}^2 N_L U_i \cos\delta(t), \quad (24)$$

$$\frac{\partial^2}{\partial t^2} N_L + (3v_e^2 k_L^2 + \omega_{pe}^2 - \omega_L^2)N_L = -\frac{1}{2}k_L^2 (U_i U_s) \cos\delta(t), \quad (25)$$

$$2\omega_i \frac{\partial}{\partial t} U_i = -v_{ei}\omega_i U_i - \frac{\omega_{pe}^2}{2} N_L U_s \sin\delta(t), \quad (26)$$

$$2\omega_s \frac{\partial}{\partial t} U_s = -v_{ei}\omega_s U_s - \frac{\omega_{pe}^2}{2} N_L U_i \sin\delta(t), \quad (27)$$

$$2\omega_L \frac{\partial}{\partial t} N_L = -v_L\omega_L N_L + k_L^2 U_i U_s \sin\delta(t), \quad (28)$$

where $U_{i,s} = |u_{i,s}^0(t)|/c$, $N_L = |n_L^0(t)|/n_0$, $\delta(t) = \varphi_i(t) - \varphi_s(t) - \varphi_L(t)$.

Now let the second-order differential U_i, U_s , and N_L be zero and assume that the three-wave phase is locked at $\delta = \pi/2$. Thus the dispersion relationships can be deduced from (24–26) to be

$$\omega_i^2 = \omega_{pe}^2 + c^2 k_i^2, \quad (29)$$

$$\omega_s^2 = \omega_{pe}^2 + c^2 k_s^2, \quad (30)$$

$$\omega_L^2 = \omega_{pe}^2 + 3v_e^2 k_L^2. \quad (31)$$

This is the same result as reported in [1,9]. However generally, the three-wave phase can not be kept in a locked state. Substituting (23) into (26) and (24) into (27), we obtain

$$\frac{\partial^2}{\partial t^2} U_i - 2\omega_i \frac{\cos\delta}{\sin\delta} \frac{\partial}{\partial t} U_i + \left(c^2 k_i^2 + \omega_{pe}^2 - \omega_i^2 - \frac{\cos\delta}{\sin\delta} v_{ei}\omega_i\right)U_i = 0, \quad (32)$$

$$\frac{\partial^2}{\partial t^2} U_s - 2\omega_s \frac{\cos\delta}{\sin\delta} \frac{\partial}{\partial t} U_s + \left(c^2 k_s^2 + \omega_{pe}^2 - \omega_s^2 + \frac{\cos\delta}{\sin\delta} v_{ei}\omega_s\right)U_s = 0. \quad (33)$$

From (6–8) and (22) we see that the amplitudes of the pumping laser light, the scattered light, and the electron plasma wave are independent of position, hence we can

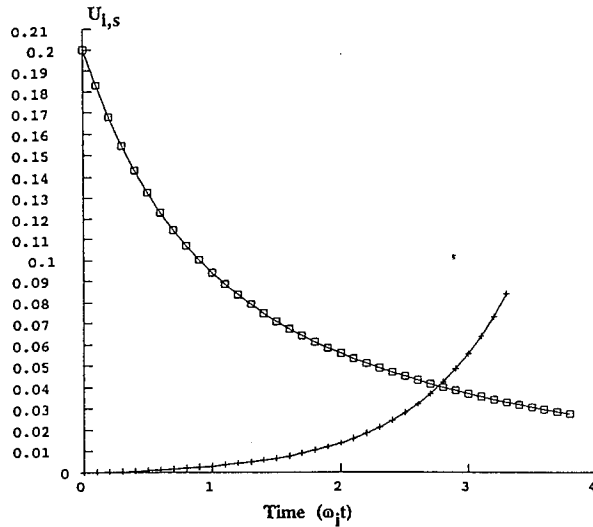


Fig. 1. The development of the pumping laser and the scattered light at different time and phase. The $U_{i,s}/c$ dependence of the time $\omega_i t$ for $\alpha = -0.8$ ($\delta = 128^\circ$), $A_i = B_i = 0.1$, $A_s = -B_s = A_i/100$, $\omega_s/\omega_i = 0.8$, $v_{ei} \approx \omega_{pe}$, $\omega_{i,s} \approx c k_{i,s}$. *: U_i , $\diamond$: U_s .

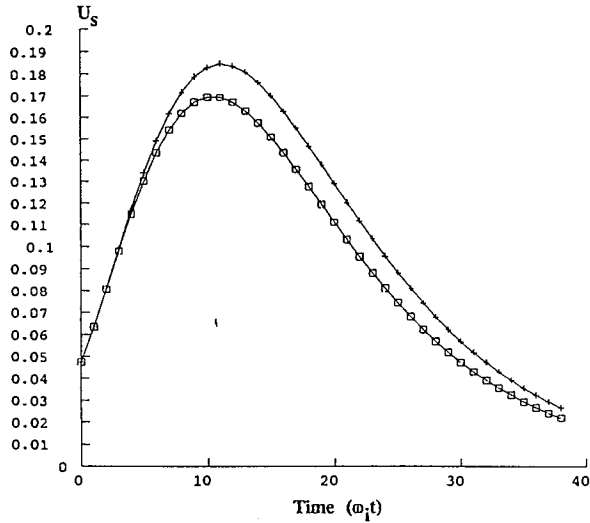


Fig. 2. Development of the amendment U_s of the SRS with time at different three-wave phase conditions. Here, $A_i/v_e = 14$. *: $\delta = 135^\circ$, $\diamond$: $\delta = 128^\circ$ for the parameters given in Fig. 1.

make the approximation $\partial U_{i,s}/\partial t \approx dU_{i,s}/dt$ and obtain

$$U_i = A_i \exp(\{\omega_i \alpha + [\omega_i^2(1 + \alpha^2) - c^2 k_i^2 - \omega_{pe}^2 + v_{ei} \omega_i \alpha]^{1/2} t\}) + B_i \exp(\{\omega_i \alpha - [\omega_i^2(1 + \alpha^2) - c^2 k_i^2 - \omega_{pe}^2 + v_{ei} \omega_i \alpha]^{1/2} t\}), \quad (34)$$

$$U_s = A_s \exp(\{-\omega_s \alpha + [\omega_s^2(1 + \alpha^2) - c^2 k_s^2 - \omega_{pe}^2 - v_{ei} \omega_s \alpha]^{1/2} t\}) + B_s \exp(\{\omega_s \alpha - [\omega_s^2(1 + \alpha^2) - c^2 k_s^2 - \omega_{pe}^2 + v_{ei} \omega_s \alpha]^{1/2} t\}). \quad (35)$$

Here $\alpha = \cos \delta / \sin \delta$ is a slowly varying quantity [1], and $A_{i,s}$ and $B_{i,s}$ are constants to be determined.

From (34,35), one can see that the three-wave phase δ must satisfy the condition $\pi \geq \delta \geq \pi/2$ in order to generate or amplify the intensity of scattered light in the plasma.

In Fig. 1, U_i and U_s are plotted as a function of $\omega_i t$ for $A_i = B_i = 0.1$, $A_s = -B_s = A_i/100$, $\omega_s/\omega_i = 0.8$, $v_{ei} \approx \omega_{pe}$ and $ck_{i,s} \approx \omega_{i,s}$. The value U_s of the SRS will increase continuously and tend to infinity with time. However, this cannot be correct because U_s is also limited by (27). To resolve this inconsistency, we consider N_L to be a measure of the disturbance caused by the electron plasma wave on the electron density [1] and neglect its second-order differential parameter $\partial^2 N_L / \partial t^2$ in (25). Then we insert (25,34) into (27) to obtain an amendment quantity to the amplitude of SRS as follows:

$$U_s^a = U_{so} \exp \left[\frac{v_{ei}}{2} t + \beta(t, \delta) \right], \quad (36)$$

where

$$\beta(t, \delta) = - \frac{\omega_{pe}^2 k_L^2 \sin 2\delta}{16\omega_s(3v_{ei}^2 k_L^2 + \omega_{pe}^2 - \omega_L^2)} \int U_i^2 dt.$$

Inserting (34,36) into (25), we have

$$\begin{aligned} N_L &= \frac{0.5 \cos(\pi - \delta)}{3v_{ei}^2 k_L^2 + \omega_{pe}^2 - \omega_L^2} U_i U_s \\ &\approx \frac{-0.5 A_i U_{so} \cos \delta}{3v_{ei}^2 k_L^2 + \omega_{pe}^2 - \omega_L^2} \exp[-0.5 v_{ei} t + \beta(t, \delta)] \\ &\quad \times \exp\{\omega_i \alpha + [\omega_i^2(1 + \alpha^2) - c^2 k_i^2 - \omega_{pe}^2 + v_{ei} \omega_i \alpha]^{1/2} t\}. \end{aligned} \quad (37)$$

Corresponding to Fig. 1, U_s^a is plotted as a function of $\omega_i t$ for $A_i/v_e = 14$, $\omega_s/\omega_i = 0.8$, and $\alpha = -0.8$ ($\delta = 128^\circ$) and $\alpha = -1$ ($\delta = 135^\circ$). From (34,36,37), one can see that at the time $t = 0$, the oscillation with the phase satisfying the condition $\pi \geq \delta \geq \pi/2$ develops into an electron plasma wave. Meanwhile, the amplitude of the scattered wave rapidly increases with time. According to (23–28) or (34–37), all amplitudes are strongly dependent on the phase of the three waves. With increasing amplitudes of the electron plasma wave and the SRS wave, the plasma collision damping becomes a major factor. Thus, the electron plasma wave and the scattered wave begin to lose energy, and their amplitudes decrease with time after peaking, as shown in Fig. 2, and finally decay altogether.

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Dimensions and Lifetime of the Plasma Focus Pinch

Sing Lee and Adrian Serban

Abstract— In spite of intensive studies of the plasma focus, scaling laws, with the exception of those for neutron yield, are not well known. This paper points out that Mather-type plasma focus devices operated in the neutron-optimized regime have remarkably little variation in a drive parameter, $(I_p/a)/\rho_0^{1/2}$, the peak drive current per unit anode radius divided by the square root of the fill density; this quantity having the value of 89 kA/cm per torr deuterium equivalent of fill gas with a standard deviation of less than 10%. This parameter controls the speed of the plasma in both the axial and radial phases; and its constancy over a wide range of plasma focus devices really indicates that these devices all operate at the same axial and radial speeds, and hence by inference they all have the same temperatures in the axial and radial phases. Using a simple dynamical model the linear dimensions and time scales of the gross plasma focus pinch are shown to be related to the anode radius of the plasma focus device. The results of experiments performed with a 3-kJ device using different anodes are in good agreement with the theoretical predictions.

I. INTRODUCTION

THE PLASMA focus is an important device for the generation of intense radiation including neutrons, X-rays, and particle beams. The physics underlying the mechanisms for the generation of these radiations in the plasma focus is not known, although there has been intensive investigations for the past three decades. Experimental and theoretical work on the focus has reached quite high levels. For example, detailed simulation work on the plasma focus had been carried out since 1971 [1] and a large range of devices has been constructed from 100 J small focus to 1 MJ large focus. Advanced experiments have been carried out on the dynamics, radiation, instabilities, and nonlinear phenomena. Yet despite all these intensive studies, very little regarding scaling appears to be known or at least documented, with the exception of the scaling law for neutron yield. In order to acquire a better overall understanding of the plasma focus it may be useful to start by looking at the scaling of simple quantities. For example, it needs to be pointed out that neutron-optimized Mather-type plasma focus, from small to large devices, all have the same drive parameter $(I_p/a)/\rho_0^{1/2}$, where I_p is the peak current driving the plasma sheath, a the anode radius, and ρ_0 is the ambient gas density. Strictly speaking, the drive parameter should include a mass sweeping factor in the density as it is known that the mass swept up by the current sheath is not 100% of the mass encountered so that the "effective" gas density is actually less. Also, a current factor should be included in the drive parameter. Not including the mass and current factors in the

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TABLE I
ACTUAL-SHOT DATA OF SOME NEUTRON-OPTIMIZED MATHER-TYPE PLASMA FOCUS DEVICES AND THEIR CALCULATED DRIVE PARAMETER. THE MEAN VALUE AND THE CORRESPONDING STANDARD DEVIATION OF THE DRIVE PARAMETER ARE 89.0 AND 7.7 kA/CM/(TORR D_2)^{1/2}, RESPECTIVELY

Device/Author [Reference]	V (kV)	W (kJ)	p (torr D_2)	I_p (kA)	a (cm)	$I_p/a\rho^{1/2}$ (kA/cm/(torr D_2) ^{1/2})
DPF-78 [16]	60	28	5	550	2.5	98.4
SPEED 2 [17]	183	70	4	1000	6	83.3
PF-360 [18]	21	60	3	750	5	86.6
Mather [19]	17.3	13.5	6.5	537	2.5	84.3
UMPF [20]	14	6	6.5	300	1.25	94.1
UNU/CTF-PFF [10,15]	14	2.9	3.5	172	0.95	96.8
Bernstein [21]	27	8	820	3.9	74.3	
POSEIDON [22]	60	280	3.8	1200	6.55	94.0

drive parameter is equivalent to assuming that these factors remain constant over the range of machines. Data of the drive parameter are compiled in Table I. In this compilation care is taken that the data represent actual neutron-optimized shots as published. Actual-shot data need to be distinguished from machine data which may give maximum current capability of a machine or design current which when combined with the pressure of an actual shot may give a misleading drive parameter since the actual shot is usually carried out not at the maximum or designed current. Thus much published data of machines could not be used in this compilation because of uncertainty over actual shot data. In Table I the value of the peak current I_p flowing into the focus tube is used as this value is more usually quoted than the plasma current and thus using the peak current more actual shot data points are available.

Table I shows that the drive parameter for a range of neutron-optimized plasma focus devices is 89 ± 8 kA/cm per (torr)^{1/2} of deuterium. The standard deviation of less than 10% is quite remarkable since the machines in the compilation range from 3 to 280 kJ and include early machines of Mather and Bernstein, advanced machines such as SPEED 2, and small training machines.

Any reasonable modeling will show that the drive parameter determines the speed in both the axial and radial phases [2], [3]. This will be shown in the following section. Having the same drive parameter indicates that the range of machines surveyed all operate with the same axial and radial speeds. This is not contradictory to the often reported speeds of just under 10 cm/ μ s for the axial phase just before the radial phase and a radial speed of about 25 cm/ μ s when the imploding shock is nearing the axis. The on-axis radial shock speed is seldom given as it is difficult to determine experimentally. Since the energetics of the plasma focus is determined by the shock speed up to the time the radial shock goes on axis,

constancy of the drive parameter gives a strong indication that the temperature is also the same over the range of plasma focus surveyed. The density also varies remarkably little, a range of two, considering the large range of energies encompassed in the survey. Thus the plasma energy density of the machines has also relatively little variation. The mechanisms for radiation of energy and particles depend ultimately on the energy density and/or the temperature. The small variations observed in these quantities over the large range of machines while on the one hand is an advantage for comparing experiments may perhaps on the other hand act as a limitation. For example, in terms of fusion neutrons, the thermonuclear fusion cross section scales as temperature $T^{4.5}$ in the region of 1 keV which is the temperature regime of the plasma focus. Would it not be an advantage to increase the drive parameter while still maintaining the strong focusing characteristics since the shocked plasma temperature scales as the square of the drive parameter [2]? By increasing the value of the drive parameter, the shocked plasma temperature is increased, and hence the thermonuclear yield. The scaling in the limit can be $Y \sim (\text{drive parameter})$ to the power of nine.

The above discussion centers around the drive parameter and its impact on plasma focus energetics. The identification of the constancy of the drive parameter as a possible limitation on focus performance may be useful in considerations of scaling. Other factors such as geometrical and temporal characteristics may also be useful for scaling of radiation performance; for example, the size of the focused plasma and the lifetime. Reviews in the literature [4]–[8] give a range of plasma dimensions of 1–15 mm in the diameter and 10–70 mm in the length and the pinch lifetime (defined as the time from the first compression to a minimum radius to the time of violent breakup of the plasma column) of tens of nanoseconds to 100–200 ns. However, no attempt has been made to discuss how these dimensions and times scale with, for example, stored energy or current. Yet by considering any simple model of the plasma focus dynamics the dimensions and time scales of the gross plasma focus pinch are easily related to the parameters of the plasma focus device.

II. THEORY

Using a snowplow model for the axial phase and a slug model for the radial phase (see Fig. 1), characteristic axial and radial transit times for the plasma shock front are, respectively, [9]–[11]

$$t_a = \left[\frac{4\pi^2(c^2 - 1)}{\mu \ln c} \right]^{1/2} \frac{z_o \rho_o^{1/2}}{\left(\frac{I_a}{a} \right)} \quad (1)$$

and

$$t_r = \left[\frac{16\pi^2}{\mu(\gamma + 1)} \right]^{1/2} \frac{a \rho_o^{1/2}}{\left(\frac{I_a}{a} \right)} \quad (2)$$

where $c = b/a$, b is outer radius of coaxial electrodes, a is inner radius, μ is permeability, z_o is length of inner electrode, I_o is characteristic current, ρ_o is ambient density, and γ is the specific heat ratio.

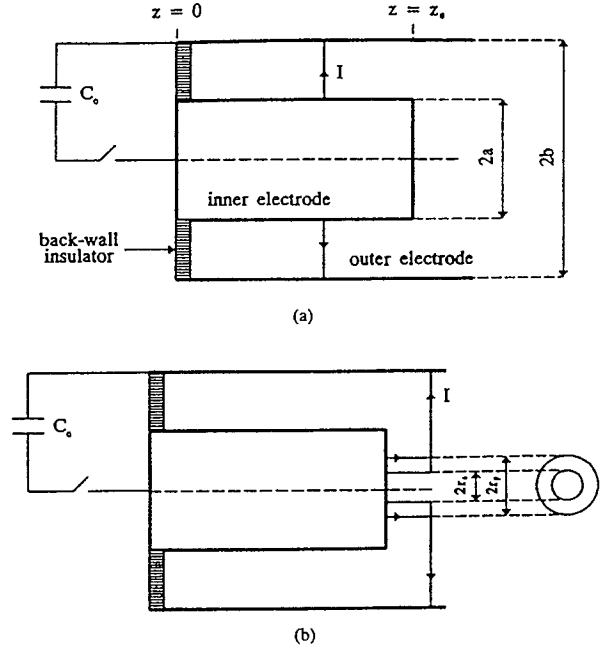


Fig. 1. Schematic of the dynamics of the plasma focus for the one-dimensional computational model: (a) axial phase—snowplow model, (b) radial phase—slug model.

From these we may write the characteristic speeds for the axial and radial shock, respectively, as

$$c_a = \frac{z_o}{t_a} = \frac{\left(\frac{I_a}{a} \right)}{\rho_o^{1/2}} \left[\frac{\mu \ln c}{4\pi^2(c^2 - 1)} \right]^{1/2} = \frac{\left(\frac{I_a}{a} \right)}{\rho_o^{1/2}} g_a \quad (3)$$

and

$$c_r = \frac{a}{t_r} = \frac{\left(\frac{I_a}{a} \right)}{\rho_o^{1/2}} \left[\frac{\mu(\gamma + 1)}{16\pi^2} \right]^{1/2} = \frac{\left(\frac{I_a}{a} \right)}{\rho_o^{1/2}} g_r \quad (4)$$

where g_a and g_r are the effective geometrical constants governing the axial and radial phases, respectively; g_r is a constant and g_a varies by less than 10% from a mean value of 0.52 over the range of $c = 1.5$ to 2 for the machines of Table I. Hence the characteristic speeds c_a and c_r depend primarily on the characteristic drive parameter $(I_o/a)/\rho_o^{1/2}$; and the operational speeds in the axial and radial phases depend only on the operational drive parameter $(I_p/a)/\rho_o^{1/2}$, where I_p is the peak current entering the focus tube. A similar parameter has been discussed earlier [12].

A radial collapse model which has proven useful for comparison with experimental work is shown in Fig. 1(b). Essentially, a zero length pinch starts at $r = a$ and elongates as it pinches inwards. The collapsing magnetic piston at position r_p pushes ahead of it a radially converging structure at position r_s . Using this model and having shown that the characteristic speed of radial transit is the same over the range of devices, it follows that the compression time $t = t_{\text{comp}}$ (see Fig. 2) depends on the radius a of the anode. As the shock converges on the axis we may define the position of the piston at this time as r_c .

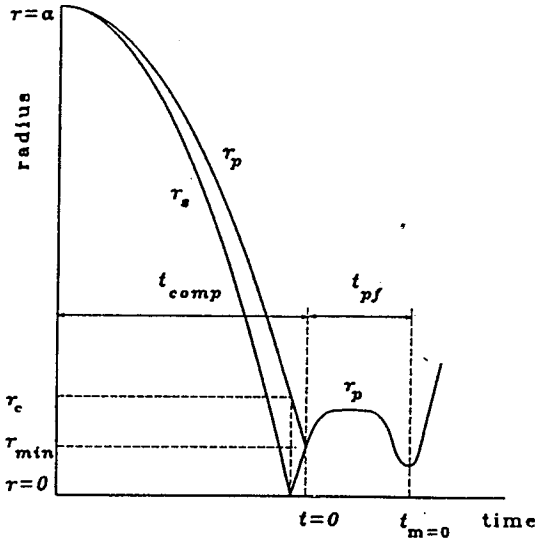


Fig. 2. Radial trajectories of shock (r_s) and piston (r_p) as a function of time.

After the shock hits the axis a reflected shock propagates outward. In the meantime the piston (see Fig. 2) continues inwards until it is hit by the reflected shock at which point the radially inward motion of the piston is reversed at position $r_p = r_{\min}$. Experimentally it is observed that the plasma column usually pinches in a second time sometimes to an even smaller radius before finally exploding outward. This ends the pinch phase and defines the quantity t_{pf} as shown in Fig. 2.

A numerical computation of this model [9]–[11], [13] shows that both r_c and $r_{\min}$ are proportional to the anode radius a .

The ending of the pinch phase is observed to be caused by instabilities. Thus we may relate the period t_{pf} to the transit time of small disturbances across the compressed plasma column. The speed of these small disturbances is practically a constant over the range of devices because of the near constancy of plasma temperature, density, and magnetic flux. Thus in such a scenario t_{pf} also depends on the radius a .

We have carried out a numerical computation with the endpoint fixed by an energy-balance method [14] and found the following for the deuterium focus: $r_{\min} \approx 0.12a$; $z_{\max} \approx 0.8a$; $t_{\text{comp}} \approx 4.5a$; $t_{pf} \approx 2a$, with a in millimeters, t_{comp} and t_{pf} in nanoseconds. Here, $z_{\max}$ is the length of the focus column measured from the face of the anode.

Similar results are applicable to the gross pinch of the plasma focus in other gases such as Argon, Neon, and Xenon. Generally for these other gases $r_{\min} \leq 0.1a$. The difference in the computation involves the value of γ . Scaling these parameters of the focus to the anode radius a is extremely useful for understanding and for applications. We have carried out experiments to confirm these theoretical results.

III. EXPERIMENTS

Experiments were carried out using a 3 kJ plasma focus device [15] operated at 14 kV in deuterium at the neutron optimized pressure of 4.5 mbar. The inner electrode was the

TABLE II
MEAN VALUES OF THE PINCH LIFETIME (t_{pf}) AND OF THE COMPRESSION TIME (t_{comp}) AS FUNCTIONS OF THE ANODE RADIUS (a)

a (mm)	t_{comp} (ns)	t_{pf} (ns)
9.5	45.1	19.5
8.75	41.1	17.6
8.5	39.2	17.1
7.5	31.4	15.2
7	29.1	14.3

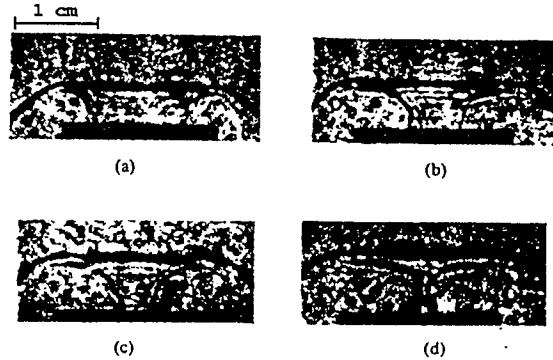


Fig. 3. Examples of shadowgraphs of plasma focus during the radial phase for an anode of 9.5 mm radius.

anode. All anodes tested were made of copper and hollow at the open end.

The diagnostics employed included [15]: shadowgraphy using a TEA nitrogen laser, current (I) and current derivative (dI/dt) using current transformer and Rogowski coil, respectively, voltage (V) using a resistive voltage probe, soft X-ray emission rate (dY_{SX}/dt) using filtered PIN diodes, and hard X-ray and neutron time-resolved measurements (dY_n/dt and dY_{HX}/dt , respectively) using two fast response plastic scintillator-photomultiplier systems in a time-of-flight arrangement. The field of view of the shadowgraph technique is above the open end of the anode. The X-ray and neutron emission rates were recorded in a radial plane with respect to the axis of the focus tube.

The dimensions of the pinch were determined from the time sequences of shadowgraphs. The timing of the shadowgraphs as well as the timing of the important periods of the evolution of the plasma focus were performed with better than 1 ns accuracy. The time reference was taken at the instant when the plasma column reached the minimum radius ($t = 0$, $r = r_{\min}$). The instant $t = 0$ was identified from the current derivative signal (the first sharp negative spike) and from the soft X-ray signal (the first spike). The pinch lifetime (t_{pf}) was defined as the duration from $t = 0$ to the instant corresponding to the development of the $m = 0$ instability ($t_m = 0$). The latter is associated with the beginning of the hard X-ray pulse.

Experiments were performed with several anodes of radii of 9.5, 8.75, 8.5, 7.5, and 7 mm, respectively [15]. For each electrode configuration a large number of discharges (more than 50) was analyzed. Our statistical analysis was performed

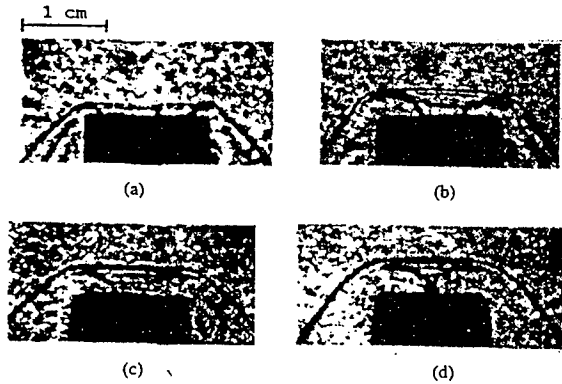


Fig. 4. Examples of shadowgraphs of plasma focus during the radial phase for an anode of 7.5 mm radius.

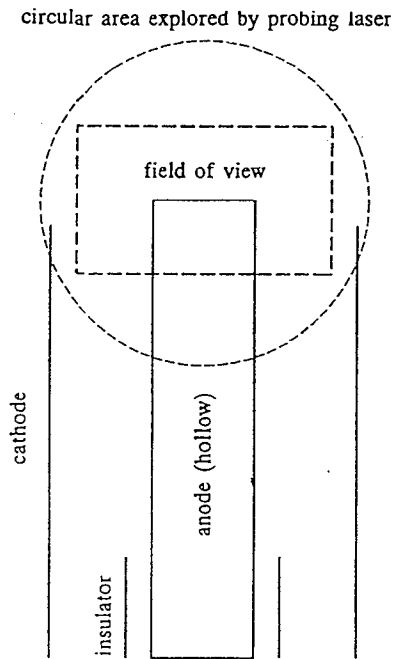


Fig. 5. Field of view of shadowgraphs at the open end of the electrode system.

on series of shots without excluding the discharges with very low neutron yield. Detailed discussions and correlations of the discharge parameters (e.g., peak current, peak axial velocity, axial transit time, radial compression time, and pinch lifetime) and neutron and X-ray emission were presented elsewhere [15]. We would like to mention only that the standard deviation of the peak discharge current was less than 2%, the standard deviation of the peak axial speed was less than 7% while the standard deviation of the neutron yield reached 60% for some anode configurations. The mean values of the pinch lifetime and of the compression time are illustrated in Table II. They show that the pinch lifetime (t_{pf}) as well as the compression time (t_{comp}) are scaled to the anode radius in agreement with the theoretical predictions.

The evolution of the plasma during the radial compression phase and pinch phase was analyzed from shadowgraphs. Some images of the plasma during the final stages of the compression phase and pinch phase are illustrated in Figs. 3 and 4 for two anodes of radii 9.5 mm and 7.5 mm, respectively. The field of view of the shadowgraphs is illustrated in Fig. 5. From the shadowgraphs, r_p is estimated with 10% accuracy.

Measurements of the axial elongation and radius of the plasma column during the radial collapse phase are in good agreement with the theoretical model. At the end of the radial implosion the following experimental values were determined:

when $a = 9.5$ mm it was found that:

$$\begin{cases} r_{min} \approx 1.2 \text{ mm} \approx 0.13a \\ z_{max} \approx 7.5 \text{ mm} \approx 0.8a \end{cases}$$

and

when $a = 7.5$ mm it was found that:

$$\begin{cases} r_{min} \approx 1 \text{ mm} \approx 0.13a \\ z_{max} \approx 6 \text{ mm} \approx 0.8a. \end{cases}$$

Here, z_{max} is the length of the focus column measured from the face of the anode. These results confirm our theoretical predictions.

IV. CONCLUSION

Numerical computations on a simple model yield the following dimensions and times for the gross pinch phase of deuterium plasma focus:

$$\begin{aligned} r_{min} &\approx 0.12a & z_{max} &\approx 0.8a \\ t_{comp} &\approx 4.5a & t_{pf} &\approx 2a \quad (t \text{ in ns, } a \text{ in mm}). \end{aligned}$$

Experimental results are presented which verify the predictions of the model.

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Developing curriculum in Singapore: teacher-academic partnerships

K. A. TOH, K. C. YAP, S. LEE, S. V. SPRINGHAM
and P. CHUA

A qualitative methodology was employed to examine collaborative reform efforts between teachers and academics in an environment where transmission-oriented teaching was rife. The teacher collaborators selected were of wide-ranging experience and backgrounds, while the students were drawn from four grade 12 classes. Data sources included classroom observations, artefacts, fieldnotes, dialogue sessions and responses to teacher and student surveys. Initially the teachers had difficulty adjusting their orientations. However, when the students adjusted well when empowered in the planning and decision making that was part of the learning process, the mediating actions of the students were sufficient to produce a positive effect on the teachers.

Initiatives for curricular reform occur in response to a felt need (Morris and Thompson 1979, AAAS 1989, Rosier and Keeves 1991, Keeves 1992). Some of these changes are well received while others are not. While centrally endorsed initiatives for change may incorporate processes of development which try to ensure that implementation closely follows the design, the same cannot be said for non-centralized initiatives. There is a plethora of literature to suggest that the task is not simple (Schwab 1969, 1973, Cuban 1979, 1993, Eisner 1979, Walker 1990). The task is made even more difficult when non-centralized initiatives operate within a centralized framework. This paper documents how a partnership between teachers and academics can operate for curriculum change in such a setting, and the practical issues surrounding the change.

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Background

Until 1987, with the introduction of independent schools, education in Singapore was centrally controlled by the Ministry of Education. By and large the supply and transfer of teachers, the curriculum taught, the textbooks used, the examination system and a host of other aspects were prescribed by the Ministry. Even with the introduction of independent schools in the late 1980s, and more recently the autonomous schools in 1993, where much of the decision making was delegated to the school principals, the umbilical cord was not entirely severed. Regardless of how the school carries out a task, it will eventually have to account for its actions when its students take the centralized examinations, just like students from other schools. There are two reasons for this: first, to forestall attempts to do things out of the ordinary to erode confidence in the school structure under the guise of independence; second, to ensure that the products of the school system are the same even though the processes employed to derive the products may be different.

With this centralized control over matters pertaining to schools, the curricula in Singapore are prescribed through syllabuses issued by the Ministry of Education. Though schools have a free hand in selecting their own textbooks from the many books available in the market, the centralized examination at specific stages serves to make the schools conform with certain benchmarks that have been established over the years.

As a result of this central control, curriculum development in Singapore in the 1960s and 1970s can at best be described as *ad hoc*. Efforts at curriculum development then came from teacher practitioners who saw it as important, for education as a whole, to bring about some changes. They felt it important to bring what was being taught in the classroom more in line with developments occurring in the western hemisphere. These indigenous attempts at curriculum development stemmed primarily from the professionalism of individual teachers and did not receive much assistance from the Ministry of Education.

With the formation in 1981 of the Curriculum Development Institute of Singapore (CDIS) a new chapter in curriculum development was opened for Singapore. Teachers were co-opted from schools to become full-time curriculum developers. This concerted attempt of a government agency at spearheading curriculum development was a complete turnaround from the situation prevailing in the 1960s and 1970s. The curriculum materials produced by CDIS competed with those available in the open market. The initial focus for the development of a prescribed curriculum was mainly on the lower grades, at the primary and lower secondary levels. Thus some centralized control was exercised over what was to be taught in the classroom. At the higher level, the CDIS was also involved in the development of curriculum materials for N level.¹ For the O and A levels, the syllabuses prescribed by the Cambridge Examinations Syndicate (CES) for overseas students dictated what was being taught by teachers.

Suffice it to say that an examination body would prefer some stability in its examination syllabuses rather than changes being made irregularly. For grades and subjects where the CDIS had jurisdiction, an agreement with

publishers gave the print materials currency for 10 years; in other words, any changes to a syllabus requiring changes to textbooks were only permitted every 10 years. It was proposed that every 10 years or so a Ministry committee would be set up to scrutinize the existing syllabuses and compare them with syllabuses elsewhere, especially those in the UK. Besides dropping irrelevant or less relevant topics, some new topics considered relevant to future living and citizenry could be introduced. Recent developments in the design of the school curriculum in England and Wales, for example, raised questions about the relationship between education and the changing needs and values of society (Parker 1993).

The CES, for the grades and subjects where examinations are carried out, also hold on to a particular syllabus and format for a good 10 years before instituting changes. New topics are introduced by content-area academics of the university through curriculum review committees, often without empirical evidence to support the feasibility and desirability of introducing these topics. The proposed introduction of an Astrophysics and Cosmology option in the syllabus for A-level Physics, for example, came from the interest of faculty members in the field and the desire to generate enough interest at the school level to feed students into undergraduate courses in that field at university. It remains to be seen whether the proportion of students who will take on this option will be compared with those taking the other options offered.

Purposes of the study

This study stems from the concern of academics for what actually goes on in the classroom. Classroom practices are remarkably stable regardless of technological changes that go on outside the classroom (Toh 1994). Many teachers, for example, still make use of optical pins to trace the ray path through a glass block and bring in ideas concerning parallax. This served its purpose in the past when an intense light beam was either not readily available or when it was not feasible to provide a darkened environment for optics experiments. With the technologies now available, optics experiments involving the tracing of the refraction path through a glass block can be more vividly shown with a laser pointer. The refraction of light using a laser pointer as the light source makes obsolete the vicarious method of tracing the ray path using pins and the concept of parallax.

Another example of classroom practices lagging behind what goes on outside concerns the teaching of microwaves. We see an invasion of microwave ovens in almost every home. In spite of this, teachers continue to mention microwaves *en passant* as an example of electromagnetic waves, without demonstrating the properties of microwaves in a tangible way. These, and many other practices, thus cast some doubt on the adequacy of schools in preparing the citizenry of the next century.

Academics and teachers can play an important role in the learning processes that go on in schools. Problems encountered can be tackled jointly with a collegial spirit. Academics, teachers and students all stand to benefit from such an enterprise. This paper is an attempt to document the

curriculum development efforts carried out jointly by a group of teachers and academics in a relationship of partnership between the teachers and academics, the latter comprising both content area specialists as well as faculty from the pedagogical area.

It was mutually recognized that the topic of electromagnetic radiation was very poorly taught in many schools, and that the partnership should view it as a social responsibility (Ramsey 1993) to look into improving its teaching. The situation was one where there was an overemphasis on the academic aspects of different parts of the spectrum, but a neglect of the pedagogical importance of the links. Attempts to link the similarities of radiowaves, microwaves, visible light and x-rays were, at best, feeble, even though each of these forms of electromagnetic radiation is now part of our everyday lives. Additionally, the treatments in schools did not exemplify the link of waves and particles with electromagnetic radiation. This situation thus did not provide a unified picture to the student of physics.

The team of four academics, collectively representing more than 80 years of teaching experience, felt that the innovations which could be introduced with the available technology would inject life into the 12th grade topic of electromagnetic radiation. They comprised specialists in content knowledge as well as specialists in pedagogical knowledge. Recognizing the importance of teachers and the experience they could bring with them to input into the curriculum development process, the potential teachers in the partnership were identified early in the study.

Methodology

Two junior colleges which were 11th and 12th grade high school centres were selected as the research sites and formed the purposive sample. They were selected for their large enrolment and consistent track record. Each of the colleges had more than 500 students taking the 12th-grade examination (A level) in Physics every year. These examinations were administered by an external agency, the Cambridge Examinations Syndicate. Each of the colleges maintained a high level of 12th-grade successes, with a high proportion of students proceeding to university. The students were generally well disciplined and motivated to study, since students who gain admission to universities do so on a competitive basis.

Four teachers, with pseudonyms Betsy, Claire, Andrew and Dennis, agreed to co-operate as part of the teacher-academic partnership. They represented a rich diversity in years of experience, years at the site and educational background (see table 1).

The academics and teachers met regularly at weekly intervals for a period of six months to develop the curriculum materials and test questions, construct and test the equipment intended and devise the experiments. The two groups brought with them to the project different perspectives and different interests. There were lively debates in many of the sessions and different perceptions surfaced as to what should be done. The academics were seen to be more persuasive in obtaining consensus for content material, while the teachers, with their greater exposure to craft

Table 1. Profiles of teachers involved in the study.

Factor	Betsy	Claire	Andrew	Dennis
Years of experience	23	3	24	1
Years at present site	6	3	14	1
Hours of teaching per week	18	20	18	20
Bachelor's degree	Physics	Physics	Physics	Physics
Country where degree was obtained	Singapore	Singapore	Malaysia	UK
Certification in subject area	Physics & Maths	Physics & English	Physics & Maths	Physics & Maths

knowledge, lobbied strongly on aspects concerning how this should be implemented.

Curriculum materials: Conscious of the features of past efforts that brought about meaningful curricular development or otherwise, the partnership systematically identified the important academic and pedagogical aspects that should be included in the development of curriculum materials for the topic of electromagnetic radiation. The partnership also felt that the development of curriculum materials should capitalize on emerging technologies that are likely to have significant pedagogical implications. For example, it was deemed important to incorporate the use of lasers and microwaves as emerging technologies, which cannot be ignored by school science, because the prices of laser and microwave sources are now at realistically low levels and are thus within the reach of schools.

The partnership recognized the importance of teachers' beliefs about teaching and learning in curriculum implementation, and therefore made provision for this in designing the module. After Miller and Seller (1985), this study saw the three broad orientations, namely transmission, transaction and transformation, that teachers could be grouped into for their curriculum orientations. To clarify each orientation, the aims, learning experiences and the role of the teacher are summarized in table 2. There is evidence to suggest that a great deal of current educational practice taking place in schools is transmission-orientated (Toh 1994). It therefore appeared as a realizable goal to work from the transmission position towards the transaction position in planning for implementation of the module. The partnership thus sought to encourage inquiry skills and decision making as part of the learning experiences of students. In other words, students were to be active constructors of knowledge, with their teachers acting as facilitators. The development of a transactional pedagogy thus involved learning with understanding since the students were encouraged through active learning to construct rather than consume knowledge. This guided the partnership's development of the curriculum materials.

The curriculum materials went through several rounds of draft with continual dialogue between the teachers and the academics. The university academics, with their workshop resources, made multiple sets of the

Table 2. Characteristics of curriculum orientations.

Factor	Transmission	Transaction	Transformation
Aims	• mastery of school subjects	• rational intelligence • problem-solving skills	• self-actualization • self-transcendence • social involvement
Learning experiences	• facts and concepts of given subject • student is passive	• inquiry skills • democratic decision making	• self-inquiry • interdisciplinary
Role of teacher	• directive • didactic	• facilitator	• integrate cognitive skills with other dimensions (aesthetics, emotional, spiritual)

equipment required for hands-on activities. The teachers, with their intimate knowledge of the students, prepared the pre-test and post-test to fit the content covered by the curriculum materials. The prepared materials were discussed and tried out by the team. The entire team of eight teachers and academics were deeply involved in various aspects of the study from start to finish, in a spirit of camaraderie, hence the term 'partnership'.

Focus of inquiry. The general focus of inquiry of this study was on the efficacy and feasibility of the module *Unifying Concepts behind Electromagnetic Radiation*, and how the module with its hands-on approach and use of emerging technologies would 'impact' on student learning. The partnership felt that a qualitative research approach was best to explore this 'impact' from the perspective of the students and teachers involved. According to Lincoln and Guba (1985: 227), the purpose of a qualitative study is to 'accumulate sufficient knowledge to lead to understanding'. They recommend the use of an emergent research design, which means that data collection and data analysis are simultaneous and ongoing activities that allow important understandings to be discovered along the way and then pursued with additional data-collection efforts.

To expand on the general focus of inquiry, the specific research questions, which still conformed to the emergent research design, were:

- (1) What are the external influences impacting on the project?
- (2) What is the impact of the project from the perspective of the teachers?
- (3) What is the impact of the project from the perspective of the students?
- (4) What is the efficacy of the module introduced?

An experimental approach could be adopted to examine the efficacy of the module as identified in (4) above, while the first three questions required a qualitative methodology.

Table 3. Techniques used for data collection.

Technique	Research question			
	1	2	3	4
Observation		×	×	
Artefacts	×			
Fieldnotes		×	×	×
Dialogue sessions	×			
Teacher questionnaire	×	×		×
Student questionnaire			×	×
Pre-test and post-test				×

Data collection methods: An eclectic approach using different methods was used to obtain the necessary data and to address the research questions. This included observation, artefacts (comprising instructional materials such as students' text, teachers' notes and laboratory instructions), fieldnotes (from the informal interviews with students during the laboratory sessions), dialogue sessions (recording the informal interviews with teachers), teacher questionnaire, student questionnaire, pre-test and post-test (see table 3). Together they provided a rich source of detailed information about what went on in the classrooms, the impact of the module on student learning and the extent to which the students were empowered in their own learning.

To increase the trustworthiness of the research data, all the research questions were examined through more than one technique to provide for validation of the findings through triangulation. The triangulation process also maximized the probability that the emergent assertions were consistent with a variety of data. The data-collection process spanned a period of eight months from September 1993 through to April 1994, with extensive site visits taking place in the months of January, February and March. To obviate a single researcher's bias, a two-person team was mandated for all observations and dialogue sessions, while field notes were cross-checked with data collected by another method. Members of the teacher-academic partnership were given the opportunity to reply to (and to change) any documented views as well as those contained in this paper to meet the criteria of validity and reliability (Lincoln and Guba 1985, Eisner 1991).

An attitude questionnaire consisting of 21 Likert-scale items was designed and validated by an expert team, and revised before being administered. The questionnaire, with an overall reliability index of 0.80, as measured by Cronbach's alpha, provided a quantitative measure of three constructs: students' interest in the module; students' perception of the clarity and organization; and students' perception of the module content with regard to experiments, examples used and tutorials provided.

Outcomes

What was learned from this study builds on the collective knowledge of the team forming the teacher-academic partnership, namely science teachers,

science teacher educators and science content educators. Generalizability is constrained by the background of the reader and intended applications the reader might be considering. It is not possible for the authors to know *a priori* how readers might apply knowledge from this study. The extent to which knowledge reported here can be applied in a particular context is a decision the reader will have to make, taking into consideration the relevance to the context the reader frames from personal experience.

As a way of conceptualizing and conveying the outcomes from the multiple data sources, the database was organized into four major assertions (Erickson 1986, Bogdan and Biklen 1992). These assertions related to research questions 1 to 4.

Assertion 1. Teacher beliefs and the overhang of examinations exert a strong influence on classroom practices

Reform is a difficult business for a variety of reasons, not the least of which is the tendency of cultures to maintain themselves in accordance with their current practices. Hence, in spite of the well-intentioned preparation of the teachers concerned for curriculum implementation through the teacher-academic partnership, there was the dilemma of the teachers continuing to be strongly influenced by their beliefs and the curricular coverage requirement of an examination board that collectively constituted the educational situation (Feldman 1994).

The relationship between teacher beliefs and classroom practices has been explored by a growing number of studies (e.g. Brickhouse 1990, Cheung and Toh 1992, Tobin *et al.* 1994). These studies have shown the importance of links between teachers' beliefs and their classroom practices. When congruence exists, they act as restraints to reform (McRobbie and Tobin 1995). In this study the teachers' beliefs and the overhang of an external examination board requirement were seen as factors which strongly influenced classroom practices.

The module introduced was an attempt to pull together the unifying concepts of electromagnetic radiation. In order to highlight the unifying concepts, emphasis would have to be placed on links across different parts of the electromagnetic spectrum. There was, however, the constant reference by the teachers to examination requirements, thus relegating to the sidelines the importance of the links provided by the unifying concepts. The teachers were also myopic to the need for a paradigm shift from transmission to transaction. They were concerned with the transmission of factual information which formed the body of knowledge upon which the students were tested during examinations, despite its obvious inadequacies. This external influence was sufficiently overwhelming to dampen their enthusiasm for a paradigm shift. Claire's pensive remarks at the start of the study reflected this:

It would have been more efficient and quicker if I had told them the concepts. I know this goes against the grain of modern-day approaches where we want the students to engage themselves in what they are studying, but doing all that slows them down too much. It is important for me to keep them moving along and on task. I have to take

strict control of the time to avoid falling too far behind. . . . If students don't understand, they should memorize the important facts and allow understanding to occur later, in its own time.

I also spend quite a fair amount of time coaching them on how answers to examination questions should be presented. I even try to make sure they know what is expected for attaining high marks. If I have some 30% of the curriculum less to cover, I could afford time for the students to do work individually, or allow for more investigative work.

This reflects on how the transmission mode of teaching reinforces memorization of the 'vocabulary list' demanded by examination bodies. With a time frame to observe, teachers, become intolerant of digression. Building understanding becomes less of a concern than covering content and preparing for success in examinations. This is indeed a far cry from the generally accepted view that schools must develop the rational process in students in order to develop their ability to think critically. When teacher beliefs are congruent with the requirements of examination boards, they can act as restraints to changes in teaching and learning practices, or, for that matter, to reforming curricula. Any attempts at reform ought to take into account the implications of this congruence. Such an environment has been confirmed by other studies. Brickhouse and Bodner (1992), for example, attributed the pursuit of grades and shortage of time, amongst others, as restraints experienced by beginning science teachers.

Assertion 2. The hands-on, practical nature of the curriculum requires a commitment by the teachers to a shift of orientation from transmission to transaction

Despite the rhetoric that science teachers value inquiry skills and the practical work which promotes such skills, the typical classroom observation shows, to the contrary, that science teachers devote a major part of their time to seat-based skills. Learning of the different aspects of electromagnetic radiation, such as microwaves and gamma rays, is often done vicariously through teacher talk and the taking of notes in many Singapore high schools. Questions asked are frequently from the notes given or from the textbook used, and students are expected to respond with the precise wording found in the notes or the textbook when answering the questions.

While there is some variation and the occasional departure from such prevailing practices, transmission and regurgitation continue to hold sway. This is most unsatisfactory, and at sharp variance with curricula that are intended to stimulate creativity. It takes away the fun of learning. In trying to avoid this pitfall, the module developed incorporated hands-on practical work to engage the students in active learning and decision making. The suggested approach for implementing the module was that of transaction (see table 2) rather than transmission. In other words, the teachers in the teacher-academic partnership would clearly need to move away from the usual transmission mode and adopt a more transactional stance when dealing with this module. It was imperative that time ordinarily used for

transmission be diverted for more interactive activities, thus empowering students to be actively involved in their own learning and decision making, with the teacher acting as a facilitator. Betsy and Dennis's reservation and uncertainty were reflected in their statements:

I was a little uncertain at first because it meant a breakaway from what I usually do. The topic is normally dealt with as a lecture. I talk through with the class concerning the wave and particle aspects of electromagnetic radiation, and no practical work is involved The demands of the module are, however, quite different. I have to refrain from telling them many things. I have to take the back seat. Not quite used to it, you know. Quite a challenge.

I felt I was losing some control over what the students have learned. But I'm sure the students, though somewhat uncertain at first, have adapted well to it. In fact, I detect that challenge in them when looking for the second and third order fringes in the diffraction grating experiment using a laser beam.

The module and the approach used created quite an impact on the collaborating teachers. They realized the challenge in refraining from telling and yet providing the circumstance to facilitate learning of the very same concepts. They confessed that the process was harder than presenting the facts in a lecture. However, they admitted that the concepts learned would be more enduring since students had a greater claim or ownership of the concepts than if the same concepts were being dished out to them. Two of the teachers even remarked:

It's good to see them thinking for a change. In the past I was doing all the thinking for them . . . thinking what they would think when I say this or say that.

It's when they *do* that they think . . . they should think more instead of just listening and accepting what someone else says.

This was indication of change in the teachers' expectation with the use of the module. The shift in orientation came around as something gradual, when the teachers saw that the students were actually able to think for themselves. What they had done in the past merely encouraged passive learning and did not empower the students to think for themselves.

Assertion 3. The active engagement by students in the hands-on practical sessions is a major indicator of student learning

In Singapore the topic of electromagnetic radiation is traditionally covered, regrettably, as a lecture (or a series of lectures) without any demonstration or hands-on practical work. This is a disappointment, considering the electromagnetic spectrum is encountered in everyday life in the form of visible light, microwaves, radiowaves, etc., and so many hands-on activities can be included. Students need to learn science by experiencing it, so that they can take ownership of the ideas and concepts. With this in mind, the module sought to engage students by getting them involved in the learning process with hands-on practical sessions. When the teachers were asked what they personally felt was different about the module, Betsy and Dennis responded as follows:

This module uses the practical approach . . . the theory lesson accompanied by practical demonstration gave students a better understanding of the concepts.

The approach of doing experiments linked to the theory learned in the lectures is to be promoted. Current practice provides for [practical] work schedule which is totally unconnected with lecture materials.

Students also lamented that their traditional laboratory practical work was unrelated to what was being taught by their physics teachers during the lectures. The following comments made by a student were typical of those of many from the class:

When carrying out laboratory activities, we merely followed the instructions telling us what to do. We did not know why we were doing them or what outcomes to expect. We just did the experiment like we were told to do. . . . If the experiments were somehow a follow-up of the lectures, perhaps we could understand what and why we were doing what we did.

The high level of student involvement in the experiments during practical classes within the module was backed up by classroom observations. They were either busy discussing with their partners how they should plan to take the readings or actively adjusting the set-up to take the readings. Often they were seen discussing with each other the link between the theory learned during the lectures and what they were working on during the practical classes. Andrew's dialogue with one of his students after completing the module supported this conclusion:

Q: I am interested in knowing what students think about the module. Thinking back over the entire module, how would you describe the module to others?

A: Hmm. . . . Well, I would describe the module as quite interesting and involving. In other classes I just sit there, even if I have something to say. I don't know why. Maybe it's because you had us involved in so many group things.

Q: Well, it is my intention to get students involved. We all tend to learn more that way. I would like to ask you a little about the practical work. How did you go about doing the practical work which did not guide you in the step-by-step way which you were used to?

A: [Pause] It did seem strange at first. We had to make up our minds what we wanted to do and planned how to do it. Talking it out with my partner gave me a clearer picture how to go about it. You know how it is . . . two heads are better than one.

Students were polled on their views of the module, and 98% of the sample responded that they would recommend the module to their peers. The three most popular reasons they gave were:

- the module facilitated their understanding;
- the module aroused their interest in the subject area; and
- the experiments in the module provided hands-on participation.

This was an indication of the students' endorsement of the module and the hands-on sessions that went with it.

As an additional source of confirmation, a summary of the students' ratings on three constructs (interest, clarity and content) is given in table 4. The item means for each of the constructs are 3.6, 3.7 and 3.4.

The mean attitude rating for the entire module is 73.7, giving an item mean of 3.5. These ratings indicate that the students' attitudes were positive towards the module.

Table 4. Students' attitude towards module.

Attitude subscale	<i>n</i> of items	Scale max.	Mean	SD
Interest	5	25	18.3	2.9
Clarity	5	25	18.6	2.5
Content	11	55	37.0	4.1
Overall attitude	21	105	73.7	7.7

Table 5. Mean scores for the pre-test and post-test.

Test	<i>n</i>	Mean	SD	<i>t</i>
Pre-test	59	11.32	4.53	2.73
Post-test	55	13.75	4.93	

Assertion 4. Students performed significantly better in achievement tests after going through the module compared with pre-tests taken before the module

In order to assess the impact of the module on the gain in content achievement of the students, two equivalent sets of achievement tests were designed. One set was intended for use as a pre-test instrument while the other was the post-test instrument. The tests covered what was dealt with in the module, and this was confirmed by doing a content analysis on both the tests constructed. The content validity was determined by the academics and the teacher collaborators in the teacher-academic partnership.²

The pre-test was administered just before the module was introduced, while the post-test was administered immediately after the implementation of the last session of the module. The students were therefore not specially prepared for the test, other than the exposure to the module. Students' performance in the achievement tests is given in table 5. The post-test mean is significantly higher ($p < 0.02$) than the pre-test mean. Their better scores at the post-test stage compared with the pre-test indicate that the module had a positive effect in bringing about understanding of the concepts covered.

Conclusion

The end of the 20th century seems to be an era of advocacy for reform (Apple 1992, Jenkins 1992, Fullan 1993). However, despite the attention given to reform (Fullan 1993) and the factors associated with initiating and sustaining reform (Sarason 1993), little attention has been given to how teacher-academic partnerships work to bring about change.

Several of the things we have learned in this study have implications for curricular reform efforts. Intended changes in teacher actions need to take

into account not only the intended behaviours of teachers, but also the existing beliefs which legitimize those behaviours. When teacher beliefs are congruent with requirements imposed externally, they can act as restraints to change. Changes in actions can be expected either through a personal commitment to change, or through the mediation of the actions of others, such as their students. In this study this was seen in the winning over of the teacher collaborators to the pedagogical advantages of moving away from the transmission-orientated approach to teaching and learning. The high level of student involvement and interaction during the study was something they saw for themselves, hence the need for them to shift towards a transaction-orientated approach. This is particularly significant for two of the teachers who had each taught for more than two decades, using the transmission mode most of the time.

A second outcome worth noting is that this move towards a more transaction-orientated approach in the module trials was achieved without sacrificing examination efficiency when compared with the traditional transmission-orientated approach. This is important for curriculum reform efforts in an achievement-orientated environment. The findings presented here show that a transaction-orientated approach, with attendant empowerment of students to take charge of their learning, is not inferior to the transmission-orientated approach. The former often provides a teaching-learning situation which is more enduring than the latter.

On the basis of this evidence it is possible to conclude that learning was not impeded by adopting a transactional approach. And since the qualitative evidence indicates the module to be well received, it could be judged to be worthwhile. It is our contention that the best way to help students to see and talk in the ways of the scientific community is by engaging them, through empowering them, in the practice of its activities.

This study was designed to explore curriculum reform efforts through a teacher-academic partnership. The findings presented here suggest that the teacher-academic partnership should not be a rigid coupling if it is to adjust to the contingencies arising out of the teaching-learning situation. Curricular changes can be effected through encouragement and support for teachers in thinking and learning about their classroom practices and the beliefs that underpin them. A caveat here may be necessary. Working with teachers may not always be sufficient, in itself, to effect change. The structure of the school system – in particular, its bureaucracy, administrative structure and value system – can create an institutional climate that is neither favourable to nor supportive of change. In such circumstances, teachers are constrained from effecting curricular changes through pressure of examinations, lack of time (as a result of overcrowded curricula), or problems arising from an unsupportive departmental head. Teachers and researchers need to be cognizant of the realities of the situation.

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Notes

1. The Ordinary-level (o-level) and Advanced-level (A-level) examinations are administered by the CES for overseas students after 10 and 12 years of schooling respectively. The Normal-level (N-level) examination is a special examination for the less able stream administered at the end of the 10th year of schooling. This is provided as an alternative to the o-level examination.
2. To ensure that the two test were reasonably equivalent, the two instruments were administered to a group of pre-service physics trainees. The mean difficulty indices (pre-test, 0.46; post-test, 0.51) and the mean biserial indices (pre-test, 0.60; post-test, 0.60) give confidence that the tests may be used as equivalent tests. Their reliability values, as determined by KR20, are 0.87 and 0.88.

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A REPETITIVE COMPACT PLASMA SOFT X-RAY SOURCE

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A Compact Plasma Focus (CPF) device with a fast charger and high repetition rate switch is being developed as a repetitive pulse soft X-ray (SXR) source for lithography. A module designed primarily to test high repetition rate capability, with a single capacitor has been observed to produce up to 0.5 J of X-rays. The capacitance is 7.85 μF , the peak discharge current is 140 kA with a quarter-period of 1.2 μs when the capacitor bank was charged to 15 kV. The X-ray spectrum from our CPF device is in the range of 0.8 - 1.4 nm. The soft X-ray yield varies with the pressure of working gas and the voltage applied to capacitor. The X-ray emission is maximum at the filling gas pressures of 0.5 mbar and 2 mbar. The module has been tested at a repetition rate of up to 10 Hz. The high current and high repetition rate necessary for high yield X-ray production is made possible with the use of pseudo spark gap switch (PSS). On the basis of these tests, a four module test system, operating at 400 kA is designed to produce 40 J of SXR per shot and will be operated at several shots per second. The four module system will have a footprint of 1 m².

INTRODUCTION

X-ray sources have many applications, for example, in X-ray spectroscopy, microfabrication, X-ray microscopy, X-ray laser pumping, and high density microelectronics lithography¹⁻⁴. It is important to develop a high quality and high intensity soft X-ray source. As an example, the lithography industry presently uses optical (UV/visible) sources for 0.5 μm feature size lithography. The optical lithography

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techniques are being extended to $0.18\text{ }\mu\text{m}$ now⁵. However, at smaller sizes, the use of shorter UV wavelengths leads to a rapid increase in the cost of optical lithography. X-ray techniques are being pursued for lithography with design rules below $0.25\text{ }\mu\text{m}$.

The main sources of high intensity soft X-rays are: synchrotron, laser-produced plasma⁶, and the plasma focus (PF) device⁷. The primary objective of this work is to develop a soft X-ray source suitable for lithography. The basic requirements for producing a good clear exposure are: photon energies about 1 keV, high energy, collimation/small spot size. For a point source size of about a millimetre, the collimation requirement limits the distance from the source to greater than hundreds of millimetres so that the amount of energy required from the point source for a 100 mJcm^{-2} on the resist at 1 m is 12 kJ. Among the available X-ray sources, the synchrotron is the best for such a purpose because of its high intensity and collimation. However, the construction of the synchrotron facility is very expensive, its operating and maintenance costs are also high. The minimum installation provides 20 beams with little possibility of a smaller installation. The PF device is a cheap, compact highly reproducible source of high-temperature pulsed plasmas (typical temperature is 1 keV, typical density is 10^{19} cm^{-3}) which does not require sophisticated techniques or expensive facilities. The minimum installation is for one beamline. These features are very important advantages when compared with other X-ray sources.

The characteristics of X-ray emission depend strongly on the CPF device operating parameters (filling gas composition and pressure, stored energy, plasma current, driver impedance, electrode material and configuration). This makes it difficult to compare the X-ray emission results on different machines, but provides several parameters to tune the PF X-ray output.

In this work, pure neon gas is used as the working gas. The experimental results show that the X-rays are emitted at the wavelength of 0.8-1.4 nm, which is suitable for lithography, for a range of gas fill pressure and capacitor charging voltage.

EXPERIMENTAL SET-UP

A PF device is generally composed of the following parts: a charger, energy storage capacitors, spark gap switches, vacuum system, discharge chamber and electrodes. PF devices may be classified as either the Filipov type⁸ or the Mather type⁹ according to the electrode geometry. Our configuration is not strictly either. It is illustrated in Fig. 1. The maximum diameters of the copper coaxial electrodes are 30 mm (inner electrode) and 55 mm (outer electrode). The outer electrode is also used as the vacuum chamber. The inner electrode is hollow so that the X-ray produced by the plasma focus can pass through this electrode to the detector. The energy storage bank is a single $7.85\text{ }\mu\text{F}$ capacitor charged to maximum of 15 kV. The total inductance of the circuit is 75 nH. The high voltage switch employed in our CPF is a

pseudo-spark switch¹⁰, which has a peak current rating of 140 kA and was operated in our experiments at a repetition rate of up to 10 Hz, even though the electrodes were not cooled. The capacitor charging device used is able to supply 9 kJ per second at 15 kV. In our experiment the repetition rate is set as 10 Hz, 5 Hz, 2 Hz, 1 Hz, 0.5 Hz and 0.1 Hz respectively. The time of the maximum compression (focus) is determined from the derivative the electrical characteristics of the plasma focus e.g. the discharge current, which is monitored with a small Rogowski coil. The voltage at the cathode of the (PSS) is monitored by a Tektronix P6015A high voltage probe with a rise time of less than 5 ns.

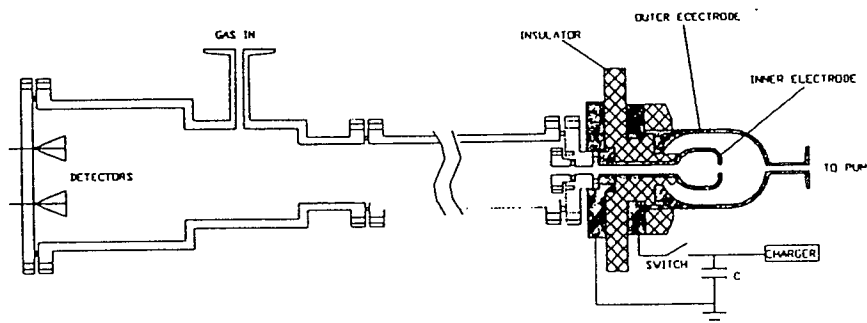


Fig. 1 Cross section view of the compact PF devices.

The X-ray emission is observed with two BPX 65 PIN diodes (PIN1 and PIN2) biased at -45 V. The silicon diodes have an effective detection area of 1 mm^2 , an intrinsic layer thickness of $10 \mu\text{m}$ and a rise time of 0.5 ns . Different thin filters are used in front of detectors to block out visible light and to provide broad band spectral resolution. PIN1 is used with the $2 \mu\text{m}$ Al filter and PIN2 is covered with $7 \mu\text{m}$ Al filter. For the present study the PIN diodes are placed in axial position about 62 cm from the focus point as shown in Fig. 1.

The timing of the X-ray emission with respect to the PF discharge is achieved by simultaneously recording the X-ray signals and the transient voltage between the electrodes and discharge current of the circuit. The sharp spikes and dips observed in the voltage oscillogram and current oscillogram correspond to the maximum of the focus discharge. X-ray emission is observed in our CPF operation with neon gas under different gas pressures and different voltages. The electrical signals are acquired with a ten channel digitising oscilloscope with an effective bandwidth of 400 MHz . Data from the oscilloscope is transferred to a computer for data processing.

EXPERIMENTS AND PRELIMINARY RESULTS

The voltage and current oscillograms show much variation with charging voltage and gas pressure. In some shots a single voltage spike and current dip is recorded,

and in some shots several spikes and dips are seen. The X-ray signals show similar phenomena.

Fig. 2 shows the current, dI/dt , voltage and signals from the two PIN diodes. In this discharge, several dips/spikes are observed in oscillograms of current (Fig. 2(a)), dI/dt (Fig. 2(b)) and voltage (Fig. 2(c)).

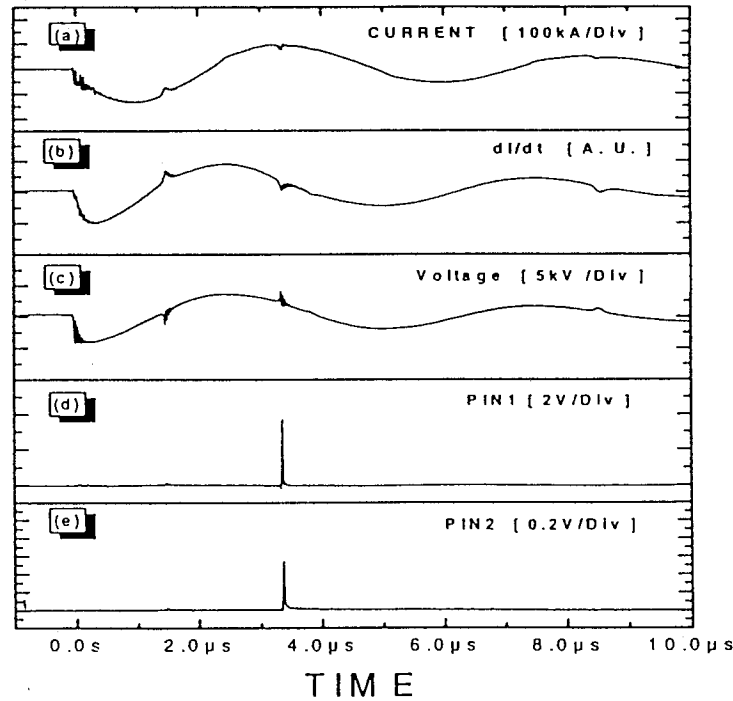


Fig. 2 Time correlation of diagnostic signals obtained in plasma focus. Experimental condition: $U_b = 15$ kV, $P = 0.5$ mbar (Neon).

There are three focus events at $1.46 \mu\text{s}$, $3.33 \mu\text{s}$ and $8.52 \mu\text{s}$ after the start of current in this discharge, but there is much more X-ray emission in the second focus than the other two focus. Comparing Fig. 2(d) and Fig. 2(e) we can see that the soft X-ray emission detected by PIN1 is ten times that detected by PIN2 in this shot. The X-ray emission lasts about 60 ns. The number of focus events and time of focusing varies with the applied voltage and the gas pressure. The corresponding X-ray pulses from the plasma focus is also changed. With a gas pressure of $P = 2$ mbar and voltage of $U_b = 13$ kV, there is only one focus arising at $3.46 \mu\text{s}$ (see Fig. 3). With a gas pressure of $P = 5$ mbar and voltage of $U_b = 13$ kV, there are two focus events arising in $1.56 \mu\text{s}$ and $3.51 \mu\text{s}$ respectively. The electrical characteristics show that the first

one is much "better" than the second one, however, X-ray emission from second focus is higher than that from first focus (see Fig. 4).

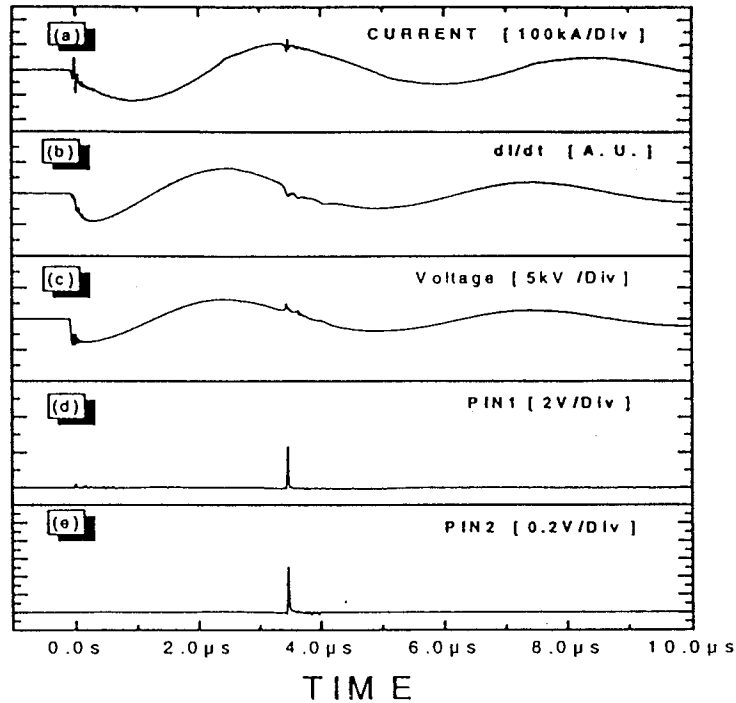


Fig. 3 Time correlation of diagnostic signals obtained in plasma focus. Experimental condition: $U_b = 13$ kV, $P = 2$ mbar (Neon).

The electrical characteristics represent a current redistribution (plasma pinching, current constricting or reconstruction, etc.), whereas SXR emission results from the hot dense plasma formation. The above fact (Fig. 4) can follow either from a low-temperature, or from a low density of the plasma formed. Taking into consideration the fact that our electrode dimensions are for much higher PF current, we have in these experiments apparently a low speed current sheath. This should result in a current constriction in the last stage (probably the inverse skin-effect is involved in this phenomenon.) rather than in plasma snow-ploughing. So it is very likely that the low SXR yield in the first half-cycle is due to a low plasma density.

From the above results (Figs. 2 and 3) we find that in our device the focus is more easily formed in positive polarity (i.e. current flows from inner to outer electrode) and X-ray emission from the focus formed in positive cycle of current is also much stronger than from other focuses. The experimental results show that the

X-ray emission depends on the pressure of working gas and magnitude and polarity of the charging voltage. The results are summarised in Fig. 5. When the capacitor is charged to 15 kV, the intensity of soft X-ray emission varies with gas pressure with maxima at 0.5 mbar and 2 mbar respectively.

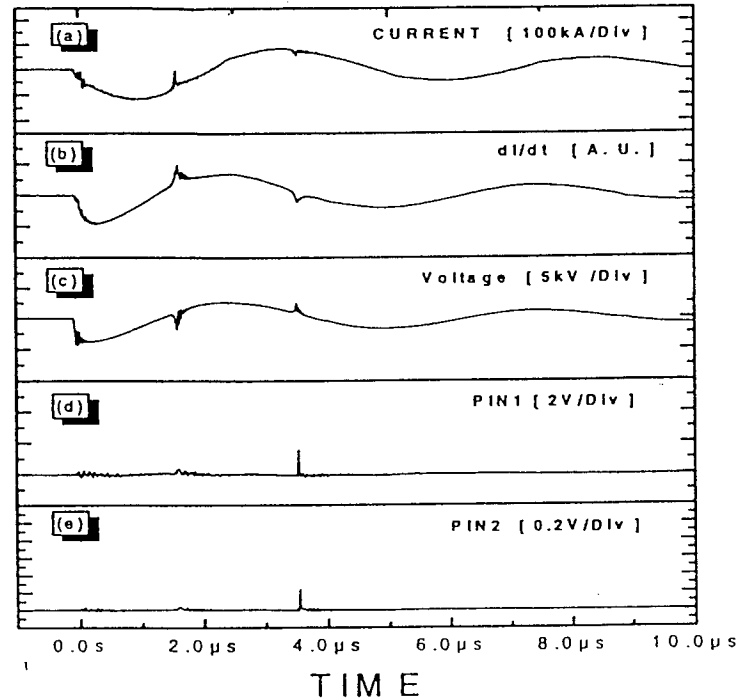


Fig. 4 Time correlation of diagnostic signals obtained in plasma focus. Experimental condition: $U_b = 13$ kV, $P = 0.5$ mbar (Neon).

CONCLUSION

So far our CPF device has been operated for more than 5000 shots at the repetition rate from 0.1 Hz to 10 Hz without maintenance. At 10 Hz we operated in bursts of only 50 shots since the electrodes were not cooled. The intensity of soft X-ray emission is up to 0.5 J per shot at the wavelength of around 1 nm. The low yield is not unexpected as this set of plasma focus electrodes is designed for a current, I , above 250 kA. The value of I/a (a =inner electrode radius) is a critical parameter in plasma focus design¹¹. Typically a value of 200 kA/cm is required for efficient PF operation¹² which will be available in our new 4 model system.

Studies have shown that plasma X-ray yield, Y_x , depends roughly on peak current, I , and pinch radius r , as $Y_x \propto I^4/r^2$.¹³ With the 4 *module system* (four electrical modules in parallel) the current will be increased by a factor of 3 and the stored energy will increase by 3 to 4 times while the focus electrodes will be the same. The scaling law suggests an X-ray yield of 81 times higher. When the system is optimised, we may expect 40J of SXR per shot. The ability of the PSS to switch at high rep. rates is crucial in determining the SXR emission power. It is estimated that at 3 Hz with a point source SXR emission power of 100 W, a trial lithographic exposure may be made in under a minute.

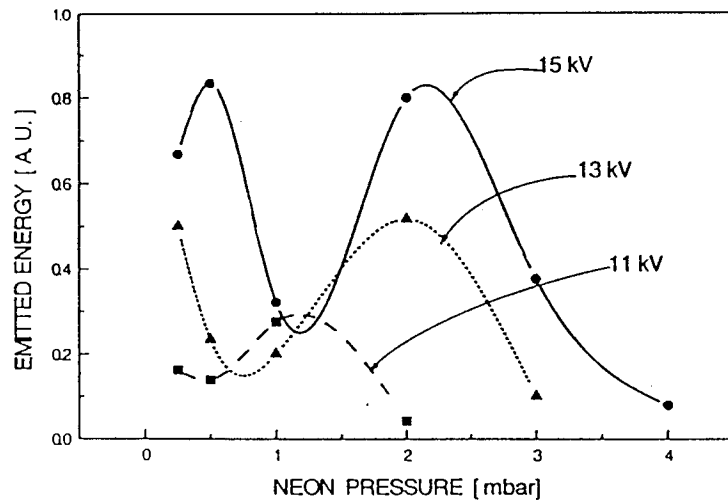


Fig. 5 Dependence of the soft X-ray emitted energy on the Neon pressure.

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NEUTRON TIME-OF-FLIGHT INVESTIGATIONS FOR STUDYING NEUTRON YIELD ENHANCEMENT IN PLASMA FOCUS

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Using the time-of-flight (TOF) method of analysis neutrons of 2.48 MeV energy were detected in speed-enhanced experiments on a 3 kJ plasma focus device. The neutron emission is characterised. The thermonuclear component is separated from the total yield and a new scaling law is proposed.

INTRODUCTION

The Plasma Focus (PF) belongs to the class known as "Dense Magnetised Plasmas". It is essentially a hydromagnetic coaxial plasma accelerator which involves the storage of magnetic energy behind a moving current sheath and the partial conversion of this energy to plasma energy during the rapid collapse (Z-pinch) of the current sheath toward the axis beyond the end of the centre electrode. The PF has attracted a lot of attention since its discovery, mainly for its high neutron output. Developed in the years from 1960 to 1964 by Filippov and independently in a variant form by Mather, the PF is not only one of the complementary fusion device between low- β tokamak and high compression inertial fusion, but also a suitable facility for understanding the fundamental problems of plasma physics, pulse power technology and other related phenomena. As the mechanism(s) of neutron production in the PF continues to be a subject of great interest, at present, efforts are devoted to developing immediate practical applications using the plasma focus as a pulsed radiation source (*i.e.* non-destructive analysis of thick objects, materials characterisation, prospection of oil and gas wells, luggage inspection for explosives and drugs, etc.). Therefore special attention is now given to methods of enhancing the radiation yield.

An assembly of data¹ produced by large (100kJ-1MJ), medium-sized (10-100kJ) and small PF devices shows the following experimentally observed features:

- (i) they follow the total neutron yield scaling law with focus current $Y_n \sim I^4$,

- (ii) plasma focus devices can be optimised either for X-ray or neutron output,
- (iii) for neutron optimised operating conditions they all:
 - (a) have the same limited peak axial sheath velocity v_{axial} of 6-10 cm/ μ s and radial on-axis collapse speed of 25 cm/ μ s. This fixes the forward shock temperature on-axis at 1.4×10^6 K, and the on-axis reflected shock temperature at 3.6×10^6 K. Further compression brings the temperature of the gross plasma column to just under 1 keV^{2,3}. The lower speed limit is easily understood in terms of poor coupling of the magnetic piston with the driven plasma layer, indicated by a low magnetic Reynolds number⁴ R_m , or in terms of low specific energy⁵. For the higher speed limit, it appears that the high R_m leads to an effective separation of the magnetic piston from the plasma layer. The plasma layer then collapses radially, whilst the magnetic piston is still driving axially⁶. Such a force-field flow-field separation is not conducive to an intense focus. Other possible mechanisms responsible for the upper speed limit are due to (1) plasma-anode interactions or more specifically, the ion (and sometimes, electron) current component, (2) development of Rayleigh-Taylor instabilities, and (3) at high velocities the mean free path increases and subsequently, the shock becomes diffusive, hence the drive is ineffective;
 - (b) are driven by a standard value^{7,8} of the drive parameter $(I_p/a)/\sqrt{\rho_0}$, the peak drive current per unit anode radius divided by the square root of the fill density, of $89(\pm 8)$ kA/cm/(torr D_2)^{1/2}. This ensures for all machines the same value of drive magnetic field in the axial phase and the same compressed energy density in the focus phase leading to the same high temperature in all devices^{3,6};
 - (c) have a maximum density⁹ of the pinched plasma of $1 - 5 \times 10^{19}$ cm⁻³;
 - (d) operate in a narrow range of deuterium pressures of several torr, and
- (iv) have a plasma impedance¹ about 0.3 Ω .

The neutron scaling law shows that the larger plasma focus devices produce more neutrons. This increased neutron yield appears to be due only to a combination of the larger volume of the focused plasma and the consequent increase in lifetime of the focused region. Any realistic modelling of the plasma focus will show that each linear dimension of the approximately cylindrical focus or pinch region is proportional to the anode radius^{2,7,10}. In the light of these factors, the idea of driving the plasma with speeds exceeding the "magic" value of 10 cm/ μ s, but at the same time trying to overcome the difficulties mentioned above and to achieve good focusing effect became challenging.

In our work we studied the performance of the plasma focus driven by peak axial sheath velocities up to 10 - 15 cm/ μ s without changing the gas filling pressure and the charging voltage. Firstly, our objective was to characterise the focus operating

with the standard electrode geometry and to correlate various plasma parameters like thickness and inclination of the sheath, size, location, and temperature of the pinch, development of macroinstabilities, X-ray production and neutron yield.

Secondly, and this was the new element introduced by our experimental work, in order to increase the current density and at the same time to limit the force-field flow-field separation, we used a stepped anode structure, which we call a composite anode (Fig. 1). The first part of the axial phase uses a regular anode designed for the standard drive parameter, but shorter than required to match the discharge peak. This regular anode is attached to a stepped-down anode of smaller radius. This is the *speed-enhanced* section (with increased value of the drive parameter) which should be long enough to increase the speed significantly above $10 \text{ cm}/\mu\text{s}$, but short enough to limit the force-field flow-field separation.

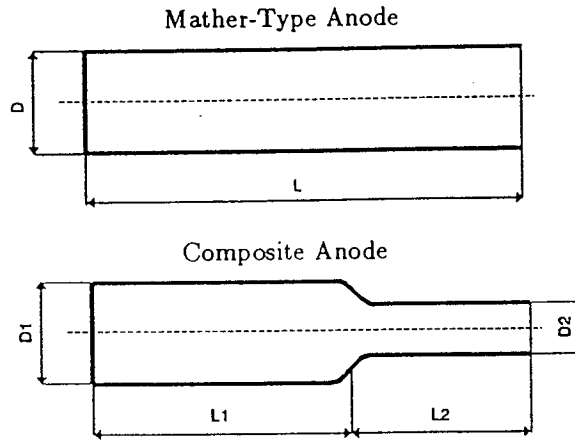


Fig. 1 Anode geometries

Our hypothesis is that a good focusing effect occurring at higher speeds implies the achievement of higher temperatures of the pinched column. This will automatically lead to an enhanced radiation output. A possible explanation of this effect is based on an idea proposed by Lee^{2,6}. He suggested that removing the speed limitation would result ultimately in a vastly improved scaling law of $Y_n \sim I^8$ which could enhance the prospects of the plasma focus as a fusion contender.

Operating the focus at higher velocities, hence higher temperatures, the thermonuclear component Y_{th} of the total neutron production is enhanced. It can be easily shown that $Y_{th} \sim I^4 v_{axial}^4$, and the beam-target component of the neutron yield $Y_{b-t} \sim I^{4.5} v_{axial}^{-1.5}$.

The total neutron yield is $Y_n = Y_{th} + Y_{b-t}$. If the experiments do not limit the speed of operation, then Y_{th} will increase above the I^4 scaling whilst Y_{b-t} will have

a scaling law poorer than $I^{4.5}$. In the limit keeping the anode radius constant whilst increasing the current,

$$Y_{th} \sim I^8 \quad \text{and} \quad Y_{b-t} \sim I^3$$

From such an analysis the following conclusions may be drawn: operating at higher speeds, above 10 cm/ μ s, should: (i) increase the thermonuclear component of the neutron yield preferentially to beam-target component and (ii) make the scaling law more favourable than I^4 , with the ultimate, most favourable scaling law being^{6,11,12} $Y \sim I^8$.

In view of such analysis, a further objective of our work was to obtain indications regarding how neutron production scales with speed.

TIME-RESOLVED NEUTRON FLUX MEASUREMENTS

In our work, the neutron and hard X-ray emission rates measurements were performed using fast plastic scintillator-photomultiplier systems in a time-of-flight (TOF) arrangement. The response time of the system used is limited to 5 ns rise time due to the response of the photomultiplier. The TOF spectrometer was placed radially with respect to the axis of the plasma focus device in a plane containing the pinch.

NEUTRON TIME-OF-FLIGHT METHOD

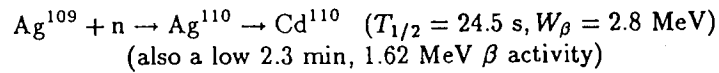
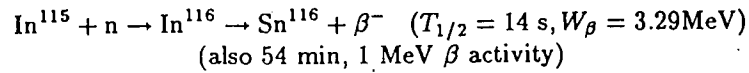
The time-of-flight method is a very powerful diagnostic technique which may be used for particles emitted one-by-one as well as in intense bursts. It is used especially for neutrons, being based on the unique relation existing between the particle energy and the experimentally measurable time which is required by the particle to travel in free motion a given distance. In the case of particles emitted in a burst, the entire energy spectrum may in principle be obtained in one measurement by recording the time-dependent rate of particles that are incident onto a detector placed at a distance x from the particle source.

The best accuracy of such measurements is limited by the value of the emission duration ΔT . It is given by the ratio¹³ $\Delta E/E = 2\Delta T/\tau$, where $\tau = x/\bar{v}$ is the average particle time of flight from the source to the detector with an average velocity $\bar{v}$. The examination of this energy resolution shows that the TOF method may be used for sources emitting short pulses of particles with a broad energy distribution and not too large average energy. This theoretical resolution may be improved by increasing the flight path. Unfortunately, for non-directioned particle sources the number of particles reaching the detector decreases rapidly with distance. Consequently, the maximum value of the flight path is limited by the intensity of emission of the source.

In our experiments the relative error of the neutron TOF method was estimated at about 30%. Therefore, spectrometric measurements could not be performed. However, the average energy of the bulk of neutrons was determined using a peak-to-peak method of analysis. There is a new spectrometry method of analysis applicable for particle sources characterised by long emission duration comparable to the time of flight^{14,15}. This method could also not be used because it requires more than two TOF detectors.

NEUTRON YIELD MEASUREMENTS

Measurements of the total neutron yield produced in a plasma focus discharge frequently imply the use of the so-called activation counter technique^{13,16,17}. The neutrons, after slowing down in a moderator, activate a metal foil placed inside a suitable counter which measures the activity produced in the foil. The detecting system is usually calibrated by means of a known radioactive neutron source. In the case of plasma focus experiments it is convenient to use either indium or silver activation counters. The two reactions commonly used are¹⁸:



In our experiments, the indium foil activation technique was used.

APPARATUS

The evolution, dynamics, and discharge characteristics of a 3 kJ plasma focus device were studied using two different types of electrode configurations (Fig. 1). The outer electrode used as cathode was not modified. The two basic kinds of geometries of the anode were: (i) one-piece Mather-type anode (OPA) presented in Fig. 1 and Table I, and (ii) a stepped anode called composite anode (CCA) illustrated in Fig. 1 and Table II. All the anodes used were hollow at the open end.

Table I: One-piece Mather-type anodes.

Name	L (mm)	D (mm)
SPF-165/19	165	19
OPA-185/15	185	15
OPA-180/17	180	17
OPA-175/17.5	175	17.5

The diagnostic techniques employed include: current and voltage measurements, shadowgraphic investigations, time-resolved neutron measurements and total neutron yield, and axial sheath velocity measurements. The plasma electron temperature during the pinch phase was determined using the filter ratio method.

Table II: Composite anode configurations.

Name	$L1$	$D1$	$L2$	$D2$
CCA-120/19+50/15	120	19	50	15
CCA-103/19+70/15	103	19	70	15
CCA-93/19+80/15	93	19	80	15
CCA-90/19+100/15	90	19	100	15
CCA-95/19+90/14	95	19	90	14
CCA-65/19+120/45	65	19	120	15
CCA-45/19+140/15	45	19	140	15

Measurements of the total neutron yield were carried out using the indium foil activation technique. The neutrons were thermalised in a hollow paraffin cylinder of 10 cm height. The thickness of the paraffin layer was 5 cm. The detector was placed on top of the focus chamber, 20 cm away from the pinch zone. The voltage applied on the GM tube was 1500 V. Our system was calibrated against an identical system, which in turn was calibrated using a Californium-252 standard neutron source. A schematic of the experimental set up is illustrated in Fig. 2(a). The calibration factor of our system (BICRON Labtech analyser with GM tube) was 3.4×10^5 neutrons/count. The estimated error of the neutron yield measurements was 20%.

Time-resolved neutron flux measurements were carried out with two TOF detectors. A schematic diagram of the experimental arrangement is shown in Fig. 2(b). Each TOF detector consists of a plastic scintillator NE 102A of 50 mm diameter and 40 mm thickness coupled to a photomultiplier EMI 9813B. The plastic scintillator was wrapped in aluminium foil except for the side facing the window of the photomultiplier. Silicon grease Dow Corning 200 was used between the plastic scintillator and the window of the photomultiplier for proper optical coupling.

Assuming a typical plasma focus discharge producing an average yield of 10^8 neutrons/shot isotropically, the estimated numbers of neutrons reaching the TOF detectors (placed radially at $3.6(\pm 0.04)$ m and $6.1(\pm 0.04)$ m, respectively) were 1150 and 400, respectively. Therefore, in order to obtain output signals (to oscilloscope) of approximately same amplitude from both TOF detectors, neutral filters were placed between the plastic scintillators and the windows of the photomultipliers (Fig. 2(b)).

The TOF detectors were enclosed in aluminium casings. Lead sheets up to 6 mm thickness were placed in front of the TOF detectors to cut off most of the hard X-rays.

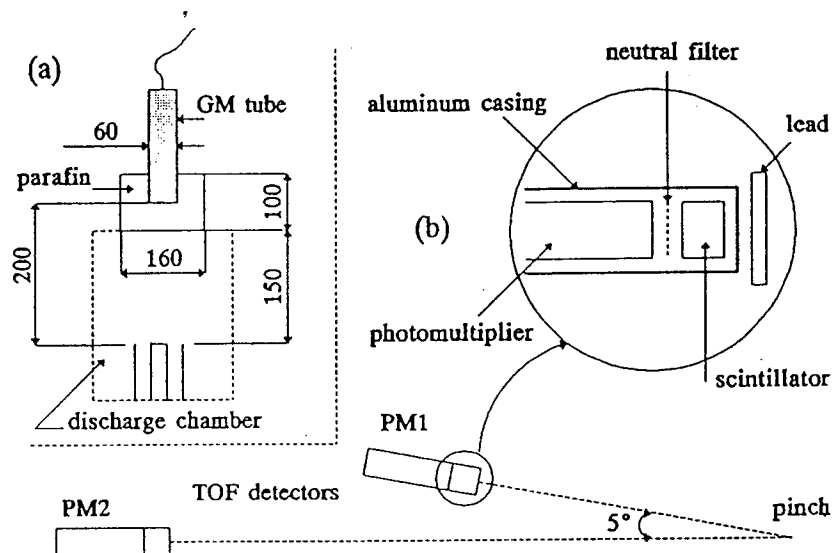


Fig. 2 Schematic of experimental arrangements for neutron measurements: (a) neutron yield; (b) time-resolved neutron flux and time-of-flight.

RESULTS AND DISCUSSION

The results of our experiments with, basically, two types of anode geometries, i.e. one-piece anode and composite or double-stage anode, show that, in terms of radiation output, there are significant differences among the electrode configurations studied. However, as for the plasma focus evolution and dynamics, practically two operating regimes are identified. One corresponds to the discharges with single voltage spike. This is an indication of a single compression of the plasma column during the pinch phase. In these cases the neutron output is above the average value for each anode geometry. The other plasma focus regime is associated with multiple voltage spikes which, in turn, indicate multiple compressions of the pinched column. The neutron productions were, generally, below the average for each electrode configuration.

The common characteristics of all electrode configurations investigated are: (i) the neutron optimised operating pressure is 4.5 mbar for the charging voltage of 14 kV, (ii) the neutron output of the plasma focus has a strong dependence on the gas filling pressure: the total neutron production has a pronounced maximum at 4.5 mbar deuterium; the neutron yield drops relatively sharply with increasing gas pressure, while deteriorating less drastically for decreasing pressures, and (iii) discharges with high neutron production are always accompanied by low soft X-ray output, but high emission in the hard X-ray region.

Using the peak-to-peak method of analysis of the neutron pulses recorded with the two TOF detectors, an average energy of the neutrons emitted radially of 2.48 MeV was determined for all electrode configurations. Therefore, the neutron pulses can be translated back in time according to their flight path. In this way, information on the neutron source was inferred.

The result of this procedure is illustrated in Fig. 3. Each signal (from the near detector and far detector, respectively) is normalised to the area under the trace which is proportional to the total neutron yield. It is seen that the two neutron signals overlap almost identically. Differences appearing at the beginning of the leading edge and the end of the trailing edge of the pulses are due to neutron dispersion.

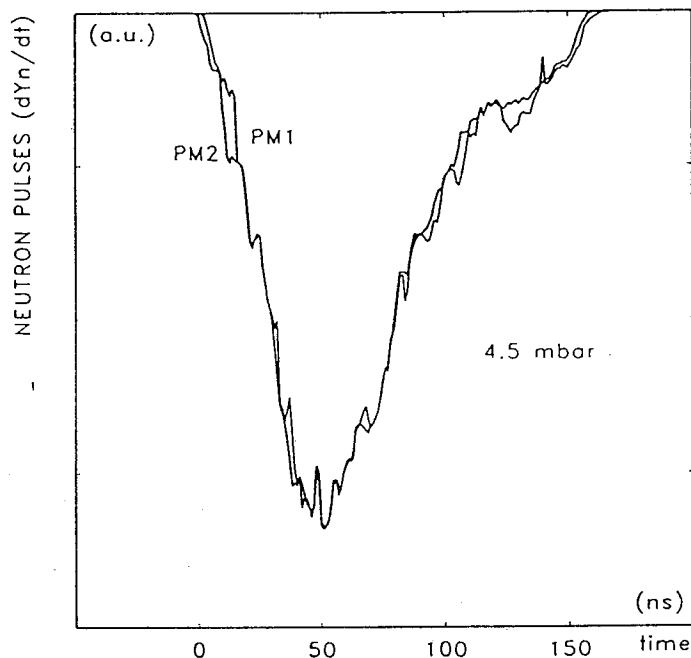


Fig. 3 Neutron pulses obtained from the TOF detectors and compensated for their time-of-flight. Inner trace: signal from PM1. Outer trace: signal from PM2. Configuration: CCA-93/19+80/15. Discharge at 14 kV, 4.5 mbar D_2 .

Based on this result we infer that the neutron emission commences at $t = 0(\pm 2 \text{ ns})$. The time reference $t = 0$ is taken at the instant when the plasma column reaches the minimum radius at the end of the radial compression phase. The pinch lifetime t_p is defined as the duration from $t = 0$ to the instant corresponding to the development of the $m = 0$ instability. It was also observed that the neutron signal

consists of two pulses, one emitted around $t = 0$ and the other one at $t = t_p$, merged together due to short values of the lifetime of the pinch. Therefore, one may estimate the number of neutrons emitted during the pinch lifetime by integrating the neutron signal dY_n/dt from $t = 0$ to $t = t_p$. In order to do so, the neutron signals from the TOF detectors have to be compensated for their flight path and overlapped with the hard X-ray pulses. Then, the neutron signals (and eventually the hard X-ray signal) are smoothened using high order polynomial functions. The procedure is illustrated in Fig. 4, where only the neutron signal recorded with the first TOF detector (PM1) is shown. The hard X-ray corresponding to the first plasma compression at $t = 0$ was cut off using lead sheets in front of the detector.

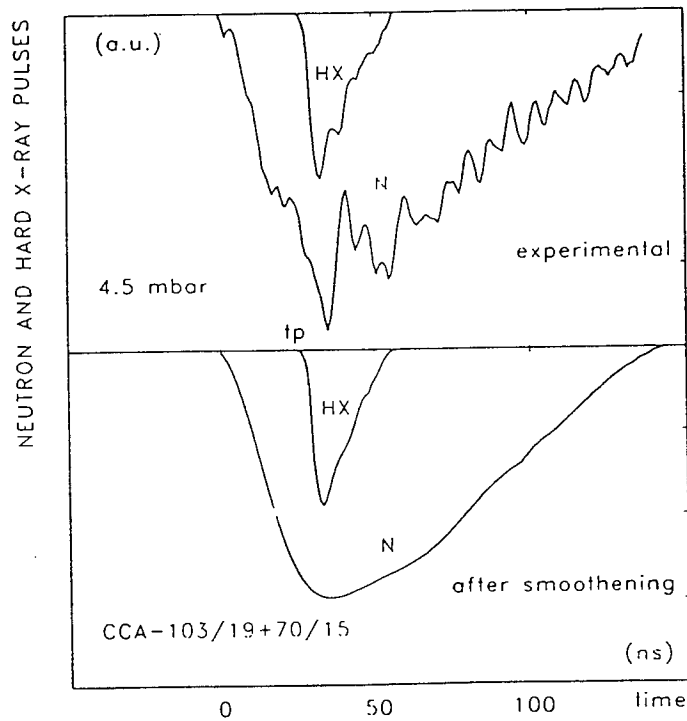


Fig. 4 Time-resolved neutron (N) and hard X-ray (HX) pulses from the first TOF detector (PM1). The neutron pulse is compensated for its time-of-flight. Experimental data (upper plot) and the corresponding pulses after smoothening (lower plot). Configuration: CCA-103/19+70/15. Discharge at 14 kV, 4.5 mbar D_2 .

The results of this procedure give values of the percentage of the neutrons emitted during the lifetime of the pinch with respect to the total yield ranging between 4% and 20% for the neutron optimised pressure of 4.5 mbar deuterium.

The plot of the average total neutron yield as a function of the peak discharge current to the power four (I^4) illustrated in Fig. 5 shows that the neutron scaling law: $Y_n \sim I^4$ does not work properly for all the electrode configurations tested in our project work. The reason is that the neutron production mechanism(s) is affected by some factors like force-field flow-field separation, electrode erosion or changes in the breakdown conditions. One could (i) separate the neutron production into two components, i.e. non-beam such as thermonuclear component, Y_{th} , and beam-target component, Y_{b-t} , and (ii) study the effect on these yield components of increasing the current density and consequently the axial speed.

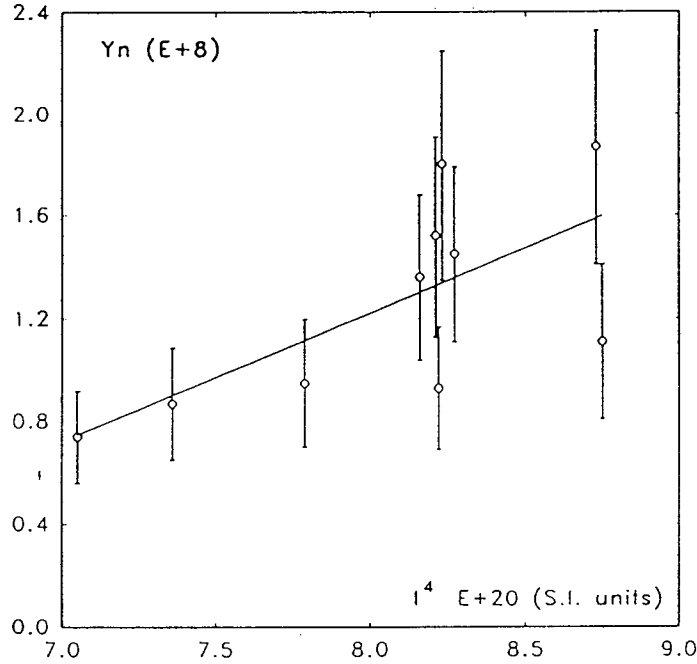


Fig. 5 Total neutron yield as a function of the peak discharge current to the power four (I^4). The hollow circles represent the mean values and the vertical error bars the corresponding standard deviations. Discharges at 14 kV, 4.5 mbar D_2 .

In earlier experimental work^{19,20} on 3 kJ plasma focus devices the reported value of the ratio $Y_{th}:Y_{b-t}$ is of the order of 15:85. It has also been proposed^{6,11,12} that the thermonuclear component can be written as follows:

$$Y_{th} = C I_{\max}^4 v_{\text{axial}}^4 \quad (1)$$

with C a constant over the range of plasma focus devices. We use our data to

investigate whether our experiments verified Eq. (1).

The results obtained for the neutron illustrated in Fig. 6. All data were included except those obtained from experiments with the following electrode configurations: OPA-185/15, CCA-45/19+140/15, and CCA-65/19+120/15. These were excluded because: (i) the breakdown conditions were changed (OPA-185/15), (ii) the speed-enhanced section of the anode was too long and led to force field flow field separation, and (iii) the reproducibility of the focus was very poor, thus affecting the mean value of the neutron yield.

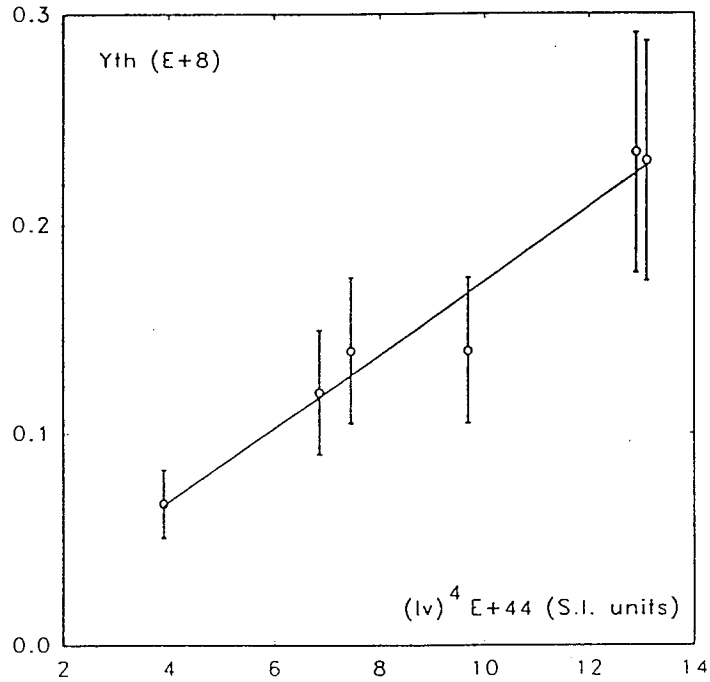


Fig. 6 The non-beam component of the neutron yield as a function of $(Iv)^4$, with I the peak discharge current and v the peak axial speed. The hollow circles represent the mean values and the vertical error bars the corresponding standard deviation. Discharges at 14 kV, 4.5 mbar D_2 .

The results (Fig. 6) confirm that the data fit Eq. (1). The value of the constant C in Eq. (1) was determined using a linear regression of the data plotted in Fig. 6: $C = 0.018$ (SI units). Thus, Eq. (1) can be written in the following manner:

$$Y_{th} = 1.8 \times 10^{-6} I_{max}^4 v_{axial}^4 (\pm 30\%) \quad (2)$$

with I_{max} in kA and v_{axial} in cm/ μ s in the range of 7 - 14 cm/ μ s.

Thus there is evidence within the limited range of our operation that the neutron yield of the plasma focus is enhanced by operating at higher speeds. We also have evidence that the X-ray production is also enhanced.

The values of the drive parameter and the corresponding neutron yield at 4.5 mbar deuterium filling pressure are listed in Table III.

Table III: Drive parameter and neutron yield.

Configuration	v_{axial} (cm/ μ s)	I_{max} (kA)	$I_{\text{max}}/a/p^{1/2}$ kA/cm/(torr D_2) $^{1/2}$	Y_n (10^8)
SPF-165/19	8.3	172.0	97.8	1.11
OPA-175/17.5	9.5	171.9	106.2	1.87
OPA-180/17	9.7	169.9	108.1	1.36
OPA-185/15	10.4	162.1	116.8	0.73
CCA-45/19+140/15	10.5	164.7	118.7	0.87
CCA-65/19+120/45	10.6	167.1	120.5	0.95
CCA-103/19+70/15	11.2	169.4	122.1	1.80
CCA-93/19+80/15	11.3	169.5	122.2	1.50
CCA-90/19+100/15		169.6	122.3	1.45
CCA-95/19+90/14	11.4	169.4	130.8	0.95

It is seen that there are two electrode configurations, i.e. OPA-175/17.5 and CCA-103/19+70/15 which produce, practically, the same neutron yield of approximately 1.8×10^8 neutrons/discharge. The increase of the current density by 15% and of the axial speed by 17% for the CCA-103/19+70/15 geometry with respect to OPA-175/17.5 does not bring an increase in the neutron output. One possibility is that by operating the plasma focus at higher speed, the non-beam component of the neutron yield such as of thermonuclear origin is enhanced (see Eq. (1)), while the beam-target component decreases according to the following expression^{6,11,12}:

$$Y_{b-t} = C' I_{\text{max}}^{4.5} v_{\text{axial}}^{-1.5} \quad (3)$$

where C' is a constant, I_{max} and v_{axial} are the peak discharge current and peak axial velocity, respectively.

It is interesting to compare the performance of CCA-103/19+70/15 and CCA-93/19+80/15 as configurations of the same family of composite anodes. These two anodes have the same length and only a difference of 1 cm in the length of the speed-enhanced section. The configuration with the longer speed-enhanced section has a slightly higher speed as expected. However, the neutron yield is reduced by 16%. This degradation of neutron yield could be interpreted as the result of a significant separation of the shock front from the driving magnetic piston during the axial phase. Such a separation is proportional to distance travelled. It appears that the increasing the speed-enhanced section from 7 cm to 8 cm results in a sufficient increase in that

separation to affect the neutron yield. With a sufficient separation, when the shock front is in its radial motion, the magnetic piston is still moving axially. Therefore, the radial compression is not driven or, if the separation is not too big, the efficiency of the drive is very poor, and leads to a low radiation yield.

The further increase of the length of the speed-enhanced section of the anode (see data for CCA-90/19+100/15 and CCA-95/19+90/14 anodes in Table III) leads to a decrease of the total neutron yield. This again is consistent with the expected effect of the force-field flow-field separation on the efficiency of the compression of the plasma column.

On the other hand, the comparison between the two high neutron output configurations, i.e. OPA-175/17.5 and CCA-103/19+70/15 geometries, in terms of soft X-ray production shows that at higher speed the soft X-ray emission is enhanced. Data analysis indicates that the plasma temperature during the pinch phase is higher. Assuming that the temperature (T) is proportional with the square of velocity⁶ (v), $T \sim v^2$, then the temperature increases by almost 40%. This is in agreement with the earlier interpretation of an enhanced non-beam neutron emission^{11,12}.

The plasma focus device can be optimised for either neutron production or soft X-ray output. The optimisation procedure has to meet conflicting requirements. The increase of the drive parameter by using a smaller radius anode is favourable for increasing the plasma temperature, thus the non-beam neutron component and the soft X-ray yield. At the same time, the pinch lifetime and dimensions are reduced accordingly⁷. Therefore, the size of the radiation source is smaller. This effect is encouraging for practical applications of the plasma focus e.g. as a soft X-ray source for lithography²¹.

CONCLUSIONS

Regardless of the electrode geometry, the neutron output of our plasma focus device has a strong dependence on the gas filling pressure. The neutron optimised pressure is 4.5 mbar. The emission of neutrons begins at the end of the compression phase when the plasma reaches its minimum radius.

Peak axial sheath velocities up to 15 cm/ μ s were achieved²². The radiation output, i.e. both neutron and soft X-ray productions increased as the speed increased. However, beyond a certain value of the peak axial speed and a certain length of the speed-enhanced section of the anode, the focusing characteristics and reproducibility were affected. We concluded that the length of the speed-enhanced section is critical. This section has to be long enough to increase the speed, but short enough to avoid the separation between the shock front and the magnetic piston. Also, the profile of the joint between the two sections of the anode plays an important role. An abrupt joint will favour the development and rapid growth of interchange instabilities which

will later affect the evolution of the focus during the final phases.

The results of the correlations of the neutron production and soft X-ray emission indicate that higher speeds enhanced the temperature of the pinched column. The non-beam component of the neutron flux taken as of thermonuclear origin was correlated with the peak discharge current and peak axial speed. The following scaling law: $Y_{th} \sim (I_{max} v_{axial})^4$, for the non-beam neutron component was proposed based on our experimental results within our range of operations. However, this scaling law has to be checked with results from other plasma focus devices operating with a broader range of energies.

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Pulsed Plasmas for Technology Training and Cooperation

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Abstract

For several aspects of training, research initiation, establishment of research facilities, international cooperation and applications, pulsed plasmas have important inherent advantages. Simple systems may be developed which are cost-effective and produce intense plasmas which provide fertile training ground for initiating experimental research. The plasma focus is one such useful device. In this context the development of the small plasma focus designated as the UNU/ICTP PFF during the 1985 UNU Training Programme on Plasma and Laser Technology is described. This device is now established in several institutions as a training and research facility. It is serving a continuing role in training and international cooperation. Experience accrued from its study is giving confidence for the development of high repetition compact plasma focus devices for high technology applications.

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1. Introduction

Pulsed plasmas have one big advantage over steady-state plasmas. With a relatively small energy storage or input power, operating in pulses, plasmas achieve far higher intensities. In this manner higher temperature, higher density plasmas are easily obtained in small, compact and low-cost packages. Certain technological and training situations may benefit from the use of such pulsed plasma packages. In this context the plasma focus has emerged as a very useful device.

The plasma focus is the most cost-effective device to produce a high temperature (1 keV) and high density (10^{19} cm^{-3}) plasma. When operated with a high Z gas it produces large quantities of soft x-rays whilst with deuterium it produces a fusion plasma. Typical operation in a 3 kJ device in 3 torr deuterium produces a burst of 10^{15} neutrons per second. The scaling law that neutron yield is proportional to the square of device energy ($Y \sim E^2$) has been experimentally established. Many plasma focus devices ranging from 100J to 1MJ have been built².

In 1985 a 3 kJ plasma focus using a single 15 kV, 30 μF capacitor was designed during the 6-month United Nations University (UNU) Plasma & Laser Training Programme in Kuala Lumpur attended by 6 UNU Fellows. Professor Abdus Salam, Nobel Laureate and Director of the International Centre for Theoretical Physics (ICTP) visited the Training Programme and provided a grant for follow-up equipment which could not be funded by UNU as it was outside the framework of its operation. Thus was launched the UNU/ICTP PFF which has since been established as research facilities in 11 countries, producing PhD's and research papers on a regular basis. Thus the UNU/ICTP PFF has enabled the 1985 UNU Training Programme to achieve the multiplicative effect it had been aimed for.

Furthermore with experience accrued from this device, several applications have been proposed and are being developed. These applications include use of a compact plasma focus, in repetitive mode, as a soft x-ray source for microelectronics lithography. The compact plasma focus is also being developed as a neutron source for tomographic systems designed for detection of hidden plastic explosives. Such systems have enormous potential for airline security.

2. UNU/ICTP Training Programmes

The UNU Training Programme was followed by ICTP sponsored programmes using the same training format. The objective of these training programmes was the initiation of experimental research in plasma physics in the trainee's home institute. Characteristics of these programmes include identification of suitable participants from institutes likely to benefit from the transfer of expertise and facilities, identification of suitable cost-effective plasma devices to focus the programme of training, comprehensively structured programmes to enable the trainee to acquire the necessary skills and experience to develop, maintain and run the experiments and the provision of essential follow-up components and equipment. As a consequence of these programmes experimental plasma/fusion/laser research has been initiated in 9 Third World countries. Facilities transferred include those in the following Table :

	UNU/ICTP PFF	EMST Flow Simulator	Nitrogen Laser System	Laser Shadowgraph System	Glow Discharge
Cairo, Al Azhar U.	x		x	x	
Jaipur, Rajasthan U.	x		x		
Delhi, Delhi U.	x*		x*	x*	
Srinaga, SP College Jakarta, LAPAN (Space research)		x*	x		
Yogyakarta, PPNY (Nuclear research)	x*		x*	x*	x
Islamabad, QAU	x*		x*	x*	
Port Harcourt, US&T	x*		x*	x*	
Sierra Leone, NUC	x*				
Songkla, PSU	x		x		
Liberia, UST			x*	x*	
Bangladesh, INST			x*		x*

* Have produced PhD/MSc theses from these facilities.

In order to consolidate the multiplicative effects of these training programmes the AAAPT (Asian African Association for Plasma Training) was inaugurated in 1988. Partially funded by the ICTP a series of training programmes, conferences, scientific exchange programmes and a newsletter was established. Today the AAAPT has an institution membership of 30 from 19 countries. The members include the APSC (Association of Plasma Studies of China) which itself is an association of important institutions in China.

3. Network of 3 KJ plasma focus installations

There exists a large variety of phenomena occurring in sub-microsecond phases in the focus, including highly nonlinear and chaotic behaviour, hence each existing plasma focus facility only manages to study some aspects of the total behaviour¹. The collation of the total behaviour meets with a major difficulty in that each plasma focus is designed differently because of different emphasis. Thus the behaviour of each machine may be differently coloured by different machine effects or boundary conditions peculiar to that machine. Another approach for a comprehensive experimental picture may be to set up a network of identical machines on an international basis.² This is not possible for big machines because of the question of cost.

On the other hand much of the physics that may be studied in large plasma focus installations can be carried out much more cost-effectively on small plasma focus devices. There is considerable savings also in experimental turn-around time. More scientific manpower resources may be harnessed in a network including also small laboratories in small nations. Furthermore a network of 15 identical machines already exists in countries including Sierra Leone, Nigeria, Egypt, Italy, Pakistan, India, Thailand, Malaysia, Singapore, Indonesia and China. The research using this 3 kJ machine, the UNU/ICTP PFF facility³ is very diversified. For example the machine in Pakistan is being used to look into a variety of problems⁴⁻⁷ including 2-D modelling, dielectric effects and instabilities and plasma radiation; one of the

two in India is being used for materials modification⁸⁻⁹; that at the ICTP¹⁰ in Trieste has been used for studies on chaos and deterministic dynamics, to bench-mark the performance of the device and to provide international training as have the ones in Malaysia which are also being used for neutron¹¹, x-ray¹² and basic studies¹³, the one in Singapore for device development, cascading focus studies¹⁴, thermodynamic effects¹⁵ focus modelling^{16, 17} radiation enhancement¹⁸⁻²⁰ and soft x-ray source for microelectronics lithography²¹, the ones in Indonesia for neutrons²² and aerospace applications²³ and the one in Shanghai was planned for laser-focus interaction. Gradual upgrading of the scientific expertise and diagnostic systems will enable the diverse results of the network of identical machines to have an impact when collated and compared perhaps under the coordination of the Asian African Association for Plasma Training (AAAPT) which has taken a leading role in the establishment of this network of devices²⁴ as a network of the ICTP.

4. Bench-marking the 3 kJ Plasma Focus

In order for the results of the network of 3 kJ plasma focus machines to be collated to form a comprehensive total body of evidence on the experimental behaviour of the plasma focus in all its aspects, identical design alone is not enough. The devices have to be compared at identical conditions of operation. In identical machines (identical C_0 , L_0 , V_0 , a , z_0 .) scaling parameters are made identical when the ambient pressure is set to be identical for each gas used. Even when the radial phase dynamical equations are considered the additional scaling parameters introduced remain identical for identical gas species and pressure. Thus bench-marking becomes a straight-forward procedure. Considering the large number of studies that have been carried out in the 3 kJ plasma focus²⁵ we propose the following bench-marks to ensure that the 3 kJ plasma focus is operated at optimum consistency with good production of neutrons (deuterium operation) and soft x-rays:

<u>Gas</u>	<u>Pressure</u>	<u>Focus Time</u>	<u>Neutron Yield</u>	<u>Soft x-ray Yield</u>
Deuterium	3.5 torr	2.6 μ s	10 ⁸	
Argon	0.7 torr	3.0 μ s		2J (estimated)
Neon	2.7 torr	3.2 μ s		4J

(Additional benchmarking characteristics of the UNU/ICTP PFF operated at 1 kV, 3.5 torr deuterium:

Peak axial speed	: 8.3 cm/ μ s
Peak radial shock speed (on-axis)	: 30 cm/ μ s (estimated)
Minimum radius of gross pinch	: 0.12a mm, (measured by shadowgraphy) where "a" is the anode radius in mm)
Maximum length of gross pinch	: 0.8a mm
Radial compression time	: 4.5a ns
Lifetime of compressed pinch	: 2a ns

The proposal is that every set of experiments carried out on each of the network of 15 identical 3 kJ plasma focus machines should comprise at least some discharges with the above bench-mark operating conditions. The results of these bench-mark shots should be carefully kept. This enables standardisation and interpolation, when necessary, of results for meaningful comparison.

5. Scaling of Plasma Focus for Fusion Neutrons

Fusion neutron yield scales as E^2 or I^4 . This is universally observed for plasma focus devices operated at standard speed. It has been noted that Mather-type plasma focus devices, small (100J) to big (1MJ) all operate, when neutron-optimised, at a standard axial speed (peak) close to 10 cm/ μ s. This is related to the remarkably constant drive parameter $(I/a)/\rho^{0.5}$ of $89 \text{ kA/cm} / (\text{torr D}_2)^{0.5}$ observed for neutron optimised devices. The near constancy of the parameter I/a is easily shown to be consistent with fusion yield scaling. Considering the E^2 scaling from 10^8 n per shot from a 3 kJ plasma focus yields a break-even at just over 300 MJ plasma focus operating in D-T at a current of some 50 MA.

But why should we operate at a fixed I/a implying a fixed speed, fixed temperature (1 keV) for all devices? There is a speed enhancement mechanism. For instance if we double the drive speeds, the temperature quadruples and at the 1-4 keV level fusion cross-sections scales more than T^4 , increasing more than 250 times. This could bring the break-even point down to a more manageable 15 MJ. However it has been observed experimentally that a plasma focus will not normally operate properly at speeds higher than 10 cm/ μ s. This mechanism has been studied and it is postulated that at higher speeds decoupling of the force field from the flow-field towards the end of the axial phase may be responsible for poor focussing. To overcome this decoupling one method is to have a stepped inner electrode with a first standard section followed by a speed-enhanced section (smaller radius) which is kept relatively short so that whilst the speed is significantly increased above the standard speed, the radial focus phase sets in before force-field flow-field becomes significant. By this method neutron enhancement has been achieved in a 3 kJ plasma focus. Could such enhancement mechanisms be incorporated into bigger devices?

6. Applications: High repetition rate plasma focus

From the viewpoint of fusion energy it is certainly necessary to scale up existing plasma focus devices to above 1 MJ. However for non-fusion applications it may be necessary to keep the energy low if for example the dense plasma region needs to be kept small (for spatial resolution) or if the radiation pulse needs to be kept short (for temporal resolution). Such is the case if the plasma focus is to be used as a point source soft x-ray microelectronics lithography or for time-resolved neutron activation analysis. For these applications high-repetition rates become necessary in order to obtain sufficient flux. Take the example of soft x-ray lithography.

It is now an established fact that optical (down to deep uv at 193 nm) lithography will reach a limit at 163 nm feature size. In order to maintain continuing progress in further and further miniaturization, the next few generations below 250 nm feature size will require soft x-ray lithography. Whilst synchrotron electron storage rings are being developed as a SXR source for this purpose, synchrotrons are relatively expensive, bulky and is a multi-beam device. Single beam compact, inexpensive point sources are also needed to play a supplementary role in situations where a single beam or a flexible multi-beam system is more economical. It is estimated that a $1\frac{1}{2}$ kw SXR (into 4π) point source emitting into a beamline with 50% transmission can deliver enough power to expose existing suitable SXR resists (100 mJ/cm^2) at a distance of 40 cm in a time interval of $1\frac{1}{2}$ sec. Such exposure speed is already sufficient for volume production purposes. A plasma focus operating at 30 shots per second producing 50J SXR per shot could serve this purpose. This requires a 2% conversion efficiency for a $2\frac{1}{2}$ kJ plasma focus.

At the NTU/NIE we are planning 2 high repetition systems. The first, designated the 4-4-4 is in collaboration with Prof V Gribkov of the Lebedev Physical Institute. This project uses a pseudo-spark

(volumetric) switch which we have recently tested to 10 shots per second at 130 kA peak current per shot. Four such switches each switching a 15 kV 8 μ F low inductance capacitor into a suitably designed focus chamber operating in Neon will be able to drive a 400 kA current producing 50 J per shot. We may reasonably expect to develop this source to produce 200 - 500 W SXR.

The second system designated the NE001, is being developed in collaboration with AASC of California. This system will also have 4 modules. Each module has a number of paralleled capacitors totally 7 μ F and is switched by a rail-gap switch. The system has a bank inductance of only 11.5 nH and running into an optimised plasma focus at 12 kV will couple in excess of 400 J into the plasma pinch from the 1.9 kJ of stored energy. We can expect 30J of SXR per shot and intend to have a pulse repetition rate of 20 shots per second, pushing up eventually to 50 shots per second to reach 1½ kW. Plans are being made to do a SXR lithography demonstration.

We are also part of a 4-nation consortium which is proposing a cost-effective high-volume baggage inspection system targetted at airport baggage security, specifically for the detection of hidden plastic explosives. This system has 3 main elements: a pulsed neutron source emitting nanosecond pulses of sufficient intensity, an efficient new detection system and a multi-tiered inspection algorithm to give 100% detection rate coupled with a minimum false-detection rate. Our role naturally is in the development of the pulsed neutron source.

7. International Collaboration

With the help of UNU, ICTP and TWAS, the AAAPT has developed a 15-machine network of a single shot 3 KJ plasma focus that has been used as facilities to produce at least 7 PhD's and numerous MSc and research papers. Advanced ideas in device development and diagnostics have been tested out in this simple machine and experience has been gained to enable launching into advanced high rep systems. The AAAPT now concentrates its efforts through a network of regional centres and a Research & Training Center at the Chinese Academy of Sciences in Beijing for the purpose of developing a sandwich PhD programme based on the comprehensive range of plasma devices at the Institute of Physics, CAS, Beijing.

The AAAPT has also played an important role in the project formulation of the proposed International Centre for Dense Magnetised Plasmas. The ICDMP plans to build within one centre a range of plasma focus and pinch device including one large (MJ) device, several medium energy devices and several small devices to act as reference machines. There are 3 main objectives : basic science, training and applications. The education, training and scientist exchange programmes of the ICDMP have been formulated based on the experience of the AAAPT.

8. Conclusion

On reflection it appears that much of the success of the AAAPT is due to the identification and development of suitable small compact systems for the transfer of research capability. Central to these systems is the small plasma focus, the UNU/ICTP PFF. Because of its pulsed nature this device produces extremely intense plasma conditions resulting in copious radiation of x-rays and fusion neutrons in addition to beams of ions and relativistic electrons. This simple cost-effective device acts as ideal training ground for research at postgraduate level and beyond. Consequent to intensive training programmes with follow-up equipment it has enabled the sustained development of experimental plasma physics in several

institutions in several countries. It has led to collaboration on an international scale. It now reaches into the future to extend its role to the ICDMP whilst providing its practitioners the confidence to push forward into high technology applications.

The present new initiative to set up a framework for international cooperation in plasma science and technology is timely. It is most appropriate that this initiative should be launched by the Institute of Advanced Studies of the UNU, since the UNU had funded in 1985 a training programme in plasma and laser technology which has led to multiplicative effects in training and cooperation and to some high technology applications which are now being developed.

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Soft x-ray emission from a small plasma focus operated in deuterium

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Abstract. Using composite anodes in a 3 kJ plasma focus device operated in deuterium, peak axial sheath velocities up to $15 \text{ cm } \mu\text{s}^{-1}$ are achieved. The temporal characteristics of the soft x-ray emission are investigated by means of filtered PIN diodes. Correlations with hard-x-ray and neutron emission as well as with electrical parameters of the discharge are performed. Two distinct operation regimes are identified regardless of the shape of the anode. Various scaling laws of the soft x-ray production are investigated. We propose a new scaling law for the soft x-ray yield.

1. Introduction

The most important directions for developing immediate practical applications using plasma focus devices are those which use the device as a pulsed radiation, i.e. soft x-ray and neutron source. Therefore, special attention has to be given to studies of radiation mechanisms. Based on these studies new methods of enhancing the radiation yield could be developed [1, 2].

When a plasma focus device is operated in deuterium as the working gas most attention is given to the neutron production. In our work soft and hard x-ray emission were correlated with the neutron production as well as with discharge and plasma parameters.

It is known that the x-ray emission characteristics depend strongly on the operating regimes and parameters (e.g. gas filling composition and pressure, stored energy, discharge current, driver impedance, electrode material, shape, profile and configuration, polarity of the inner electrode). Amongst them, the composition of the gas and the filling pressure have the strongest influence. When deuterium is used, the working pressure for the highest x-ray yield does not coincide with the neutron optimized output pressure [3, 4].

Good focusing effect is usually obtained in plasma focus experiments when the peak axial sheath velocity is in the limited range of $6\text{--}10 \text{ cm } \mu\text{s}^{-1}$ and the drive parameter defined as the peak drive current per unit anode radius divided by the square root of the fill density (or pressure) $(I_{\text{max}}/a)/p^{1/2}$ is $89 \text{ kA cm}^{-1} (\text{torr D}_2)^{-1/2}$ [5].

The lower speed limit is easily understood in terms of poor coupling of the magnetic piston with the driven plasma layer, indicated by a low magnetic Reynolds number R_m [6], or in terms of low specific energy [7]. For the

higher speed limit, it appears that the high R_m leads to an effective separation of the magnetic piston from the plasma layer. The plasma layer then collapses radially, whilst the magnetic piston is still driving axially [8]. Such a large separation is not conducive to an intense focus. Other possible mechanisms responsible for the upper speed limit are due to (i) plasma–anode interactions or, more specifically, the ion (and sometimes, electron) current component, (ii) development of Rayleigh–Taylor instabilities, and (iii) at high velocities the mean free path increases and subsequently, the shock becomes diffusive, hence the drive is ineffective.

In the light of these facts, the idea of driving the plasma with speeds exceeding the ‘magic’ value of $10 \text{ cm } \mu\text{s}^{-1}$, but at the same time trying to overcome the difficulties mentioned above and to achieve good focusing effect, became challenging. Of course, one of the possibilities of increasing the speed is to reduce the gas filling pressure, but in this way one switches from one operating regime to another with poor focusing as one of the known effects.

In this paper we report results of experiments with a 3 kJ plasma focus [9] driven at peak axial sheath velocities up to $15 \text{ cm } \mu\text{s}^{-1}$ [10] with good focusing and without changing the gas filling pressure and the charging voltage. Firstly the standard Mather-type geometry of the plasma focus electrodes (referred as SPF-165/19, i.e. 165 mm length and 19 mm diameter) was investigated and neutron-optimization experiments were performed. Correlations of various plasma parameters such as thickness and inclination of the sheath, size location, and temperature of the pinch, development of macroinstabilities, x-ray production and neutron yield were performed. Secondly, in order to increase the value of the drive parameter and at the same time to limit the force-field–flow-field separation and earlier

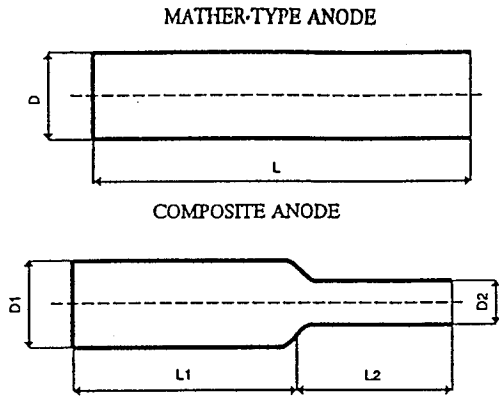


Figure 1. Types of anode used.

Table 1. Composite anodes.

Name	L1	D1	L2	D2
CCA-120/19 + 50/15	120	19	50	15
CCA-103/19 + 70/15	103	19	70	15
CCA-93/19 + 80/15	93	19	80	15
CCA-90/19 + 100/15	90	19	100	15
CCA-95/19 + 90/14	95	19	90	14
CCA-65/19 + 120/45	65	19	120	15
CCA-45/19 + 140/15	45	19	140	15

development of Rayleigh–Taylor instabilities, we used a special anode geometry based on an idea proposed by Lee [8, 11] to accelerate the plasma structure at higher axial velocities. This was a stepped anode structure, which was called a composited anode (see figure 1 and table 1). The first part of the axial phase uses a regular anode designed for the standard value of the drive parameter or $89 \text{ kA cm}^{-1} (\text{torr D}_2)^{-1/2}$, but shorter than required to match the discharge peak. This regular anode is attached to a stepped-down anode of smaller radius. This is the so-called speed-enhanced section with significantly enhanced value of the drive parameter which should be long enough to increase the speed significantly above $10 \text{ cm } \mu\text{s}^{-1}$, but short enough to limit the force-field-flow-field separation.

Our hypothesis is that a good focusing effect occurring at higher speeds implies the achievement of higher temperatures and energy densities of the pinched column. This will automatically lead to an enhanced radiation output.

2. Experiment set-up and diagnostics

The block diagram of the experimental set up is illustrated in figure 2. The focus device [10] always operated at 14 kV (2.9 kJ) in deuterium. The diagnostic techniques and the corresponding equipment are as follows (see figure 2).

- (i) Current $\{I(t)\}$ and current derivative $\{dI/dt\}$ measurements: Rogowski coils.
- (ii) Voltage $\{V(t)\}$ measurements: resistive voltage probe.

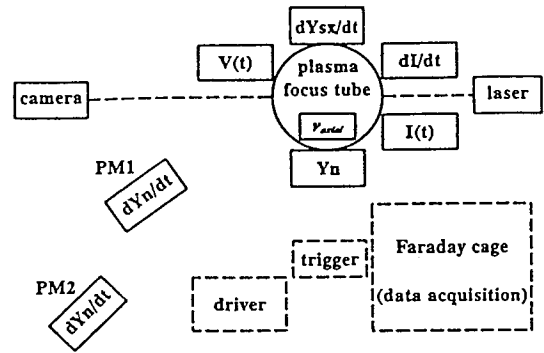


Figure 2. Experimental set-up.

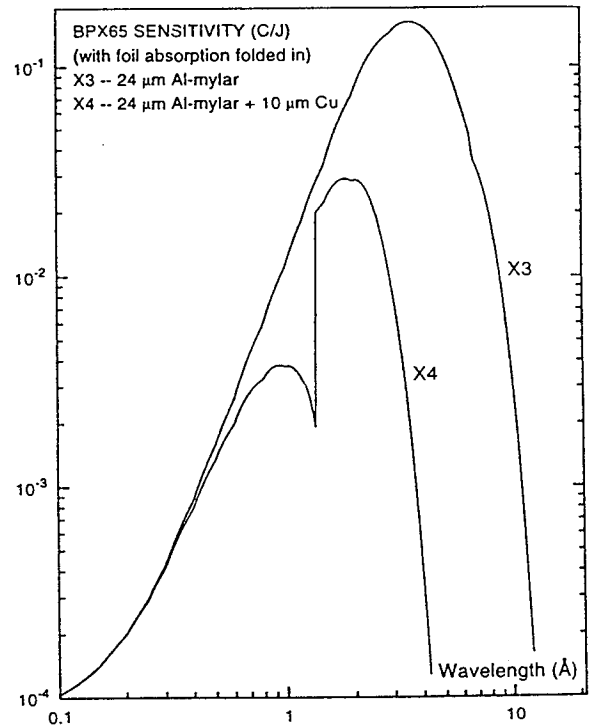


Figure 3. Sensitivity characteristics of the soft x-ray detectors.

(iii) Peak axial speed $\{v_{axial}\}$ measurements: optical fibre axial speed detector [12].

(iv) Soft-x-ray emission rate $\{dY_{sx}/dt\}$: five-channel soft x-ray spectrometer [13] with BPX65 p-i-n diodes. In our experiments two channels, i.e. X3 (24 μm Al-Mylar) and X4 (24 μm Al-Mylar + 10 μm Cu) were used. The sensitivity characteristics of the detectors are illustrated in figure 3. To estimate the electron temperature (T_e) the filter ratio method [14, 15] was employed.

(v) Time-resolved hard-x-ray $\{dY_{HX}/dt\}$ and neutron flux $\{dY_n/dt\}$ measurements: two plastic scintillator-photomultiplier systems (TOF detectors PM1 and PM2).

(vi) Total neutron yield measurements $\{Y_n\}$: neutron activation counter [16, 17].

(vii) Shadowgraphic investigations: optical equipment for laser shadowgraphy [10].

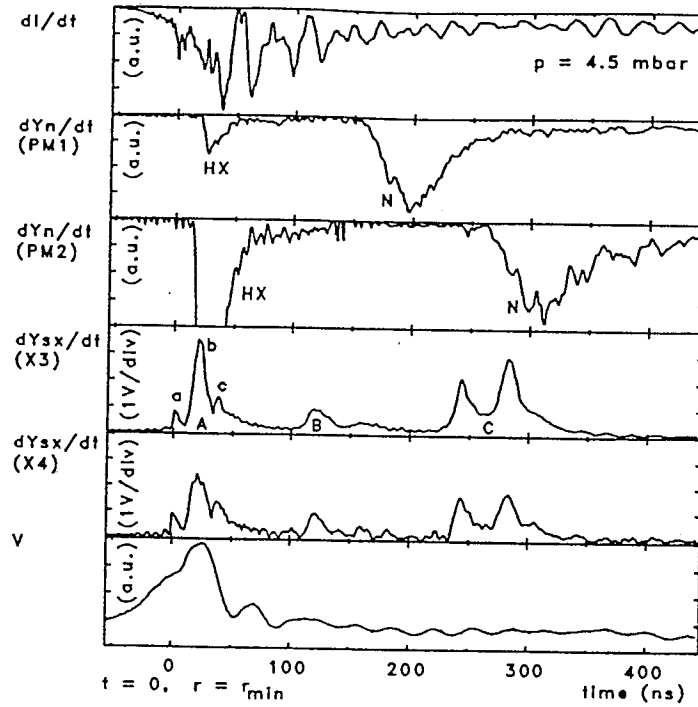


Figure 4. A 500 ns window for a discharge corresponding to one voltage spike regime. From top to bottom the traces are current derivative (dI/dt), two neutron (dY_n/dt) and associated hard-x-ray pulses recorded from the TOF detectors (PM1, PM2), soft x-ray emission rate (dY_{sx}/dt) from two filtered PIN diodes (X4, X3) and voltage probe signal (V), with all vertical axes in arbitrary units. The time $t = 0$ is taken at the instant of time when the plasma column reaches the minimum radius (r_{min}). Configuration: standard Mather-type anode.

3. Results and discussion

3.1. Standard Mather-type electrode geometry

3.1.1. Focus regimes and soft x-ray emission rate.

Two distinct regimes for the plasma focus dynamics were identified [10]. One corresponds to the discharges with one voltage spike associated with one main focusing period. The soft x-ray emission rate dY_{sx}/dt signals (see figure 4) show a first soft x-ray burst (marked 'A' in figure 4) with three peaks associated with the pinch phases i.e. (i) the end of the radial implosion to minimum radius (see peak 'a'). (ii) the quiescent phase (see peak 'b') corresponding to the onset of the $m = 0$ instability and (iii) the unstable and decay phases (see peak 'c'). Similar results have already been reported [18]. A second soft x-ray emission period (second burst) starts after approximately 60–120 ns (marked 'B' in figure 4). It has a 10 ns risetime and lasts for 30–100 ns. Its amplitude is usually lower than the first soft x-ray burst. However, in some discharges with not so high neutron production it may be almost one order of magnitude higher, in which case it shows a sharper risetime of 2–8 ns. No indication of a second plasma compression or another hard-x-ray or neutron pulse was observed. The cause of this second compression may be the remnant plasma filaments breaking up in very small plasma structures. The third soft x-ray emission period (third burst) begins at $t = 200$ –300 ns (marked 'C' in figure 4) and is associated with the

vaporized copper jet emitted from the inside and/or the rim of the anode [19]. The two peaks have usually 10–20 ns risetime and 30 ± 10 ns FWHM, but in some shots this emission period may be extended for more than 300 ns. The overall soft x-ray production of this regime is usually small.

The second plasma focus regime exhibits two or more voltage spikes corresponding to two main compressions of the hot and dense plasma. Subsequently, two (or sometimes even three) neutron pulses are detected. The soft x-ray emission characteristics are basically similar to those described earlier. However, the second soft x-ray burst is accompanied by second hard-x-ray and neutron pulses and hence is associated with the second collapse which could be ascribed to the break-up of the plasma filaments into 'hot spot'.

Table 2 shows the average values of the axial transit time, peak axial sheath velocity, peak discharge current and drive parameter for the standard Mather-type anode as well as for the other-piece Mather-type anodes and composite anodes.

3.1.2. Correlation between soft x-ray and neutron productions.

Simultaneous neutron and soft x-ray measurements were made for correlation purposes. By integrating the dY_{sx}/dt signal from one of the filtered PIN diodes (X4), the total soft x-ray yield was obtained. The integration was performed for the first soft x-ray burst only (during the

Table 2. Average values of the axial transit time, peak axial sheath velocity, peak discharge current and drive parameter for different electrode configurations.

Configuration	t_{axial} (μs)	V_{axial} ($cm \mu s^{-1}$)	I_{max} (kA)	$(I_{max}/a)/\rho^{1/2}$ (kA cm^{-1} (torr D_2) $^{-1/2}$)
SPF-165/19	2.656	8.3	172.0	97.8
CCA-45/19 + 140/15	2.476	10.5	164.7	118.7
CCA-65/19 + 120/15	2.469	10.6	167.1	120.5
CCA-103/19 + 70/15	2.402	11.2	169.4	122.1
CCA-93/19 + 80/15	2.377	11.3	169.5	122.2
CCA-90/19 + 100/15	2.419		169.6	122.3
CCA-95/19 + 90/14	2.473	11.4	169.4	130.8

focus phase) and for the whole emission period (the total yield). By subtracting the value of the yield generated during the pinch phase from the total yield, the value of the soft x-ray yield emitted post-focus (late emission) was obtained. These three values characterizing the soft x-ray production were plotted against the total neutron yield for a large number of shots at 4, 4.5 and 5 mbar deuterium. We concluded that (i) high neutron yield is accompanied by large emission in the hard-x-ray region and low emission of soft x-rays; (ii) x-ray production increases for low operating pressures; (iii) a DPF device may be optimized either as a soft x-ray source or as a neutron source. Correlations between the soft x-ray production and neutron yield at the neutron-optimized pressure of 4.5 mbar are illustrated in figure 5. The results show that the maximum soft x-ray yield peaks for lower-neutron-yield shots. The emission during the pinch phase (focus) shows a smooth peak at high neutron productions. This feature can be associated with either high electron temperature (T_e) or high electron density (n_e) or both, as the intensity of the soft x-rays produced by bremsstrahlung is proportional to $n_e^2 T_e^{1/2}$.

In figure 6 the dependence of the soft x-ray production on pressure is plotted. Although no experiments were performed at pressures below 4 mbar D_2 , we infer that the plasma focus cannot be optimized for both neutron and soft x-ray production and that in deuterium the optimum soft x-ray yield is obtained at a pressure below the neutron-optimized value.

The bulk of the overall soft x-ray emission including the first burst is strongly dominated by copper lines, as can be inferred from the ratio of the signals of the two filtered PIN diodes. However, in a few discharges, at the moment of maximum compression electron temperatures T_e in the range 1.2–1.9 keV were determined using the filter ratio method. The values for T_e should be taken as the gross electron temperature of the plasma column as no consideration is taken of the fine structure present in the pinch such as 'hot spots'.

3.2. Composite anodes

3.2.1. Focus regimes and soft x-ray emission rate.

For the composite anode configurations (see table 1 and figure 1) one can also identify the same two types of pattern or regimes of the plasma dynamics. The average values of the axial transit time, peak axial sheath velocity,

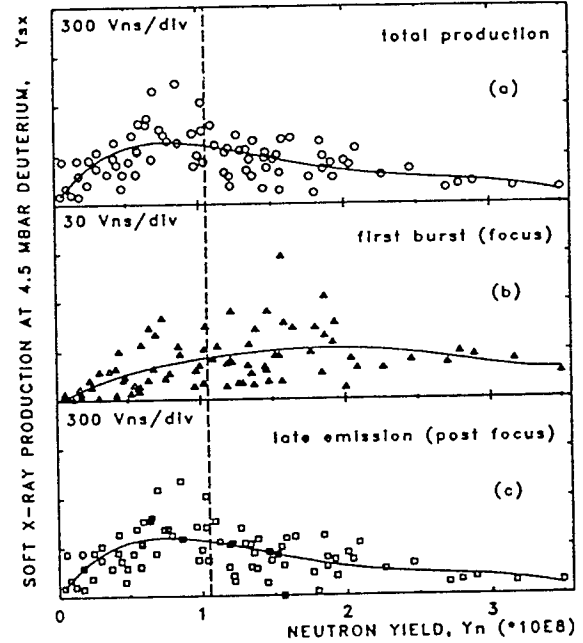


Figure 5. Correlation between soft x-ray production Y_{sx} and neutron yield Y_n at 4.5 mbar deuterium; (a) total production (focus and post-focus emission), (b) soft x-rays produced during the pinch phase (focus), (c) post-focus soft x-ray yield. The vertical dotted line corresponds to the mean neutron yield. Configuration: standard Mather-type anode.

peak discharge current and drive parameter are illustrated in table 2.

In the case of discharges with one voltage spike associated with one main focusing period (see figure 7) the soft x-ray emission rate (dY_{sx}/dt) shows practically one long-lasting burst of 200 ns. The features (spikes) of this soft x-ray burst can be described and interpreted in the following manner: the first spike beginning some 5 ns before the end of the compression has a relatively large risetime of 5–6 ns. This could indicate (i) an increase of the electron temperature during the compression phase due to a higher implosion velocity, (ii) emission of copper lines from the rim of the inner electrode, (iii) the presence of induced high electric fields due to the development of microinstabilities in a reduced plasma column size (it was shown the the radius and length of the pinched column

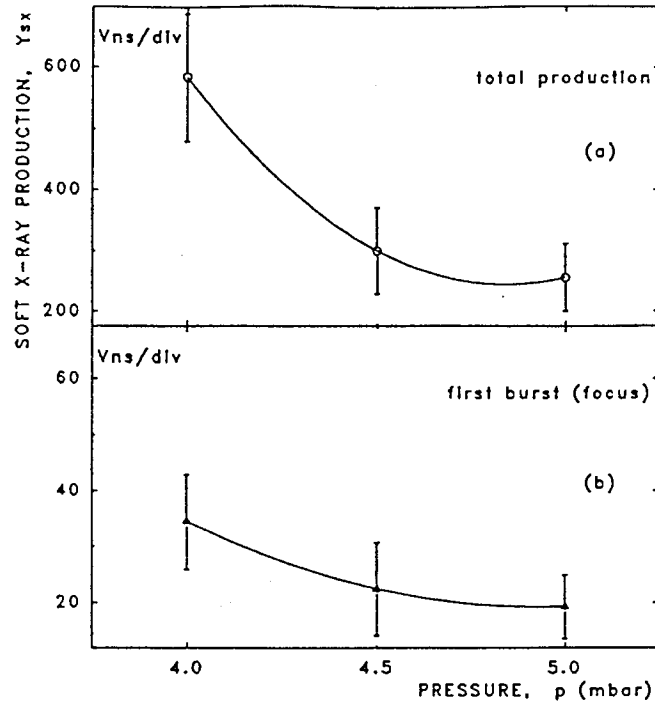


Figure 6. Dependence of soft x-ray production on pressure. The open circles represent the mean values and the vertical error bars the corresponding standard deviations; (a) total production, (b) soft x-ray emission associated with the pinch (focus) phase. Configuration: standard Mather-type anode.

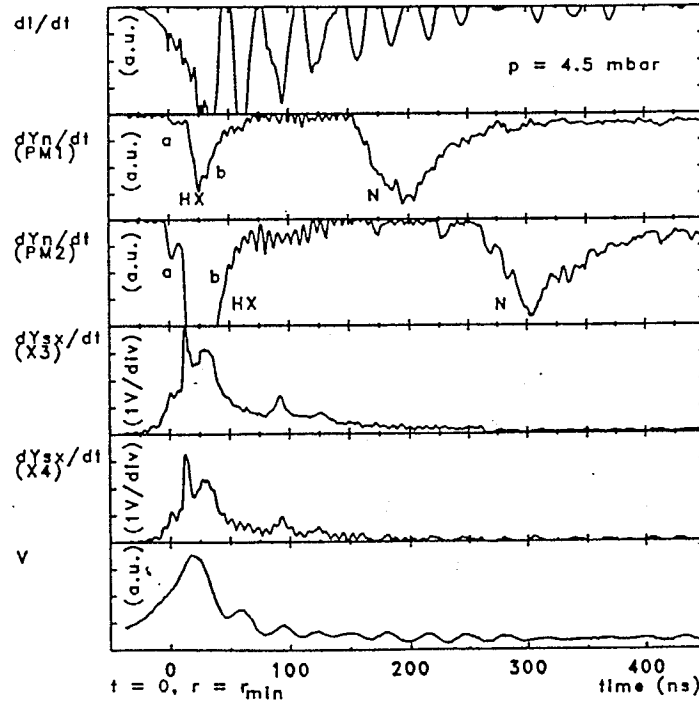


Figure 7. A 500 ns window for a discharge at 14 kV in 4.5 mbar deuterium. From top to bottom the traces are current derivative (dI/dt), hard-x-rays and neutron pulses (dY_n/dt) detected by TOF detectors PM1 and PM2, soft x-ray emission rate (dY_{sx}/dt) from two filtered PIN diodes (X3 and X4) and voltage probe signal (V). Configuration: CCA-103/19 + 70/15. Oscilloscope settings identical to those for the discharge illustrated in figure 4.

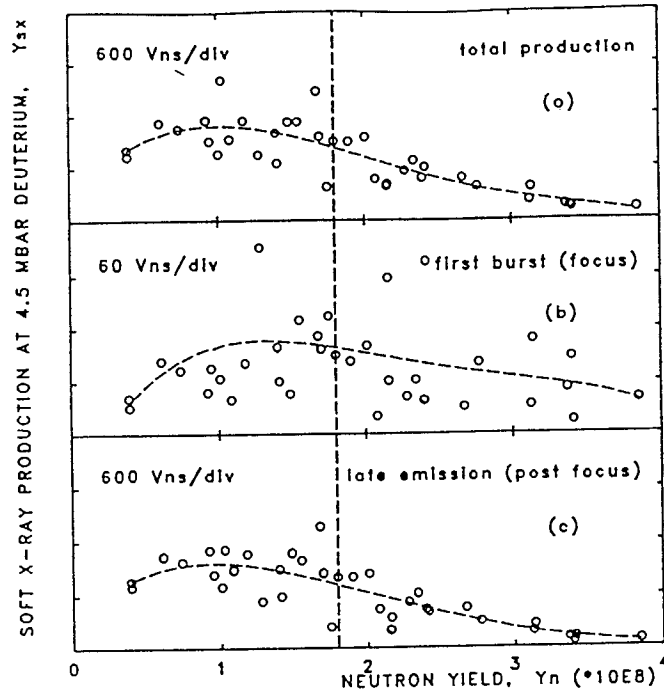


Figure 8. Correlation between soft x-ray production Y_{sx} and neutron yield Y_n at 4.5 mbar deuterium: (a) total production (focus and post-focus emission); (b) soft x-ray production during the pinch phase; (c) post-focus yield. The vertical dotted line indicates the average neutron yield. Configuration: CCA-103/19 + 70/15.

are scaled to the anode radius [5]), or (iv) a combined effect of all of the above. The presence of the harder-x-ray component around the instant of time $t = 0$ made temperature measurements by filter ratio method practically impossible. The second spike of the soft x-ray signal corresponding to the x-ray emission during the quiescent phase has a larger amplitude, a faster risetime of 1–2 ns and 5–8 ns FWHM. Its peak is associated with the onset of the $m = 0$ instability at the end of the stable pinch phase. During the unstable and decay phases, it is possible to have the onset of some additional local plasma compressions of plasma filaments or 'hot spots' leading to x-ray emission in both soft and hard regions. The third soft x-ray spike is not as sharp as the first two and decays gradually over a long period of time of 40–60 ns. Around the instant of time $t = 100$ ns the soft x-ray signal exhibits one or two slow-rising, broad and low-amplitude spikes (see figure 7) associated with the vaporized copper jet arising from the anode.

The hard-x-ray emission is associated and correlated with neutron emission occurring in locally compressed plasma: the higher the neutron yield, the higher the hard-x-ray production. With the x-rays, the situation is reversed.

The discharges exhibiting multiple voltage spikes associated with several compressions of the hot and dense plasma are always accompanied by low neutron production but high emission in the soft x-ray region lasting for almost 1 μ s. The temporal evolution of our measured parameters is basically similar to that described for the standard configuration.

3.2.2. Correlation between soft x-ray and neutron productions. Figure 8 shows that at 4.5 mbar (neutron-optimized pressure) low neutron yield is accompanied by a high total soft x-ray production, whereas for discharges with very high neutron output the soft x-ray yield drops significantly. The curves of the total soft x-ray output as a function of neutron yield peak at around 10^8 neutrons per discharge, showing again that the plasma focus device can be optimized for either neutron or soft x-ray production. The soft x-ray emission during the pinch phase shows a rather 'smooth' and constant profile with a large plateau region from 10^8 to about 2×10^8 neutrons/discharge. Figure 8(c) shows that the post-focus soft x-ray emission follows practically the shape of the production during the pinch phase is about one order of magnitude lower than the total. In the following discussions on the enhancement of the soft x-ray emission references will be made to the total soft x-ray yield as well as to the production during the focus period. As our measurements show a strongly copper-contaminated plasma, the soft x-ray output includes bremsstrahlung radiation from the pinch and Cu lines.

3.3. Discussion

Various scaling laws of the soft x-ray yield i.e. $Y_{sx} \sim I^n$ and/or $Y_{sx} \sim I^n v_{axial}^n$, with $n = 2-4$, were investigated. Figure 9 (upper trace) illustrates the plot of Y_{sx} as a function of I^4/a^2 with a the radius of the anode. The

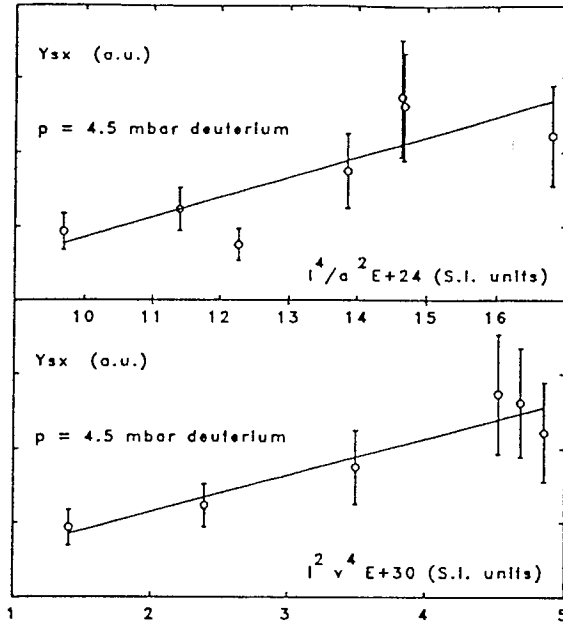


Figure 9. Soft-x-ray production as a function of I^4/a^2 (upper plot) and $I^2 v^4$ (lower plot), with I the peak discharge current, a the anode radius and v the peak axial speed. The open circles represent the mean values and the vertical error bars the corresponding standard deviations.

operating pressure is 4.5 mbar deuterium. It is seen that there is only one datum which cannot fit the linear plot. This corresponds to a one-piece anode geometry (not described here) for which not only the x-ray production, but the neutron yield and reproducibility of the focus were significantly affected by the changing of the breakdown conditions.

In the light of the scaling law of the axial speed [20] the function $Y_{SX} \sim I^4/a^2$ is equivalent to $Y_{SX} \sim I^2 v_{axial}^2$. This shows that for a given operating pressure, the soft x-ray production increases with the square of the peak axial speed in the range of 7–14 cm μs^{-1} . Therefore, it appears that the soft x-ray output may also be increased by using the appropriate double-stage anode with the speed-enhanced section long enough to obtain higher speed, but short enough to avoid the force-field-flow-field separation.

However, this scaling law is still not very accurate. If the soft x-ray yield corresponding to the standard SPF-165/19 anode geometry is taken as reference, one would expect an increase of about 1.85-fold for the CCA-103/19+70/15 configuration. The experimental data, however, show an increase of approximately 3.7-fold, this suggests another possible scaling of the soft x-ray production:

$$Y_{SX} \propto I_{max}^2 v_{axial}^4 \quad (1)$$

Figure 9 (bottom trace) illustrates the plot of the total soft x-ray output according to the proposed scaling law given by (1) for the working pressure of 4.5 mbar deuterium. This plot shows that our available experimental data fit better

the new scaling law. However, the value of the working pressure of 4.5 mbar does not correspond to the optimized soft x-ray regime. The soft x-ray output depends strongly on the gas filling pressure. Therefore, our empirical scaling law has to be considered with caution. Further investigation is required.

Our analysis of the soft x-ray production shows that at higher speed the soft x-ray emission is enhanced. Since the dimensions and lifetime of the pinch are scaled to the anode radius [5] the final volume of the pinched column is approximately 35% smaller in the case of the CA-103/19 + 70/15 anode compared to the standard one. The fact that soft x-ray emission is enhanced by approximately 120% shows that the plasma temperature during the pinch phase is higher. Assuming that the temperature is proportional to the square of velocity [8], then the temperature increases by almost 40%. This is in agreement with the interpretation of an enhanced non-beam neutron emission [1]. On the other hand, increasing the length of the speed-enhanced section, and hence the final axial velocity, the focusing characteristics become poorer. This fact could be interpreted as an effect of a force-field-flow-field separation of the plasma structure which is not conducive to good focus.

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Electromagnetic wave pulse amplification induced by the reflection from relativistic plasma fronts

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Abstract

For a radiation pulse with incidence normal to an incoming plasma front, the reflective index at the front of the plasma serves as a reflector. A description is given of the up-shift frequency of the radiation pulse and the reflection coefficient developments with different plasma densities from an initial state to saturation and decaying are studied. The results show that the reflection coefficient is closely correlated both to the velocity of the plasma front and the amplitude of the Langmuir wave. We obtained reflection coefficients that are larger than those from a moving mirror at the same speed. However, at special points the reflection coefficient is independent of the amplitude of the Langmuir wave.

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A reflector of electromagnetic radiation moving with a relativistic speed has many interesting properties [1–10]. If the reflectivity $\eta > 1$, the radiation pulse may be amplified by the relativistic moving front. The extra energy is supplied by the kinetic energy of the moving front [7,8].

In our recent papers [7–10], the reflection of a radiation pulse from an oncoming ionization front was studied. The resulting reflection coefficient was well above previous predictions. The results showed that upon reflection from an ionization front with an optimum density, the up-shift frequency of a radiation pulse would exceed twice the driver frequency and the reflected energy would exceed the incident energy.

However, the critical problems of this kind of ion-based front are how to get a high ion density and how to increase the reflectivity. As mentioned earlier [3,5], general methods only generate high-energy ions or electrons but are unable to produce high density. Even if very high-density fronts are obtained, the effective reflection coefficient may still be very low and the ion front may still act like a poor mirror [10].

In order to achieve better results, some proposals have been made. One of them is that for a radiation pulse normally incident to an incoming electron front, the reflective index discontinuity serves as a reflector [11,12]. Three

types of waves will appear in the process: the incident, reflected and transmitted waves. An electron beam is called overdense when the electron density is larger than the critical density ($N > N_{cr}$) and underdense in the opposite case $N \leq N_{cr}$. An underdense beam is a non-ideal reflector since a radiation pulse can partially transmit into it. In the regime of $N > N_{cr}$, the transmission is cut off and the energy reflectivity η reaches its maximum value [11,12]. The electron front then acts exactly as an ideal mirror and 100% of the incident photons are reflected. If the reflectivity $\eta > 1$, i.e., the radiation pulse is amplified by the electron front. The extra energy is supplied by the kinetic energy of the moving electrons [12].

In this Letter, we explore a high-temperature plasma produced by a high-power laser irradiation as a reflector to achieve frequency up-conversion and pulse amplification. A description of the development of the reflection coefficient with different plasma densities, and the up-shifted frequencies of the radiation pulse are presented. The results show that the reflection coefficient is closely correlated to the speed of the plasma fronts and the amplitude of the Langmuir wave. Considering a Langmuir wave, the reflection coefficient is larger than that of the reflections from a moving mirror at the same speed. However at two special density points, the reflection coefficients are inde-

pendent of the amplitude of the Langmuir wave.

We begin by studying the motion of the plasma reflection interface. As in earlier papers [8,10], we consider a test radiation polarized in the y direction incident from the right upon a plasma front that moves from the left. The electromagnetic fields are described by Maxwell's equation:

$$c \nabla \times \mathbf{B} = \partial \mathbf{E} / \partial t + 4\pi \mathbf{J}, \quad (1)$$

$$c \nabla \times \mathbf{E} = -\partial \mathbf{B} / \partial t, \quad (2)$$

here c is the speed of the light, $\mathbf{E}$ and $\mathbf{B}$ are the electric field vector and the magnetic field vector respectively, $\mathbf{J}$ is the total electric current which includes the current induced by polarization and magnetization as well as the current associated with the magnetic mode. In the laboratory frame, where the plasma front is in motion, the moving boundary condition is determined by [10,13]

$$\mathbf{n} \times (\mathbf{E}_1 - \mathbf{E}_2) - (\mathbf{n} \cdot \boldsymbol{\beta})(\mathbf{B}_1 - \mathbf{B}_2) = 0, \quad (3)$$

$$\mathbf{n} \times (\mathbf{H}_1 - \mathbf{H}_2) + (\mathbf{n} \cdot \boldsymbol{\beta})(\mathbf{D}_1 - \mathbf{D}_2) = 0, \quad (4)$$

where $\boldsymbol{\beta} = \mathbf{v}/c$, $\mathbf{v}$ being the velocity vector of the moving boundary, $\mathbf{H}$ and $\mathbf{D}$ are the magnetic and the electric displacement vector respectively, $\mathbf{n}$ is the unit vector normal to the surface of the front. The subscripts 1 and 2 denote the electromagnetic fields on the right-hand side of the plasma front and on the left-hand side of the front, respectively. The electric current vanishes at the boundary since the electrons have zero velocity in the moving frame [8,10]. On the right-hand side of the front, where the neutral gas is assumed to have the dielectric properties of the vacuum, the transverse fields are determined by

$$D_1 = E_1 = E_i e^{-i(\omega_i t - k_i x)} + E_r e^{-i(\omega_r t - k_r x)}, \quad (5)$$

$$H_1 = B_1 = E_i e^{-i(\omega_i t - k_i x)} - E_r e^{-i(\omega_r t - k_r x)}, \quad (6)$$

and the transverse current $J_1 = 0$, where $k_i = \omega_i/c$ and $k_r = -\omega_r/c$ are the wavenumbers of the incident and reflected modes. On the left-hand side of the front, where the plasma is fixed in the moving frame and the magnetic mode is a static magnetic field ($E_m = 0$, $\omega_m = 0$) [1,2,8], the transverse fields and the current can be expressed as

$$D_2 = \epsilon E_2 = \xi^2 E_i e^{-i(\omega_i t - k_i x)} + \xi^2 E_L e^{-i(\omega_L t - k_L x)}, \quad (7)$$

$$B_2 = \mu H_2 = \xi E_i e^{-i(\omega_i t - k_i x)} - \xi E_L e^{-i(\omega_L t - k_L x)} + B_m e^{ik_m x}, \quad (8)$$

$$J_2 = \frac{i\omega_i}{4\pi} \left[(1 - \xi^2) E_i e^{-i(\omega_i t - k_i x)} + \frac{\omega_L^2 - c^2 k_L^2}{\omega_i \omega_L} \times E_L e^{-i(\omega_L t - k_L x)} - \frac{ck_m}{\omega_i} B_m e^{ik_m x} \right]. \quad (9)$$

Here $\xi = kc_i/\omega_i$, $\mu = 1$, $\epsilon = \xi^2$, k_i and k_m are the wavenumbers of the transmitted and the magnetic modes, the subscripts r , i , m , L denote the reflected, transmitted electromagnetic waves, static magnetic field and the Langmuir wave, respectively.

Inserting Eqs. (5)–(9) into the boundary conditions gives the phase-matching conditions

$$\omega_i(1 + \beta) = \omega_r(1 - \beta) = \omega_i(1 + \xi\beta) = \omega_L - \beta ck_L = k_m v, \quad (10)$$

and the following relations

$$(1 + \beta)E_i + (1 - \beta)E_r - (1 + \xi\beta)E_L - \left(1 - \beta \frac{ck_L}{\omega_L}\right)E_L - \beta B_m = 0, \quad (11)$$

$$(1 + \beta)E_i - (1 - \beta)E_r - \xi(1 + \xi\beta)E_L + \left(\frac{ck_L}{\omega_L} - \beta\xi^2\right)E_L - B_m = 0. \quad (12)$$

Considering that the current on the front in the moving frame is zero and substituting the phase matching conditions into Eq. (9), we get

$$\beta(1 - \xi^2)E_i + \frac{\beta(\omega_L^2 - c^2 k_L^2)}{\omega_L \omega_i} E_L - (1 + \xi\beta)B_m = 0. \quad (13)$$

According to Eq. (10) and the dispersion relation $\xi^2 = 1 - \omega_L^2/\omega_i^2$, we have

$$\frac{\omega_L}{\omega_i} = \sqrt{N}, \quad (14)$$

$$\frac{ck_L}{\omega_i} = \frac{1}{\beta}(\sqrt{N} - 1 - \beta), \quad (15)$$

$$\frac{\omega_r}{\omega_i} = \frac{1 + \beta}{1 + \xi\beta}, \quad (16)$$

$$\frac{\omega_r}{\omega_i} = \frac{1 + \beta}{1 - \beta}, \quad (17)$$

$$\xi = \frac{ck_i}{\omega_i} = \frac{-\beta N + (1 + \beta)\sqrt{(1 + \beta)^2 - N\gamma^{-2}}}{(1 + \beta)^2 + \beta^2 N}, \quad (18)$$

where N is the relative plasma density, and $\gamma = (1 - \beta^2)^{-1/2}$ is the Lorentz factor. From Eqs. (14)–(18), the frequencies of the reflected, transmitted modes, plasma Langmuir wave mode and the relative plasma critical density, N_{cr} , can be obtained as

$$\omega_r = \omega_i \frac{1 + \beta}{1 - \beta}, \quad (19)$$

$$\omega_i = \omega_i \frac{(1 + \beta)^2 + \beta^2 N}{(1 + \beta) + \beta\sqrt{(1 + \beta)^2 - N\gamma^{-2}}}, \quad (20)$$

$$\frac{ck_L}{\omega_L} = \frac{ck_L/\omega_i}{\omega_L/\omega_i} = \frac{1}{\beta\sqrt{N}}(\sqrt{N}-1-\beta), \quad (21)$$

$$\frac{\omega_L^2 - c^2 k_L^2}{\omega_L \omega_i} = \frac{(1+\xi\beta)[\beta^2 N - (\sqrt{N}-1-\beta)^2]}{\beta^2 \sqrt{N}(1+\beta)}, \quad (22)$$

$$N_{cr} = \frac{1+\beta}{1-\beta}. \quad (23)$$

As we can see, the up-shift frequency ω_r will increase with the speed of the moving boundary which has already been reported [1,8,10], and the frequency ω_r of the reflected pulse that is much larger than that of the driver light frequency ω_i can be easily obtained.

Let $t = E_r/E_i$, $r = E_r/E_i$, $m = B_m/E_i$ and $\alpha = E_L/E_i$. Eqs. (11)–(13) together with Eqs. (19)–(22) may lead to the result that the coefficients of reflection, transmission and magnetic fields are:

$$t = \frac{1}{(1+\xi)(1+\beta\xi)^2 + (1+\beta)\beta(1-\xi^2)} \times \left\{ 2(1+\beta)(1+\beta\xi) + \left[(1+\beta)\frac{ck_L}{\omega_L} - (1+\beta\xi^2) - \frac{\beta(\omega_L^2 - c^2 k_L^2)}{\omega_L \omega_i} \right] \alpha \right\}, \quad (24)$$

$$r = \frac{1}{2(1-\beta)(1+\beta\xi)} \times \left\{ [(1-\xi)(1+\beta\xi)^2 - (1-\beta)\beta(1-\xi^2)] t - \left[(1-\beta)\frac{ck_L}{\omega_L} + (1-\beta\xi^2) \right] (1+\beta\xi)\alpha - (1-\beta)\beta\frac{\omega_L^2 - c^2 k_L^2}{\omega_L \omega_i} \alpha \right\}, \quad (25)$$

$$m = \frac{1}{(1+\beta\xi)} \left[\beta(1-\xi^2)t + \frac{\omega_L^2 - c^2 k_L^2}{\omega_L \omega_i} \beta\alpha \right]. \quad (26)$$

From Eqs. (24)–(26), one may see that the amplitude of the Langmuir wave will obviously affect all coefficients of the reflected, the transmission and the magnetic mode. The energy reflectivity η can be calculated from the reflection coefficient r through [7,10]

$$\eta = W_r/W_i = |r|^2 K, \quad (27)$$

where W_r and W_i are the reflected and the incident energies respectively, and $K = (1-\beta)/(1+\beta) = 1/N_{cr}$.

A plasma front is called underdense when $N < N_{cr}$. In the overdense region $N > N_{cr}$, from Eq. (18) we may see that the transmission of the radiation is cut-off and the reflection decreases as well so that to get a large reflection coefficient one should consider underdense fronts [8,10].

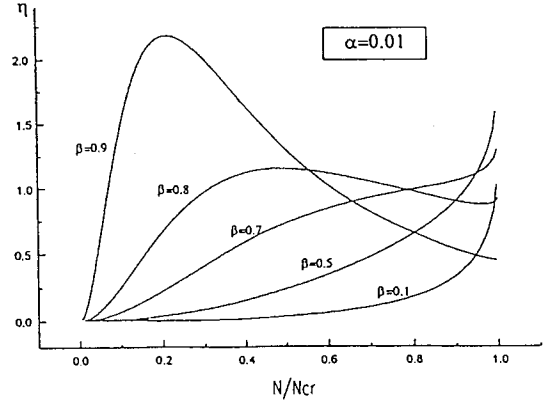


Fig. 1. Reflection from a plasma front: the energy reflectivity η dependence on the plasma density N/N_{cr} for $\alpha = 0.01$ and $\beta = 0.9, 0.8, 0.7, 0.5$ and 0.1 .

In Fig. 1, the reflectivity η is plotted as a function of N/N_{cr} for $\alpha = 0.01$ and $\beta = 0.9, 0.8, 0.7, 0.5$ and 0.1 . The most distinct feature of this figure is that the reflection coefficients for $\beta < 0.8$ increase together with the plasma densities and they have a maximum value at $N = N_{cr}$. Each maximum reflectivity for the $\beta \geq 0.8$ curves is in the underdense region. The results in Fig. 1 show that the maximum reflectivity at the optimum density is still much lower than the reflection from a moving mirror at the same speed [10,14].

In Fig. 2, the reflectivity η is plotted as a function of N/N_{cr} for $\beta = 0.7$ and $\alpha = 0.1, 0.5, 1.0$ and 2.0 . The maximum reflection coefficient for the $\alpha = 0.1$ curve (see Fig. 2) is larger than that for $\alpha = 1.0$. Moreover at the two special points ($\eta \approx 0.42$, $N/N_{cr} \approx 0.32$ and $\eta \approx 1.02$, $N/N_{cr} \approx 0.9$), the reflection coefficients are independent of the amplitude of the Langmuir wave. The maximum reflectivity in the figure is less than $\eta = 1.6$. This result

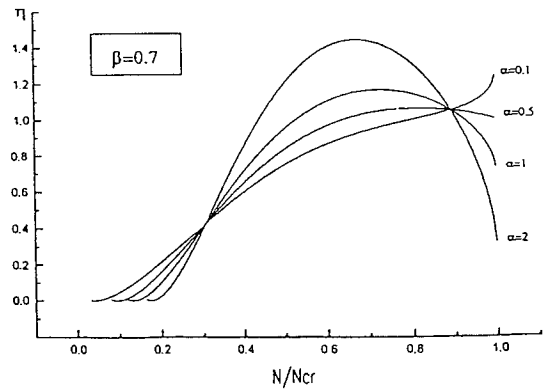


Fig. 2. Reflection from a plasma front: the energy reflectivity η dependence on the plasma density N/N_{cr} for $\beta = 0.7$ and $\alpha = 0.1, 0.5, 1.0$ and 2.0 .

indicates that the incident pulse may be not effectively amplified. However, the curves in Fig. 3 also imply that a large amplitude ($\alpha > 1.0$) of the Langmuir wave will assist to yield a large reflection coefficient. With a small amplitude of the Langmuir waves ($\alpha < 0.5$) one does not obtain a similar result.

In Fig. 3, the reflectivity η is plotted as a function of N/N_{cr} for $\beta = 0.9$ and $\alpha = 0.1, 0.5, 1.0$ and 2.0 . The maximum value of the reflection coefficient for each curve obviously increases with the amplitude of the Langmuir wave, and all those values are in the underdense region. Similar to the curves in Fig. 2, two special points ($\eta \approx 1.0$, $N/N_{cr} \approx 0.07$ and $\eta \approx 1.0$, $N/N_{cr} \approx 0.64$) are independent of the parameter α . However the optimum densities corresponding to the maximum reflections for $\beta = 0.9$ are nearer to the origin point than that for $\beta = 0.7$ curves in the density axis. The calculation shows that the maximum reflectivity from the optimum plasma front is larger than unity, i.e., the reflected pulse has more energy than the incident pulse. This effect of pulse amplification shows the analogy with the relativistic moving mirror. Similar to a moving mirror, the moving interface itself cannot exist without the energy supply from the plasma drivers. In this case, it is reasonable to assume that a part of the drive energy is converted to the incident pulse and results in pulse amplification [10]. However, Figs. 1, 2 and 3 also show that the reflections from the optimum plasma front are still lower than the reflection from a moving mirror at the same speed [10,15] and all those fronts may be called poor mirrors.

If we continue to increase the amplitude of the Langmuir wave or increase the parameter α , the reflection coefficient will obviously increase. Meanwhile the optimum density value N_{opt} , corresponding to the maximum value of the reflectivity will shift from the underdense region to the near critical density region. As seen in Fig. 4, the reflectivity η is plotted as a function of N/N_{cr} for

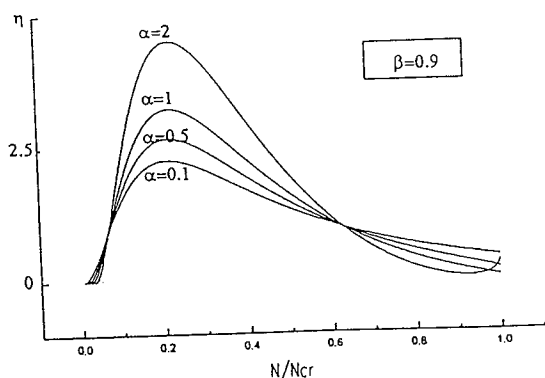


Fig. 3. Reflection from a plasma front: the energy reflectivity η dependence on the plasma density N/N_{cr} for $\beta = 0.9$ and $\alpha = 0.1, 0.5, 1.0$ and 2.0 .

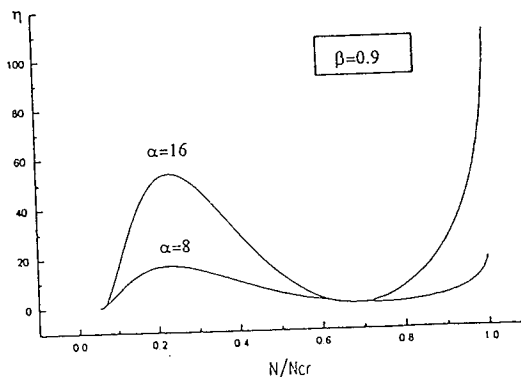


Fig. 4. Reflection from a plasma front: the energy reflectivity η dependence on the plasma density N/N_{cr} for $\beta = 0.9$ and $\alpha = 8.0, 16$.

$\beta = 0.9$ and $\alpha = 8$ and 16 . The calculated result shows that the reflection from the optimum plasma front is much larger than the reflection from a moving mirror at the same speed. This characteristic is very important because it can be used to amplify a shorter wave laser. In general, a large amplitude of the Langmuir wave can be produced by high-power laser irradiation or by the laser beat-wave method [15,16].

As a special example, let us assume that the amplitude of the Langmuir wave is equal to zero, and that the coefficients of the reflected, the transmission and the magnetic field can be derived from Eqs. (24)–(26) as

$$t = \frac{2(1+\beta)(1+\beta\xi)}{(1+\beta\xi^2)(1+\beta\xi) + (1+\beta)(\beta+\xi)}, \quad (28)$$

$$r = \frac{(1+\beta)[(1-\beta\xi^2)(1+\beta\xi) - (1-\beta)(\beta+\xi)]}{(1-\beta)[(1+\beta\xi^2)(1+\beta\xi) + (1+\beta)(\beta+\xi)]}, \quad (29)$$

$$m = \frac{2\beta(1+\beta)(1-\xi^2)}{(1+\beta\xi^2)(1+\beta\xi) + (1+\beta)(\beta+\xi)}. \quad (30)$$

Those are the same expressions for describing the propagation of the electromagnetic radiation in the presence of oncoming ionization fronts as in earlier reports [7,8]. The fact that the approaches yield the same formula under the assumption of the amplitude of the Langmuir wave being zero confirms the correctness of our analysis. It also implies that Eqs. (24)–(26) are valid for the more general condition describing electromagnetic wave pulse amplification induced by the reflection from relativistic moving fronts.

Finally, two points should be mentioned: (i) our results only apply to the special restrictive case in which the velocity of the ionization front β , the density of the front N , and the phase velocity of the Langmuire wave ω_L/k_L

satisfy the phase-matching condition $\omega_L/ck_L = \beta\sqrt{N}/(\sqrt{N} - 1 - \beta)$, (ii) there will be slippage between the ionization front (moving at β) and the Langmuir wave front (moving at ω_L/ck_L). However, in this communication we shall not consider the case of slippage, but instead we use a simple approximation of phase-matching together with a moving boundary condition to calculate the effect of the Langmuir wave on the electromagnetic wave pulse amplification. If we let $\beta = \omega_L/ck_L$, there will be no slippage between the ionization front and the Langmuir wave front, and we have another different result to describe electromagnetic amplification under a no-phase-matching condition. We are now trying to use a new model including the slippage effect to calculate more detailed processes for electromagnetic wave amplification. We will present those results in a forthcoming paper.

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A transmission grating spectrograph and its application in both laser plasma and plasma focus

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A new transmission grating spectrograph for soft x-ray measurement in pulsed plasmas was designed and studied. The spectrograph has an adjustment system with three degrees of freedom, together with an electronic-controlled camera. This design makes it easy to align and use for laser-produced plasmas or the plasma focus. The spectrograph provides spatially resolved spectrum in two dimensions and has a wavelength range of 0.3–30 nm. A transmission grating was used to obtain spatially resolved spectra from plasmas produced by laser-irradiated solid target and gas filled plasma focus. Such a spectrograph is suitable for coupling with a soft x-ray streak camera or a soft x-ray charge coupled device detector for time-resolved studies. © 1997 American Institute of Physics. [S0034-6748(97)04707-2]

I. INTRODUCTION

Laser-produced plasmas (LPPs) and plasma focus (PF) are intense emitters of pulsed soft x-rays.^{1–3} They have received growing interest for production of soft x-rays in the range 0.1–30 nm. These soft x-ray sources have applications in x-ray microscopy, spectroscopy, plasma physics, x-ray lithography, and measurement of the population dynamics of transient plasma producing data for comparison of experimental results with plasma modeling in order to predict soft x-ray laser action.^{4–6}

There are various schemes for measuring soft x-rays, as for example, using diffraction from a crystal spectrograph (CS), a stigmatic grazing grating spectrograph (SGGS), or a transmission grating spectrograph (TGS). Generally, a crystal spectrograph is used to measure x-ray wavelengths between the 0.1 and 2 nm region.^{7,8} A reflection SGGS enables us to obtain wider range of soft x-ray spectra (2.0–30 nm) with one-dimensional spatial resolution.^{9,10} However, SGGS is very expensive, difficult to align for x-ray energy measurements, and cannot be coupled with a charge coupled device (CCD). Previously we reported the design and examination of our crystal spectrograph and a stigmatic grazing incident grating spectrograph in plasma x-ray measurements.^{8,10} Here

we have developed a new pinhole TGS used for measuring soft x-ray spectra (0.3–30 nm) and diagnosing soft x-ray sources both in laser plasma and in the plasma focus system.

Transmission gratings with a wide range of grating constants, diffraction coefficients, and mechanical properties are available. From these an optimum choice of a dispersive element and spectroscopic scheme in accordance with the aims of diagnostics can be made. Among the parameters relevant to optimization are spectral range, luminosity, dispersion, and spatial and spectral resolution.¹¹

II. BASIC STRUCTURE AND PARAMETERS

A diffraction grating may consist of metal film with a large number of evenly spaced parallel lines or grooves. Common laboratory gratings have 1000 or 2000 grooves per

mm. For soft x-ray reflection (SXR) measurements we use a diffraction grating consisting of a flat gold film in which 1000 lines per mm are ruled through.

According to diffraction principle, the distribution of diffraction light on the focal plane is¹²

$$y = c' a \frac{\sin u}{u} \frac{\sin N v}{\sin v} \times \sin 2\pi \left(\frac{t}{T} - \frac{r_0}{\lambda} - \frac{(N-1)(a+b)\sin \theta}{2\lambda} \right); \quad (1)$$

here $u = (\pi a \sin \theta)/\lambda$, $v = [\pi(a+b)\sin \theta]/\lambda$, and N is the number of grooves. The amplitude and intensity may be expressed as

$$A = C' \frac{\sin u}{u} \frac{\sin N v}{\sin v}, \quad (2)$$

$$I = C'^2 a^2 \frac{\sin^2 u}{u^2} \frac{\sin^2 N v}{\sin^2 v}, \quad (3)$$

where C' is a constant, a is the width of the space between two metal lines, b is the width of the metal line, and N is the total number of lines or grooves for a grating.

Complete constructive interference of the waves occurs when the phase or path difference satisfies

$$(a+b)\sin \theta_k = \pm k\lambda, \quad k=0,1,2,\dots, \quad (4)$$

where θ is the angle of the rays diffracted from normal incident direction, and $d \sin \theta$ is the path difference between adjacent rays. The grating constant is given by

$$d = (a+b). \quad (5)$$

The relationship between x-ray wavelength λ_y and the spatial position y on the film was obtained for the spectrograph geometry shown in the Fig. 1 by considering $\theta_a = \arctg(y_{a0}/L)$, where y_{a0} is the distance from $y=a$ to $y=0$, and $\lambda_a = (d/k)\sin \theta_a$ from grating Eq. (4). The simple analytical expression for the relationship between wavelength λ_a and position y_{a0} is

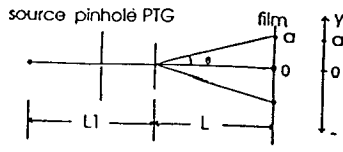


FIG. 1. Pinhole transmission grating (PTG) spectrograph geometry and soft x-ray diffraction trace.

$$\lambda_o = \frac{d}{k} \sin \left[\arctg \left(\frac{y_{ao}}{L} \right) \right] \quad (6)$$

The position of the detector in our spectrograph is very flexible. It was installed with two pieces of a pinhole transmission grating spectrograph (PTGS) with diameters of 50 and 25 μm , respectively. This design makes it possible to compare different characteristics of PTGS and measure and analyze the different spectral structure from LPP and PF.

III. RESOLUTION AND DISPERSION

We know that the light intensity in the focal plane must be zero when $\nu = k' \pi / N$ [see second part of Eq. (3)], and $k' \neq N, 2N, 3N, \dots$. That is,

$$(a+b) \sin \theta_{k'=0} = \pm k' \frac{\lambda}{N}, \quad k' = 1, 2, 3, \dots, N-1, N+1, \dots, 2N-1, 2N+1, \dots \quad (7)$$

Using Eq. (4), we may rewrite the above equation as

$$d \sin \theta_{k'=0} = (kN+1) \frac{\lambda}{N}, \quad k = 1, 2, 3, \dots \quad (8)$$

Since $\theta_{k'=0} = \theta_k + \Delta\theta$, substituting Eq. (4) into Eq. (8) gives

$$\Delta\theta = \frac{\lambda}{N(a+b) \cos \theta_k} \quad (9)$$

We approximate $\cos(\Delta\theta) \approx 1$, and $\sin(\Delta\theta) \approx \Delta\theta$ for soft x-ray diffraction. Equation (9) shows that the angular spread of the diffracted spectral line will become very narrow when N is large.

According to grating Eq. (4), we have angle dispersion equation

$$\frac{d\lambda}{d\theta} = \frac{(a+b) \cos \theta}{k} \quad (10)$$

The minimum wavelength difference $\Delta\lambda$ corresponding to the minimum angular spread of the diffracted width spectral line $\Delta\theta$ is

$$\delta\lambda = \Delta\lambda = \left(\frac{d\lambda}{d\theta} \right) \Delta\theta \quad (11)$$

Substituting Eqs. (9) and (10) into Eq. (11) yields

$$\delta\lambda = \frac{\lambda}{kN} \quad (12)$$

and we obtain the resolution for grating spectrographs (GSs) as

TABLE I. The basic parameters of the PTGS.

Grating constant	$d = 1/N_0$	$1 \times 10^{-3} \text{ mm}$
Range of wavelength	$\lambda_{\min} \sim \lambda_{\max}$	0.3–30 nm
Incident angle	β_{in}	0°
Dispersion (for 1.3 nm)	$\theta = \arcsin(\lambda/d)$	0.07°
Diameter of grating	W	50 μm
Total number of grooves	$N_{\text{tot}} = W \times N_0$	50
Resolution ($k=1$)	$R_1 = kN_{\text{tot}}$	50
Width of spectral line	$\Delta\lambda_s = \lambda/R_1$	$2.43 \times 10^{-2} \text{ nm}$
Source of PTGS distance	$L1$	200 mm
PTGS to film distance	L	400 mm
Magnification of image	$\alpha = L/L1$	2

$$R = \frac{\lambda}{\Delta\lambda} = kN. \quad (13)$$

Practical factors will affect the value R and reduce the resolution below the theoretical value. High resolution spectra may be obtained with increasing k and the N number. There are some technological problems, however, in making a large N grating. Furthermore, increasing the order k will result in spectral line overlap. For example, when,

$$k_1 \lambda_1 = k_2 \lambda_2, \quad (14)$$

the lines at λ_1 and λ_2 will be superimposed on the detector. In practice, only the first few orders are easily distinguished.

According to Refs. 11, 13, and 14, we built a PTGS with an electronically controlled camera as shown in Figs. 1 and 2. The basic parameters are listed in Table I.

When the diameter of a soft x-ray source is $S=100 \mu\text{m}$ and the distance from the source to PTGS is $L1=20 \text{ cm}$ as shown in Fig. 1, the angular spread caused by the x-ray source size is

$$\Delta\theta_s = \arctan(S/L1) = 0.028^\circ. \quad (15)$$

Differentiating Eq. (4) we obtain $k\Delta\lambda = \Delta\theta d \cos \theta$. Eliminating θ in this equation by using Eq. (4) and assuming $\Delta\theta = \Delta\theta_s$, $k=2$, $\Delta\lambda = \Delta\lambda_s$, the source broadening for a soft x ray of wavelength 1.3 nm is

$$\Delta\lambda_s = 0.5 \sqrt{d^2 - \lambda^2} \Delta\theta_s = 0.24 \text{ nm}. \quad (16)$$

Assuming the profiles of the spectral lines and source broadening are Gaussian distributions, the total width of the spectral line is

$$\Delta\lambda = \sqrt{\Delta\lambda_s^2 + \Delta\lambda_i^2} \approx 0.24 \text{ nm}. \quad (17)$$

It is clearly seen that $\Delta\lambda_s \gg \Delta\lambda_i$, and that the PTGS' resolution is mainly determined by source broadening. The diameter of the x-ray source produced by the laser is small (30–80 μm) which gives a source broadening of $\Delta\lambda_s = 0.05\text{--}0.20 \text{ nm}$. The size of the plasma in the PF is about 100–300 μm , with a corresponding source broadening of $\Delta\lambda_s = 0.25\text{--}0.40 \text{ nm}$. It is better to increase distance $L1$ to minimize the full width at half-maximum (FWHM) $\Delta\lambda_s$ of the spectral line. The parameter $L1$ is mainly limited by magnification of the image $\alpha = L/L1$ and the x-ray intensity on film $I \sim 1/(L1+L)^2$.

The spatial resolution depends on the diameter of the PTGS itself. Its principle is identical to that of a pinhole

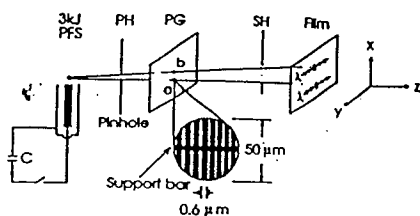


FIG. 2. Schematic diagram of x-ray experiment with two pinhole grating (symbol *a* and *b*) spectrograph. PFS: Plasma focus x-ray source; PH: pinhole; SH: shutter; C: capacitor; PG: pinhole grating with a support bar that protects the grating from damage by the shock wave.

camera. The diameters of our two PTGS are 25 and 50 μm . The distance from the soft x-ray source to the PTGS is 200 mm, and the distance from the PTGS to the recording film is 400 mm. The image of the soft x-ray source is magnified by 2 $\times$ and the spatial resolution is about 30 and 60 μm , respectively. A spectrogram with better spatial resolution can be obtained if we decrease the diameter of the PTGS.

IV. PHOTOGRAPHIC FILMS FOR SOFT X-RAY DETECTION

We have investigated the use of several types of films as soft x-ray detectors. The no-screen films (Kodak No-screen film, S-5F No-screen film, etc.) are very sensitive, and are very suitable for use with various grazing grating spectrographs for the soft x-ray range (5–30 nm).¹⁰ The no-screen films are very soft and quite easy to damage. In our experiments with a PTGS for soft x-ray (0.3–30 nm) measurements several soft x-ray films such as Kodak direct exposure film, S-5F film, can be used. We used two Kodak x-ray films (TMG/RA-1 and TMS/RA-1) in the experiments but most of the results were obtained with TMG/RA-1.

V. THE EXPERIMENTS

Two experiments were performed: one in the laser plasma facility (LPP) and the other in the plasma focus laboratory (PFL) as shown in Fig. 2. The LPP experiment was carried out on Nd glass of the laser facility with a laser pulse of 5 J of 1.064 μm light in a FWHM of 1 ns. The laser beam was focused to an 80- μm -diam spot onto the flat surface of a Au (or Al) target with an aspheric lens. The power density on the target was $4 \times 10^{13} \text{ W/cm}^2$. The LPP device was described in detail in a previous paper.⁸

The x-ray emission from a 3 kJ plasma focus¹⁵ was studied. The system had a total capacitance of 30 μF and an internal inductance of 110 nH and can be operated at a charging voltage of up to 15 kV. The standard operating conditions of the single-pulse, discharge system was in the 11–15 kV range with a neon or argon gas filling pressure between 2.0 and 4.5 Torr. The input energy varied from 1.8 to 3.3 kJ under these operating conditions. The machine parameters that were varied in this work were the filled gas pressure, the capacitor charging voltage, and the inner electrode configuration. The CPF device was described in detail

in previous papers.^{15,16} The spectrograms were densitometered and computer processed to obtain the spectral intensities.

VI. EXPERIMENTAL DATA AND RESULTS

The new PTGS developed in this work enabled us to study a wide range of soft x-ray emission characteristics in both the LPP and PF systems. The PTGS has two-dimensional spatial resolution and positioning of the detector is very flexible. A PTGS can be installed with two pinhole gratings as shown in Fig. 2.

The plasma x-ray sources produced by laser or PF are quite different. In general, the emission of soft x-rays from a LPP is very bright and confined to a small spot. PF x-ray emission is high intensity, from a cylinder, and has a wide spectral emission range. Viewed end on it approximates a spot source but with a fairly large diameter. The properties of the plasma sources demanded that our PTG spectrograph must have a flexible adjustment system. Moreover there is a strong shock wave associated with the expansion of the hot dense plasma. The spectrograph was designed to accommodate this strong shock.

A typical spectrum of the laser plasma x-ray emission obtained by a PTGS with a diameter of 50 μm is shown in Fig. 3(a). The photo or spectrogram from the same LPP source using a 25 μm PTGS taken at the same time is shown in Fig. 3(b).

The x-ray spectrogram shown in Fig. 3 consists of three spectral bands. The bands are classified according to atomic structure. The O band is from electron transitions to the O shell in Au ions and the N band is from the N-shell electron transitions. The intensity of the O band is strongest, and the intensity of the N band is stronger than that the P band. This implies that the majority of the ions in the plasma is in the region of Au⁺⁷ to Au⁺⁹. We can predict that, if we increase (or decrease) the intensity of the incident laser or the plasma electron temperature, a stronger intensity of N-band (or P-band) soft x-ray radiation would be observed.

Another interesting phenomenon is that the relative intensity of O bands and N bands in Fig. 3(a) is quite different from that in Fig. 3(b) although they are obtained from the same x-ray source. From the geometry of the grating and their diameters ($D_a = 50 \mu\text{m}$ and $D_b = 25 \mu\text{m}$), the intensity of soft x-rays obtained by the 50- μm -diam grating should be four times as large as that from the 25- μm -diam grating. However, the microdensitograms of the spectrograms exhibit almost the same density for the two O bands and about three times the difference for the two N bands shown in Figs. 3(a) and 3(b). This could be because the intensities of the O bands are so strong that they saturate the x-ray film. This would result in a higher error in the estimation of the relative intensity for the O band in Fig. 3. However, the intensities for the N-band radiation are not so strong and would still be in the linear region of the response curve of the x-ray film.

Generally the x-ray energy obtained by a PTGS with a diameter of 50 μm is always larger than that obtained by a PTGS with a smaller diameter. It is quite difficult to record P-band spectral emission from LPP using a small grating [see Fig. 3(b)]. The FWHM $\Delta\lambda$ of O-band and N-band spec-

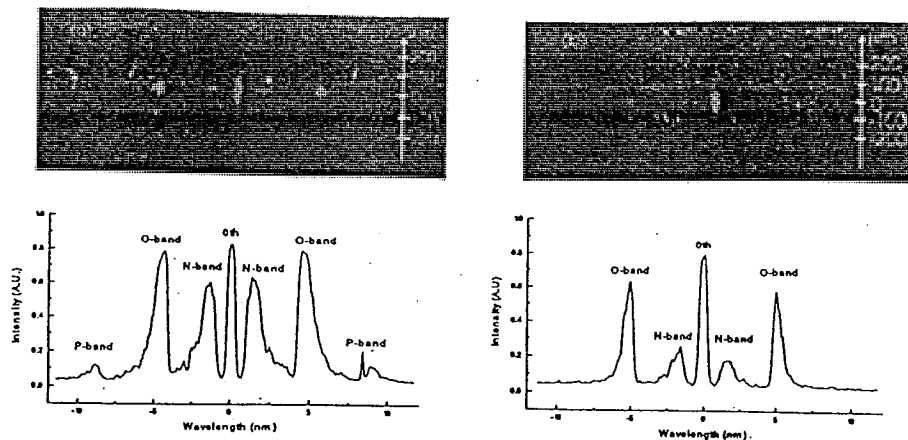


FIG. 3. X-ray spectra from an Ar target irradiated with a laser pulse intensity of 10^{13} W/cm² using (a) a PTGS with diameter of $D_a = 50 \mu\text{m}$ and (b) $D_a = 25 \mu\text{m}$. The microdensitometer tracings of the spectrograms are obtained at $x=0$, in which the intensity of the O band is strongest.

tra in Fig. 3(a) is also larger than that in Fig. 3(b). According to the density distribution on the film and the geometry of the spectrograph together with Chaker's and Shnopper's methods of data processing,^{11,17,18} the real distribution of the emitted x-ray spectral lines can be obtained. A detailed description of the real distribution was also presented in Li's thesis. When the x-ray film is overexposed, it becomes difficult to get the real distribution of the x-ray intensity.

The various degrees of ionization, spectral lines with different intensity distributions and different spatial structures, were obtained. Following the method described in Sec. II, we identified and classified those spectral lines which belong to the electron transitions of N-, O- and P-band neon ions over the wavelength range of 1.1–10 nm. The intensity of the O-band spectrum is highest and the area in which that ion is observed is the largest. The x-ray continuum is emitted primarily near the surface of the target. Figures 4(a) and 4(b) present microdensitograms of the 0th order and other spectral band intensity spatial distributions.

The spatial region and the intensity of x-ray emission from the LPP increase thereby increasing laser irradiance on the target. A large plasma source can result in serious spectral line overlap.

It is very easy to align and take various images of

sources and x-ray spectra from LPP with PTGS. It was observed that the focused plasma produced in neon gas filled plasma focus emits strong hydrogenlike and heliumlike line radiation superimposed onto a relatively low background of the free-free and free-bound continuum. However, it is more difficult in PF experiment because of its different characteristics. The first factor is the strong shock wave.¹⁹ We needed to install a pinhole in front of the PTGS to minimize the shock wave effect. The strong shock wave is formed after the x-ray emission phase. The characteristics of the shock wave in plasma focus are similar to those produced in the electromagnetic shock tube. This shock wave propagates into a neutral, nonconducting gas and would break the foil (window) and PTG if we were to choose a pinhole with a diameter of 4 nm or larger as the aperture in front of the PTGS. We cannot select a pinhole with too small a diameter because a very small pinhole will limit the region of measurement and make the system more difficult to align. Usually, a pinhole with a diameter of 2 nm was used with the PTGS. The second factor is that there is a larger bright visible radiation source in addition to the x-ray source,²⁰ and we had to use an Al foil to block out the visible light. The Al foil absorbs part of soft x-ray energy. In particular, it prevents some of the extreme ultraviolet (UV) radiation (wavelength 5–50 nm) from pass-

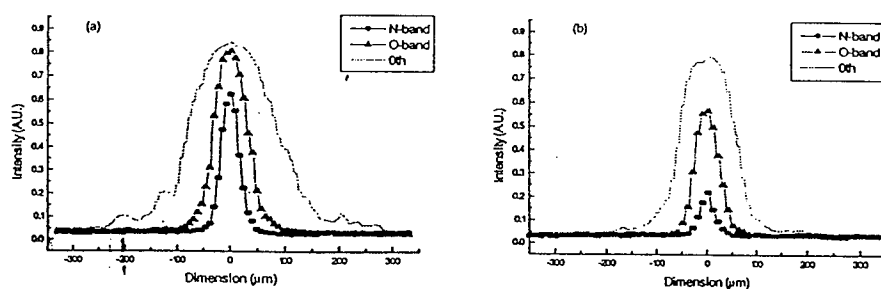


FIG. 4. (a), (b) The spatial distributions of the x-ray intensities from the curves in Figs. 3(a) and 3(b).

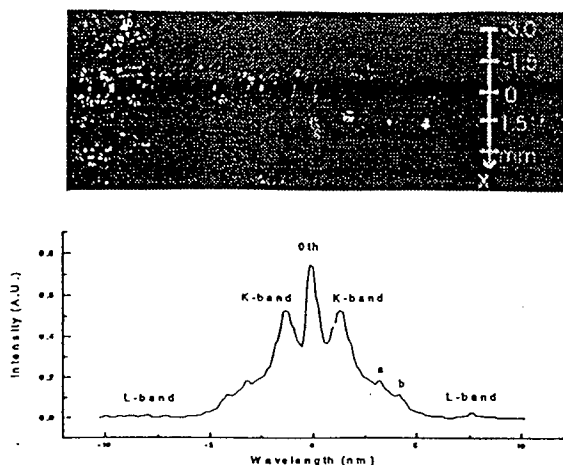


FIG. 5. X-ray spectrum emitted from PF and its microdensitometer tracing of the spectrogram at $x=1.5$ mm. The diameter of the PTGS is $D=50$ μm .

ing through the PTGS onto the recording film. The absorption for 3 nm soft x-rays is almost 20 times more than that for 0.8 nm x-rays if the attenuating coating is made of a 100-nm thick Formvar film plus a 400-nm-thick aluminum film.⁸ We also could not use too thin a foil as the window because of the strong shock wave. Therefore, two or three pulses of x-ray radiation from the PF are used to achieve the x-ray energy required to expose the film.

A typical example of the spectrum obtained from Ne filled PF is shown in Fig. 5. X-ray radiation comes mainly from electron transitions of K and L band in neon ions. It is very difficult to identify a single spectral line in Fig. 5. Comparing this to soft x-ray spectral results obtained by a (CS) under the same experimental conditions, it is deduced that the K band consists mainly of electron transitions of $1s-np$ lines from the H-like ion and $1s^2\ s2p$ lines from the He-like ion, and the L band consists mainly of lines from the electron transition from the Li-like neon ion. An example of the spectrum obtained by CS from a Ne gas-filled PH is shown in Fig. 6.

The intensity of the satellite spectrum is in general, quite weak and the spectral peak intensities from electron transition $1s-np$ states of H-like ions are slightly stronger than those of He-like ion lines. The spectral solution is not very

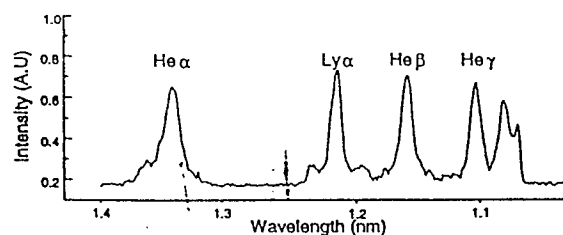


FIG. 6. Microdensitometer trace of the x-ray emission spectrum emitted from a highly ionized neon plasma.

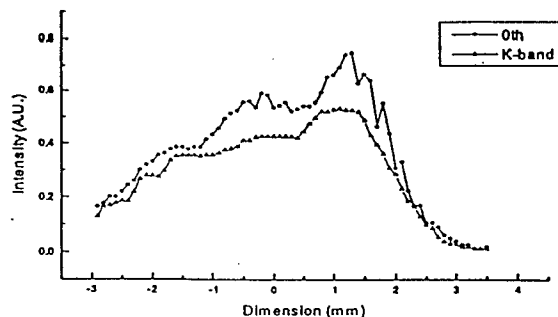


FIG. 7. Spatial distributions of x-ray intensities in response to the curves in Fig. 5.

good. One of reasons for this poor solution is that x-ray source broadening on the spectral line is quite large. The diameter of the plasma x-ray source is estimated to be 350 μm . By comparing curves in Fig. 3 to that in Fig. 5, one would also observe that there is a big difference in their spectral resolution and spectral overlap.

In Fig. 5, we also observe two lines marked a and b . Line λ_a may be second-order diffraction of the K band because $\lambda_a=2\lambda_{K\text{ band}}$, and the radiation of λ_b is from impurity ions.

Figure 7 shows the spatial distributions of 0th-order diffraction spectrum and K -band intensities along the x -axis direction. In the image the plasma emission is a thin column 7 mm long. The spatial distribution of intensity shows a non-uniform structure. This structure, in fact, is mainly due to a cloud of plasma situated in the space between the electrodes that has several localized bright spots.

A similar study of plasma soft x-ray emission features from Ar gas filled PF was also made. We still observed a few clear spectral lines. The strongest band of soft x-ray emission was localized in the 2.7 nm wavelength region. We identified those lines as L -shell emission from Ar ions.

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Microcomputer Simulated Experiments in the Teaching of Multi-Channel Laser System in an Undergraduate Course

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In this article, the authors describe the use of microcomputer simulated experiments in teaching the multi-channel laser system in an undergraduate course. The simulation described here was carried out by students in the context of a Year 4 undergraduate physics laboratory course on pulse technology. The objective of the course was to give the students experience in computation pulsed electrical circuits and in comparing the computation with experiments. To help students understand the sequence of firing of this multi-channel system, we use microcomputer simulated experiments based on circuit analysis and numerical computation with microcomputers. Firstly, the system of equations is kept simple at the level of Kirchhoff's rules applied to a time-dependent coupled circuit. Secondly, the numerical integration uses the simplest linear approximation. The prediction from the computation of the "prolong sequencing" of five laser channels has been verified experimentally. The results show that the microcomputer simulated experiments provide a powerful tool for a more comprehensive understanding of the multi-channel laser system.

As microcomputers become more powerful, it is not surprising that microcomputers will play an important role in physics experiments, simulated experiments (Cordes, 1990), and in the teaching of undergraduate science courses (Danesh, 1991; Venugopalan, 1990; Campanario, 1990). Even with the basic programming language, the use of microcomputer analysis

will provide a powerful tool in the understanding of pulsed laser systems. The computation simulation discussed in this paper was carried out by students as part of a series of activities in the context of a Year 4 undergraduate physics laboratory course on pulse technology. The objective of the course was to give students experience in simulating pulsed electrical circuits based on coupled second-order differential equations. The series of activities started with computation of a single L-C-R mesh with resistance (R) adjusted, so that with the fixed values of inductance (L) and capacitance (C), solutions exhibited the three modes of oscillation. These results were compared with experimental measurements. The other activities included a 10-mesh, L-C network which the students modelled and simulated to obtain computer solutions which they then compared with the "square" voltage pulse measured experimentally across a matched resistor R at the output mesh.

In order to engage the students in more challenging and contemporary work using the same simple computational methods, the next part of the course introduced the students to circuit computation involving existing pulsed plasma and laser devices. To keep the models manageable, inductances and resistances were assumed constant. Some of the computed results, particularly those involving the oscillatory discharge, currents, voltages, and time sequences, were compared with experiments.

At the end of the course, a review was held with the students to decide which material should be expanded or deleted for future courses. The students were of the opinion that the simulation of the nitrogen laser was the most interesting and challenging and should be retained as an integral part of the course. Based on this experience we believe that microcomputer simulated experiments give a ready and interesting approach to the understanding of important aspects of pulsed circuitry, enabling, for example, laser electrical parameters such as the pulsed laser current powering the lasing to be computed and optimised as a function of the laser inductance and capacitance treated as controllable parameters.

MULTI-CHANNEL SEQUENCE NITROGEN LASER SYSTEM

In a recent development, three nitrogen lasers were connected as an electrical network so that the lasers were fired in sequence (Lee et al., 1989). The system has the potential of multiframeing at precise intervals of a few nanoseconds with each frame having the full power of a single nitrogen laser pulse. This had been predicted by a simple computation based on circuit analysis. We consider here the multi-channel lasers to be fired in sequence as shown in Figure 1.

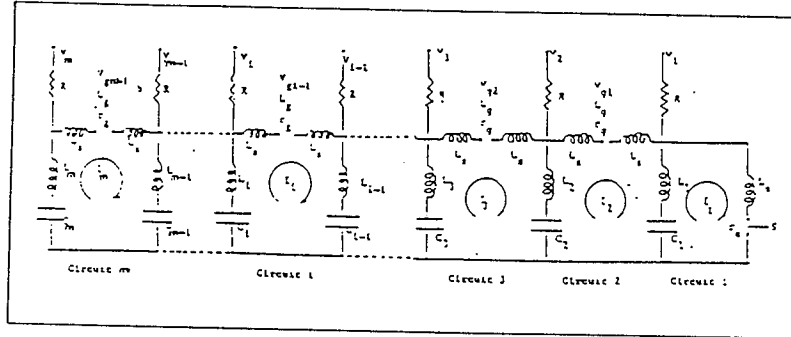


Figure 1. Circuit diagram of the multi-channels sequenced nitrogen laser system

In the circuits, L , C , and R , are the inductance, capacitance, and resistance respectively. I is the current and V is the charging voltage.

Before applying Kirchhoff's laws to "complicated" circuits, we first reviewed Kirchhoff's loop rules which state that

1. the sum of the potential differences (V) around a closed loop is zero, or

$$\sum \Delta v = 0 ;$$

2. the sum of the currents (I) entering a junction is equal to the sum of the currents leaving the same junction, or

$$\sum I_{in} = \sum I_{out} .$$

Applying Kirchhoff's loop rules to the single L-C-R circuit when the circuit is driven by an emf (ϵ), gives

$$\epsilon - IR - \frac{Q}{C} - L \frac{dI}{dt} = 0, \text{ or}$$

$$\epsilon - IR - L \frac{dI}{dt} - \frac{\int Idt}{C} = 0$$

where Q is written as $\int Idt$.

We then applied Kirchhoff's law on currents and voltages to our complicated circuit. We wrote the general circuit voltage equations in the following manner:

$$(L_g + L_1) \frac{dI_1}{dt} - L_1 \frac{dI_2}{dt} + r_g I_1 = V_1 - \frac{\int (I_1 - I_2) dt}{C_1} \quad [i = 1] \quad (1)$$

$$\begin{aligned} (2L_g + L_g + L_{i-1} + L_i) \frac{dI_i}{dt} - L_i \frac{dI_{i+1}}{dt} - L_{i-1} \frac{dI_{i-1}}{dt} + r_g I_i \\ = (V_i - V_{i-1}) + \frac{\int (I_{i+1} - I_i) dt}{C_i} + \frac{\int (I_{i-1} - I_i) dt}{C_{i-1}} \quad [i=2, \dots, m] \end{aligned} \quad (2)$$

$$\begin{aligned} V_{g1} = (V_{i+1} - V_i) + \frac{\int (I_i - I_{i+1}) dt}{C_i} - \frac{\int (I_{i+1} - I_{i+2}) dt}{C_{i+1}} + L_i \frac{dI_i}{dt} \\ + L_{i+1} \frac{dI_{i+2}}{dt} - (2L_g + L_i + L_{i+1}) \frac{dI_{i+1}}{dt} \quad [i=1, 2, \dots, m-1] \end{aligned} \quad (3)$$

To simplify the system of equations, the variables of the equations were normalized in the following manner:

$$\tau = t/t_0,$$

where the unit time was referenced to the characteristic discharge time of the branch $L_1 - C_1$, that is, $t_0 = \sqrt{L_1 C_1}$; also a unit current was referenced to the undamped discharge current amplitude of the $L_1 - C_1$ branch, that is, $I_0 = V_1 / \sqrt{L_1 / C_1}$. Also

$$i_1 = I_1 / I_0, i_2 = I_2 / I_0, \dots, i_i = I_i / I_0,$$

and

$$v_{g1} = V_{g1} / V_1, v_{g2} = V_{g2} / V_1, \dots, v_{gi} = V_{gi} / V_1.$$

We thus obtained the following normalized equations:

$$\frac{dv_1}{d\tau} = (1 - f(v_1 - v_2)) \frac{dv_2}{d\tau} - \alpha_e v_1 / (1 + \beta_e) \quad [i = 1] \quad (4)$$

$$\begin{aligned} \frac{dv_i}{d\tau} = & [(v_i - v_{i-1}) + (\int (v_{i+1} - v_i) d\tau / \delta_i) + \int (v_{i-1} - v_i) d\tau / \delta_{i-1} \\ & + \beta_i \frac{dv_{i+1}}{d\tau} + \beta_{i-1} \frac{dv_{i-1}}{d\tau} - \alpha_g v_i] / (\beta_{i-1} + \beta_i + \beta_g + 2\beta_s) \\ & [i = 2, 3, \dots, m] \end{aligned} \quad (5)$$

$$\begin{aligned} v_{gi} = & (v_{i+1} - v_i) + (\int (v_i - v_{i+1}) d\tau / \delta_i) - (\int (v_{i+1} - v_{i+2}) d\tau / \delta_{i+1}) \\ & + \beta_i \frac{dv_i}{d\tau} + \beta_{i+1} \frac{dv_{i+2}}{d\tau} - (2\beta_s + \beta_i + \beta_{i+1}) \frac{dv_{i+1}}{d\tau} \quad [i=2, \dots, m-1] \end{aligned} \quad (6)$$

The scaling parameters were

$$\begin{aligned} \beta_e &= L_e / L_1, \beta_2 = L_2 / L_1, \beta_3 = L_3 / L_1, \dots, \beta_i = L_i / L_1, \\ \beta_s &= L_s / L_1, \beta_g = L_g / L_1, \\ \delta_2 &= C_2 / C_1, \delta_3 = C_3 / C_1, \dots, \delta_i = C_i / C_1, \\ v_2 &= V_2 / V_1, v_3 = V_3 / V_1, \dots, v_i = V_i / V_1, \end{aligned}$$

and

$$\alpha_e = r_e / \sqrt{(L_1 / C_1)}, \alpha_g = r_g / \sqrt{(L_1 / C_1)}$$

where r_e and r_g were, respectively, the spark gap and laser channel resistance, and the preset breakdown voltages of the laser channels were written, normalized to V_1 , as $F_1, F_2, F_3, \dots, F_i$.

INTEGRATION USING MICROCOMPUTER

Equations (4) and (5) were treated as coupled second-order differential equations to be numerically integrated step by step. These equations were considered as m coupled equations for solving the m time-dependent variables i_i 's, thus forming a closed system of equations provided we had additional relationships connecting the current integrals with the corresponding currents and with the corresponding current derivatives. Two additional equations were needed for each current i_i . No new generating equations were needed for these additional equations. Instead any linear approximations could have been used. For example, we could use the following schematic to obtain succeeding quantities (step $n+1$) from preceding quantities (step n):

$$(f i_i d\tau)_{n+1} = (f i_i d\tau)_n + (i_i)_n \Delta\tau + \left(\frac{di_i}{d\tau} \right)_n (\Delta\tau)^2 \quad (7)$$

and

$$(i_i)_{n+1} = (i_i)_n + \left(\frac{di_i}{d\tau} \right)_n \Delta\tau \quad (8)$$

where $\Delta\tau$ is the time step from step n to step $(n+1)$, and a quantity subscripted $n+1$ denotes the value of that quantity at the $(n+1)$ th time step to be computed from relevant quantities at the n th step whose values are denoted by subscripts of n .

To complete the numerical scheme, we also wrote the governing equations in a form suitable for numerical step-by-step computation. They were

$$\left(\frac{di_i}{d\tau} \right)_{n+1} = \left[1 - (f(i_i - i_{i+1}) d\tau)_{n+1} + \left(\frac{di_i}{d\tau} \right)_n - \alpha (i_i)_{n+1} \right] / (1 + \beta_s) \quad [i=1] \quad (9)$$

and

$$\begin{aligned} \left(\frac{dv_i}{d\tau} \right)_{n+1} &= [(v_i - v_{i-1}) + \left(\int (v_{i+1} - v_i) d\tau \right)_{n+1} / \delta_i + \left(\int (v_{i-1} - v_i) d\tau \right)_{n+1} \\ &+ \beta_i \left(\frac{dv_{i+1}}{d\tau} \right)_n + \beta_{i-1} \left(\frac{dv_{i-1}}{d\tau} \right)_{n+1} - \alpha_g(v_i)_{n+1}] / (\beta_{i-1} + \beta_i + \beta_g + 2\beta_s) \\ &[i = 2, 3, \dots, m] \end{aligned} \quad (10)$$

The computer program for computing the numerical integration is shown in the Appendix. To check the accuracy of the approach of numerical computation, the time incremental steps were set to 0.002, 0.001, and 0.0005 for each corresponding computation. Because the results were almost identical, we deduced that the computer program and the method of computation were acceptable.

MICROCOMPUTER SIMULATED EXPERIMENTS OF MULTI-CHANNEL LASER SYSTEM

The equations, numerical method, and the computer program were developed for computing voltages across the laser channels and laser currents of multi-channel sequenced nitrogen lasers. In this paper, we discuss the simulated experiments of the prolonged sequencing mode of a five-channel sequenced nitrogen lasers system.

In this case study, a system with identical laser heads and with all capacitors identical and charged to the same voltage was considered. The parameters were

$$\begin{aligned} L_c &= 12 \text{ nH}, L_1 = L_2 = L_3 = L_4 = L_5 = L_6 = 0.15 \text{ nH}, \\ L_g &= 0.1 \text{ nH}, L_s = 0.1 \text{ nH}, \\ C_1 &= C_2 = C_3 = C_4 = C_5 = C_6 = 10 \text{ nF}, r_g = 0.08 \Omega, \\ r_c &= 0.12 \Omega, V_1 = V_2 = V_3 = V_4 = V_5 = V_6 = 16 \text{ kV}, \end{aligned}$$

giving scaling parameters of

$$\begin{aligned} \beta_c &= 80, \beta_2 = \beta_3 = \beta_4 = 1, \beta_g = 0.7, \beta_s = 0.7, \\ \delta_2 &= \delta_3 = \delta_4 = \delta_5 = \delta_6 = 1, \alpha_g = 0.7, \alpha_c = 1, \\ v_2 &= v_3 = v_4 = v_5 = v_6 = 1, \text{ and } F_1 = F_2 = F_3 = F_4 = F_5 = 1.3 \end{aligned}$$

Here $t_0 = \sqrt{L_1 C_1} = 1.2$ ns, $I_0 = 130$ KA. The results of the simulated experiments are shown in Figure 2, and the laser pulses have the following characteristics for the first three laser channels.

First pulse : amplitude = $0.43 I_0$, FWHM of Power = $2.5 t_0$;
 Second pulse : amplitude = $0.45 I_0$, FWHM of Power = $2.3 t_0$;
 Third pulse : amplitude = $0.44 I_0$, FWHM of Power = $2.2 t_0$;

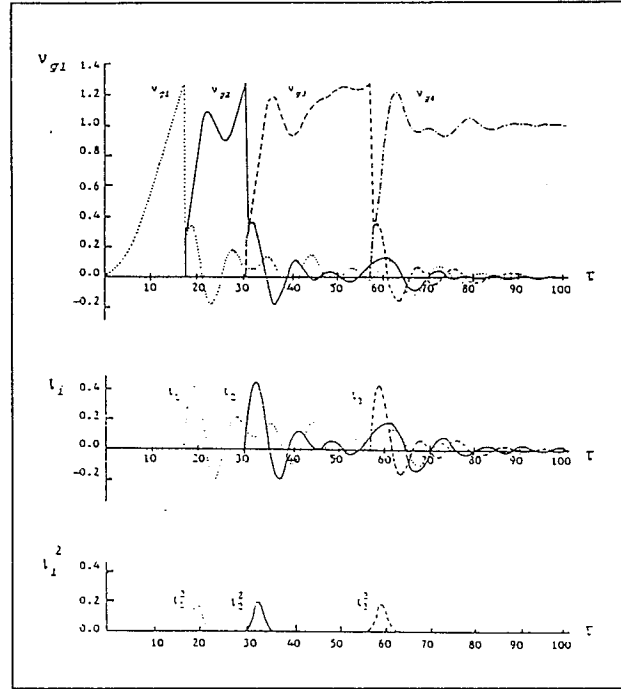
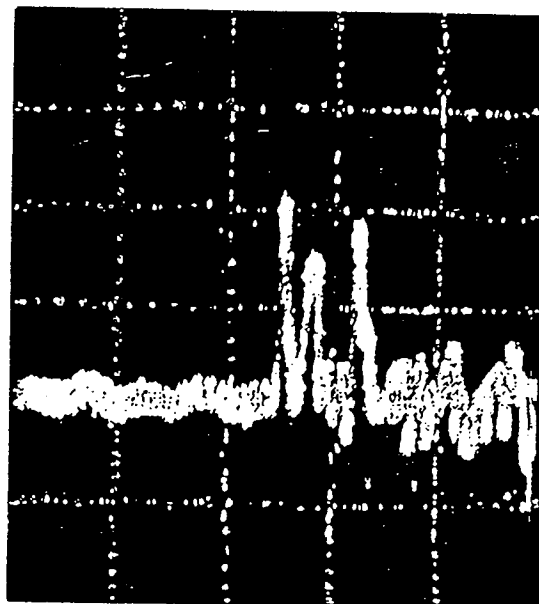


Figure 2. Computed voltages across the laser channel, laser currents, and laser currents squared as functions of time. Parameters used are those for a "prolong sequencing" mode.

These are the pulses responsible for producing the nitrogen laser pulses, and the three pulses separated, respectively, by $12.9 t_0$ and $26.6 t_0$. That is, a relatively widely spaced laser pulse was predicted. However, the voltage crossing laser Channel-4 was unable to reach the preset value, so no laser pulse occurred in this laser channel. No laser pulse was predicted also in laser Channel-5. The predictions based on computation were consistent with the experiments in which only three pulses appeared on the oscillogram as shown in Figure 3.



Time scale: 100ns/division

Figure 3. Oscillogram of photodiode signal monitoring the five-channel sequenced nitrogen laser operated in the prolonged sequencing mode; time scale: 100 ns/div. Shot with three laser pulses in "prolonged sequence."

SUMMARY

The above example, the simulated experiments of the "prolonged sequence" mode, illustrate that an electrical network based on Kirchhoff's rules for circuit currents and voltages can be used for firing and powering several nitrogen lasers in sequence. The predictions from the simulated experiments, based on the simple computation of prolonged sequence mode, have been tested experimentally with an arrangement of five nitrogen lasers having identical capacitances and charged to the same voltage. This gives confidence that simulated experiments from simplifications

of computations highlighted in this study have not detracted from the power and usefulness of circuit analysis applied even to such apparently complex cases. Thus, we believe that a good computer simulated experiment can be used effectively in teaching complicated physical concepts and events.

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APPENDIX

```

10 REM Sequential Laser-PS-laser
100 J2=6:K1=250:N1=100:J1=J2+2:XX=5
110 DIM R(J1),Q(J1),I(J1),V(J1),D(J1),B(J1),M(J1),F(J1),X(J1)
120 READ BG,BS,AE,AG,D
130 LPRINT BG,BS,AE,AG,D
140 FOR J=1 TO J2
150 READ D(J),B(J),M(J),F(J)
160 LPRINT D(J),B(J),M(J),F(J)
170 NEXT
180 T=0:S(1)=1/(1+B(1))
190 SCREEN 1,0,0
200 CLS
210 FOR K=1 TO K1
220 FOR N=1 TO N1
230 T=T+D
240 J=0
250 J=J+1
260 IF J>J2 THEN GOTO 320
270 GOSUB 1200
280 IF V(J)>F(J) THEN GOSUB 1300
290 IF X(J)=1 THEN GOTO 250
296 IF V(J)>F(J) THEN LPRINT J,T,V(J)
300 IF V(J)>F(J) THEN X(J)=1
310 NEXT N
320 GOSUB 1300
340 NEXT K
350 STOP
360 END
300 DATA 0.7,0.7,1.0,0.7,0.005
310 DATA 1.50,1.1,1.5
320 DATA 1.1,1.1,1.5

```

APPENDIX (continued)

```

S30 DATA 1.1,1.1,1.3
S40 DATA 1.1,1.1,1.3
S50 DATA 1.1,1.1,1.3
S60 DATA 1.1,1.1,1.3
1200 Q(J)=Q(J)+I(J)*D+.5*R(J)*D*D
1210 I(J)=I(J)+R(J)*D
1230 IF J>1 THEN GOTO 1255
1240 R(J)=(1-Q(J)+Q(J+1)+R(J+1)-AE*I(J))/(1+B(J))
1245 V(J)=(M(J+1)-1)+(Q(J)-Q(J+1))/D(J)-(Q(J+1)-Q(J+2))/D(J+1)+R(J)+B(J+1)*R(J+2)
      )-(1+2*BS+B(J+1))*R(J+1)
1250 GOTO 1270
1255 IF J>2 THEN GOTO 1260
1256 R(J)=(M(J)-M(J-1)+(Q(J+1)-Q(J))/D(J)+(Q(J-1)-Q(J))/D(J-1)+B(J)*R(J-1)-R(J-1)
      )-AG*I(J))/(1+B(J)+BG+2*BS)
1257 GOTO 1265
1260 R(J)=(M(J)-M(J-1)+(Q(J+1)-Q(J))/D(J)+(Q(J-1)-Q(J))/D(J-1)+B(J)*R(J-1)-B(J-1)
      )*R(J-1)-AG*I(J))/(B(J-1)+B(J)-BG+2*BS)
1265 IF J=J2 THEN GOTO 1270
1266 V(J)=M(J+1)-M(J)+(Q(J)-Q(J+1))/D(J)-(Q(J+1)-Q(J+2))/D(J+1)+B(J)*R(J)+B(J+1)
      *R(J+2)-(2*BS+B(J)+B(J+1))*R(J+1)
1270 RETURN
1300 X=T*XX
1305 FOR JJ=1 TO J2-1
1310 VG=160-V(JJ)*80
1335 PSET(X,VG)
1340 NEXT
1350 RETURN
1360 PSET(X,IG)
1370 IG=160-I(JJ+1)*[(JJ+1)*80
:
1380 IG=160-I(J+J)*80

```

Electron lithography using a compact plasma focus

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Abstract. A 1.6 kJ plasma focus source was demonstrated as an electron source for microlithography. Resolution better than $0.5\ \mu\text{m}$ was obtained. The total energy in the beam and the energy of electrons was estimated from the lithographs to be $>20\ \text{mJ}$ per shot with energy $>20\ \text{keV}$ and $>1\ \text{J}$ with energy $\sim 10\ \text{keV}$.

1. Introduction

The advancement of semiconductor technology has depended heavily on the development in optical lithography. However the continuing trend towards smaller-scale-length devices has pushed optical lithography to its limits due to diffraction. Current optical techniques can produce lithographs with scale lengths of the order of the wavelength of light used. The smallest wavelength used is $193\ \text{nm}$ from the ArF laser. The transmission (or lack of it) at such small wavelengths prevents the use of the sophisticated techniques required to make such lithographs. There has been interest in research into using other sources like electron beams, x-rays, EUV and ion beams for lithography since the 1980s. However each of these lithography technologies still has its associated problems which have to be solved before they become practical.

One problem associated with electron-beam lithography has been the amount of time needed for each lithograph. Traditionally, electron-beam lithography has been done by using a focused electron beam. Very small structures can be made as the beam can be focused to a very small diameter as the wavelength associated with $\sim 10\ \text{keV}$ electrons is small ($0.1\ \text{nm}$). The time taken to perform a direct write on the resist is long due to the sequential nature of this process. Higher speeds are possible if the beam is shaped [1] and even higher if a projection system [2] is used. Even in the projection systems, the masks used are relatively small compared to x-ray masks. This is because of the difficulty in producing a large-diameter high-energy electron beam and also because of the difficulty in making the rigid mask. Unlike an x-ray mask, the electron mask cannot be easily made with a transmitting rigid substrate as the transmitted electrons will be deflected in random directions by the

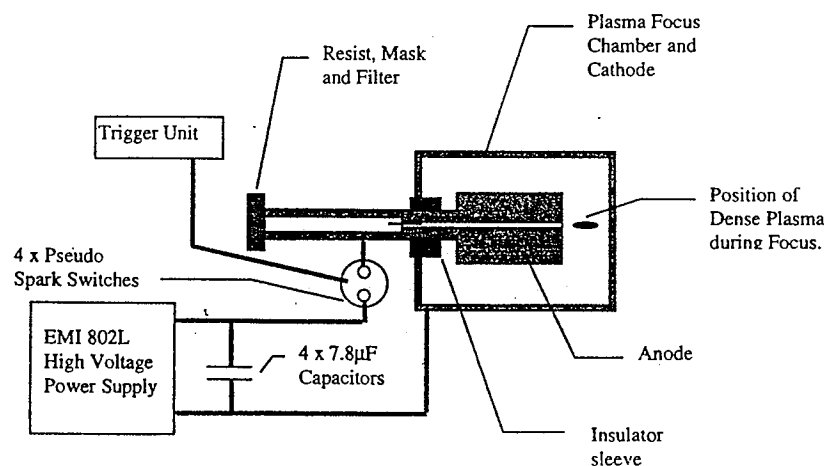


Figure 1. Schematic of the apparatus.

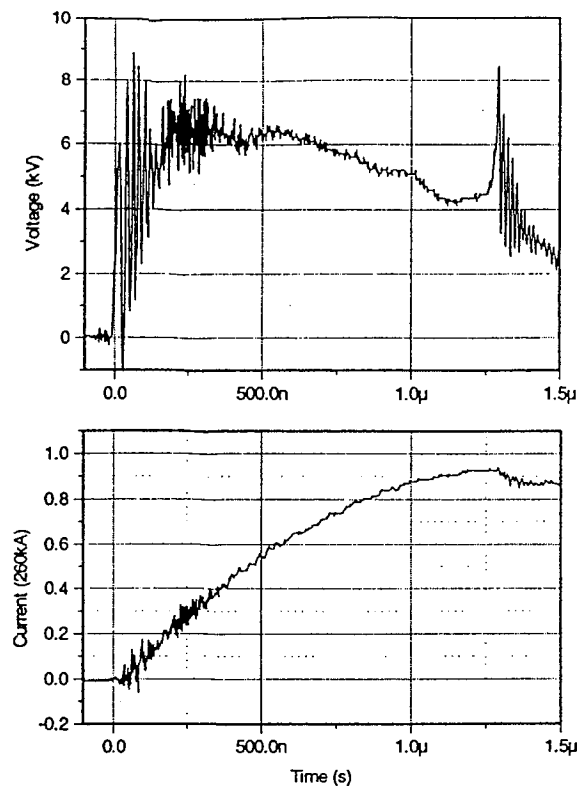


Figure 2. Electrical signals for a typical shot at 10 kV.

substrate which will reduce the resolution [3]. This is because the electron stopping power is relatively insensitive to material compared with the attenuation of x-rays which is much stronger for higher-atomic-number materials.

Energetic electron beams have long been observed in the plasma focus traveling into the positive centre electrode during the time of focus pinch. The time duration of the electron beam is about 10 ns for small ($\sim$ kJ) plasma focus. For example, Rhee *et al* [4] measured about 1 J of electrons per shot in a 1–10 kA, 10–20 ns pulse of 27–280 keV electrons from a 3 kJ focus charged to 17 kV. The conversion efficiency to electrons is not very high in comparison with conversion to soft x-rays but all the electrons can be utilized due to their directionality.

The operating principle of the plasma focus can be found from the original papers [5–8] but can be briefly described as follows:

The plasma focus consists of a coaxial electrode system separated by an insulator sleeve (see figure 1) and initially in a low-pressure gas atmosphere.

(1) Breakdown: When the switch is closed, a high voltage is applied across the electrodes. This causes a breakdown along the insulator sleeve.

(2) Run-down: The plasma formed from the gas along the insulator is lifted off from the insulator. A shock is formed from the gas which is swept in to the thin layer of shocked plasma which is pushed along, between the coaxial electrodes to the end of the anode by the force associated with the magnetic field and current flowing through the

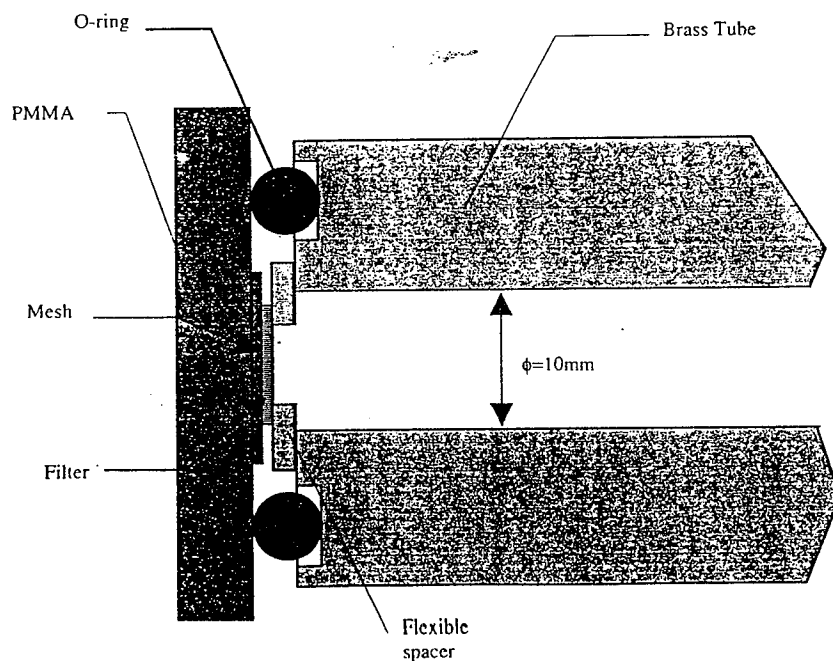


Figure 3. Diagram showing positions of filter mask and resist.

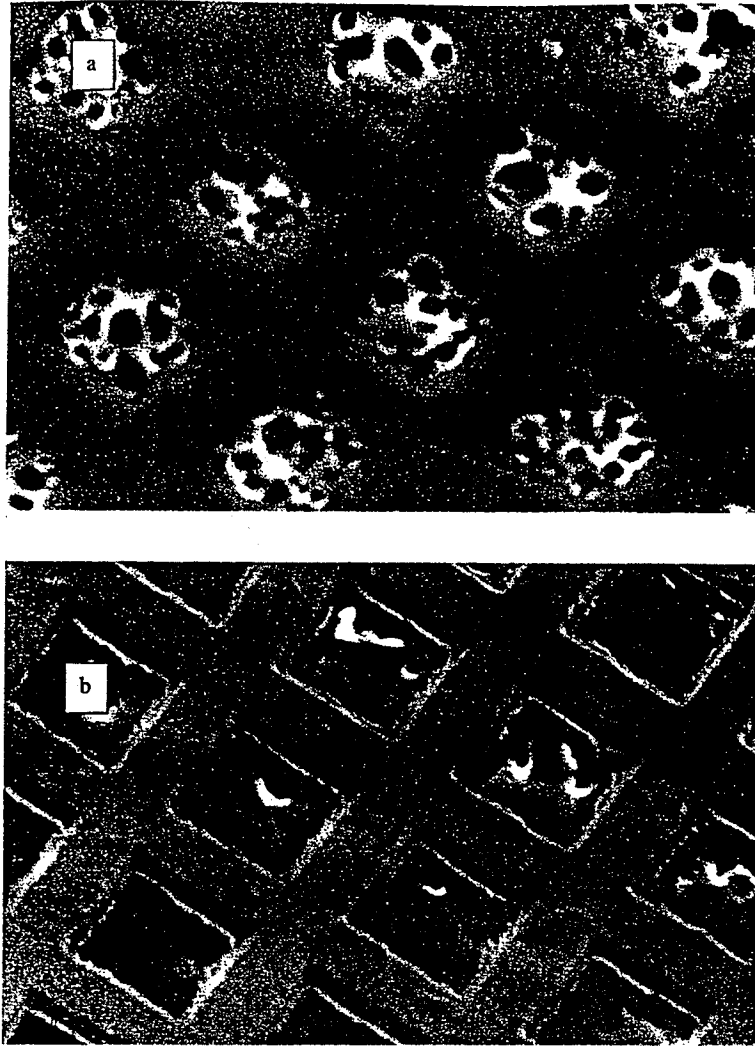


Figure 4. Images obtained from a scanning electron microscope of (a) a lithograph using 5 μm mesh, 2 μm aluminium foil and 400 shots and (b) 5 μm mesh.

plasma.

(3) Radial compression: The plasma compresses and pinches on axis at the end of the anode. During this compression, the inductance associated with the plasma focus increases rapidly as the plasma becomes a very thin column. This produces a large voltage spike across the electrodes. It is during the end of this phase that the electrons are emitted. Several mechanisms could be possible for the production of these electrons. Some examples of these mechanisms are described by Beg *et al* [9].

2. Experiment

The 4-4-4 compact plasma focus was used in these experiments. The device is a plasma focus [5-8] operated with 7 mbar of neon as the working gas and driven by a bank of four 7.8 μF capacitors switched using four pseudo

spark gaps (thyratrons) [10]. An EMI 802L high-voltage power supply was used to charge the capacitors to 10 kV. The maximum repetition rate limited by the charger is 5 shots per second. Figure 1 is a schematic of the device. The focus chamber itself [11,12] has an outer electrode (cathode) with a diameter of 5 cm and a 3.5 cm long hollow anode with a diameter of 3 cm. The electrons formed at the plasma at the tip of the anode flows through the hole in the anode to expose the resist.

The discharge current was measured with a Rogowski coil and has a risetime (quarter period) of 1.5 μs and a peak current of 230 kA. The voltage across the focus tube was measured with a Tektronix P6015A high-voltage probe. Typical oscilloscope traces of the current and voltage are shown in figure 2. The plasma focus was found to be optimized for soft x-rays when the focus event was at 1.35 μs from the current start. For optimized electron or x-ray yield, the speed of the plasma shock wave has to be

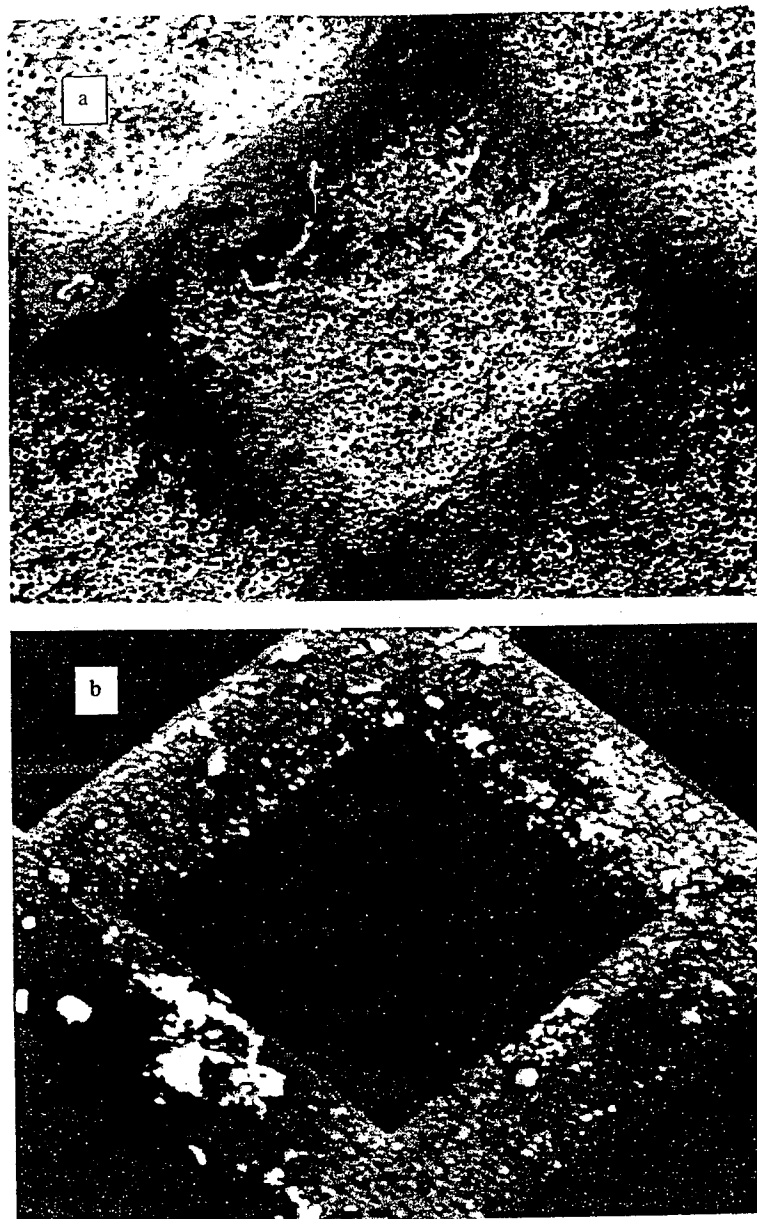


Figure 5. (a) Lithograph with 20 shots, (b) optical picture of mesh used for lithograph in (a) and figure 6.

within a certain range and the maximum compression has to occur when the current is high. Near the current peak, the current is fairly constant in time. To get the optimum speed, we can change the gas density and thus also change the time to maximum compression.

The finest mask used was a $1\text{ }\mu\text{m}$ thick gold mesh with features $5\text{ }\mu\text{m}$ in size. Figure 3 shows how the mask was held to the resist. A $2\text{ }\mu\text{m}$ aluminium filter was placed in front of the mask to protect it from the debris from the plasma focus pinch only 20 cm from the resist. The filter is also used to reduce the amount of electrons incident on the resist. In this arrangement, electrons and x-rays from the plasma focus are incident on the resist.

The resist used was thick (1.5 mm) PMMA. This was

developed after exposure with a developer [13] made of 60% diethylene glycol monobutyl ether, 20% morpholine, 5% ethanolamine and 15% water for 1–2 h at 37°C . A typical lithograph image is shown in figure 4(a).

No image was obtained when a permanent magnet with $5\text{ cm} \times 1.8\text{ cm}$ poles was placed at the tube between the anode and the resist such that the 0.2 T field is perpendicular to the focus tube axis. This shows that charged particles were responsible for the lithographic image in the absence of the magnetic field. In this case the charged particles are electrons since ions would be emitted away from the positive centre electrode. The Larmor radius of electrons with energy less than 30 keV is less than 3 mm. This means that the electrons are either deflected to miss the

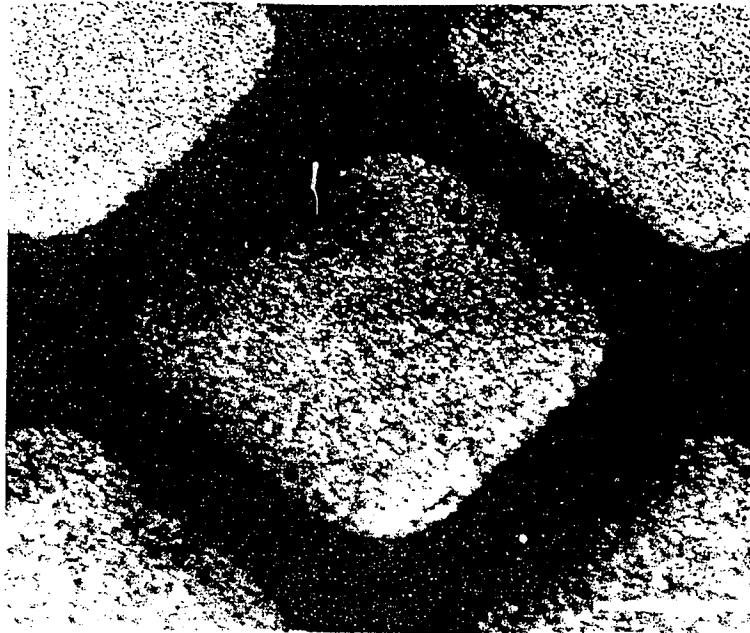


Figure 6. Lithograph obtained with 10 shots.

resist or gyrate in the magnetic field until they slow down and recombine.

3. Results

Typical results are shown in figures 4–6. The pictures of the lithographs are taken using a JEOL scanning electron microscope.

Figure 4(a) shows a lithograph obtained with an exposure of 400 shots. Figure 4(b) shows the mask used. The edge of the lithograph is smooth in figure 4(a) whereas the mesh shows irregular features finer than $0.5\ \mu\text{m}$. This is taken as the resolution of the lithograph. This is however an underestimate as the thickness of the mesh is reduced at the edges, which means the contrast of the small features would be small. Deep pits are observed in the exposed areas. The depth to which the resist can be etched is the depth to which the electrons can penetrate. The depth is about $0.5\ \mu\text{m}$ to $3\ \mu\text{m}$ inside the pits so that the energy of the electrons can be estimated from electron range tables [14] to be less than 10 keV after the filter. The energy of the electrons before the filter (up to 20 keV) was also obtained from the range tables. The amount of electrons produced by the source can be obtained from the known sensitivity [11, 15] of PMMA to electrons. The sensitivity is $500\ \mu\text{C cm}^{-2}$ for 10 keV electrons so the amount of energy required for an exposure is about $5\ \text{J cm}^{-2}$. Since 250 shots was the minimum needed for a good exposure, the electron beam energy incident on the resist per shot is $20\ \text{mJ cm}^{-2}$.

Lithographs were also obtained without using the $2\ \mu\text{m}$ Al filter. In this case less than 10 shots were needed for a good exposure. This shows that there is a much

larger number of slower ($\sim 10\ \text{keV}$) electrons capable of depositing about $1\ \text{J cm}^{-2}$ per shot on the resist.

We can see that the scattering of electrons due to the filter is important by comparing figures 5(a), 5(b) and 6. Figure 5(a) shows a lithograph taken using the $100\ \mu\text{m}$ mesh shown in figure 5(b) with a 20-shot exposure. The areas just under the wires have been exposed and etched. However this is a strongly overexposed lithograph and with a smaller exposure a better lithograph can be obtained. This is shown in figure 6 where the same mask and configuration was used but with an exposure of only ten shots.

It was found that the electron beam was wide enough to expose greater than 1 cm diameter at 20 cm from the focus. This means that the electron beam has a full angle greater than 3° which is limited by the tube leading up to the resist.

4. Discussion and conclusion

A 1.6 kJ plasma focus source was demonstrated as an electron source producing $50\ \mu\text{A}$ average current 10 keV electron beam. This can be compared to conventional electron-beam lithography systems where a current of 10 pA to 250 nA is used [3]. If $100\ \text{J cm}^{-2}$ is deposited fast enough that the heat is not conducted away, then the change in temperature is about 250°C which would damage the PMMA [3, 16]. In our experiments, marks were seen on many of the resists even before development indicating a strong overexposure or overheating. A resolution of better than $0.5\ \mu\text{m}$ was demonstrated.

Acknowledgments

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Compact plasma focus soft x-ray source with high repetition and high intensity

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ABSTRACT

We have developed two Compact Plasma Focus (CPF) devices operating in neon with high repetition rate capacity to be used as a repetitive pulse soft x-ray (SXR) source for lithography. A single capacitor module 1-1-1 (7.85 μF) was used to test high repetitive rate capability and was observed to produce soft x-rays in the wavelength range of 0.8-1.4 nm at up to 10 Hz. The discharge current rises in 1.2 μs to peak value of 140 kA at 15 kV charge. The soft x-ray yield varies with the pressure of working gas, the value and polarity of voltage applied to capacitor. On the basis of this module we have designed a four module test system for SXR designated as the NX1. The peak discharge current is 270 kA when the capacitor bank (7.8 μF $\times$ 4) is charged to 12kV. It produces 100J of soft x-ray per shot in single shot mode, in the wavelength range of 0.8 to 1.4nm and a spot size of below 1mm viewed end on. With a repetitive rate of up to 3Hz this gives 300W of average SXR power. The NX2 is a second system that has been designed and constructed. It will be operated at peak currents in excess of 300kA into water-cooled electrodes at repetitive rates up to 20Hz to produce 300W SXR in burst durations of up to 5 minutes. It is estimated that with such a SXR yield into a well designed beamline and a reasonably sensitive resist an exposure could be made in less than 10 seconds. Pushing such x-ray sources further to 2 kW output will make their intensity sufficient for SXR lithography with reasonably high throughput to be of industrial interest.

Keywords: plasma, soft x-ray source, lithography.

1. INTRODUCTION

X-ray sources have many applications, for example, in X-ray spectroscopy, microfabrication, X-ray microscopy, X-ray laser pumping, and high density micro-electronics lithography^{1,2,3,4}. It is important to develop a high quality and high intensity soft X-ray source. As an example, the lithography industry presently uses optical (uv/visible) sources for 0.5 μm feature size lithography. The optical lithography techniques are being extended to 0.18 μm now⁵. However, at smaller design rules, the use of shorter UV wavelengths leads to a rapid increase in the cost of optical lithography. X-ray techniques are being pursued for lithography with design rules below 0.25 μm .

The main sources of high intensity soft X-rays are synchrotron, laser-produced plasma⁶, and the plasma focus (PF) device⁸. The primary objective of this work is to develop a soft X-ray source suitable for lithography. The basic requirements for producing a good clear exposure are: photon energies about 1 keV, high energy, and collimation or small spot size. For a point source size of about a millimeter, the collimation requirement limits the distance from the source to not less than 30cm so that the amount of energy required from the point source for a 100 mJcm^{-2} on the resist at 30 cm is 1 kJ. Among the available X-ray sources, the synchrotron is the best for such a purpose because of its high intensity and collimation. However, the construction of the synchrotron facility is very expensive, its operating and maintenance costs are also high. The minimum installation provides 20 beams with little possibility of a smaller installation. The PF device is a cheap, compact highly reproducible source of high-temperature pulsed plasmas (typical temperature is 1 keV, typical density is 10^{19} cm^{-3}) which

does not require the sophisticated techniques or expensive facilities. The minimum installation is for one beamline. These features are very important advantages when compared with other X-ray sources.

The characteristics of x-ray emission depend strongly on the CPF device operating parameters (filling gas composition and pressure, stored energy, plasma current, driver impedance, electrode material and configuration). This makes it difficult to compare the X-ray emission results on different machines, but provides several parameters to tune the PF X-ray output.

In this work, pure neon gas is used as working gas. Experimental results show that the X-rays are emitted at the wavelength of 0.8-1.4 nm, which is suitable for lithography, for a range of gas fill pressure and capacitor charging voltage.

The maximum conversion into x-rays require the following:

- 1) good transfer from stored energy to plasma energy
- 2) good transfer from plasma energy to x-ray energy

The first condition requires a design where the focus has a large inductance compared to the capacitor bank inductance. The second condition requires that the plasma be confined at a high enough density for long enough for the x-rays to be emitted. This means that the current should be high when the focus occurs and that the speed of the plasma must be matched to that which produces a temperature where the neon ions are at the right ionization stage for x-ray emission.

2. APPARATUS

The plasma focus soft x-ray sources used in these experiments are low energy ~2kJ plasma focus operated in neon [8-9]. A general view of the NX2 is shown in figure 1

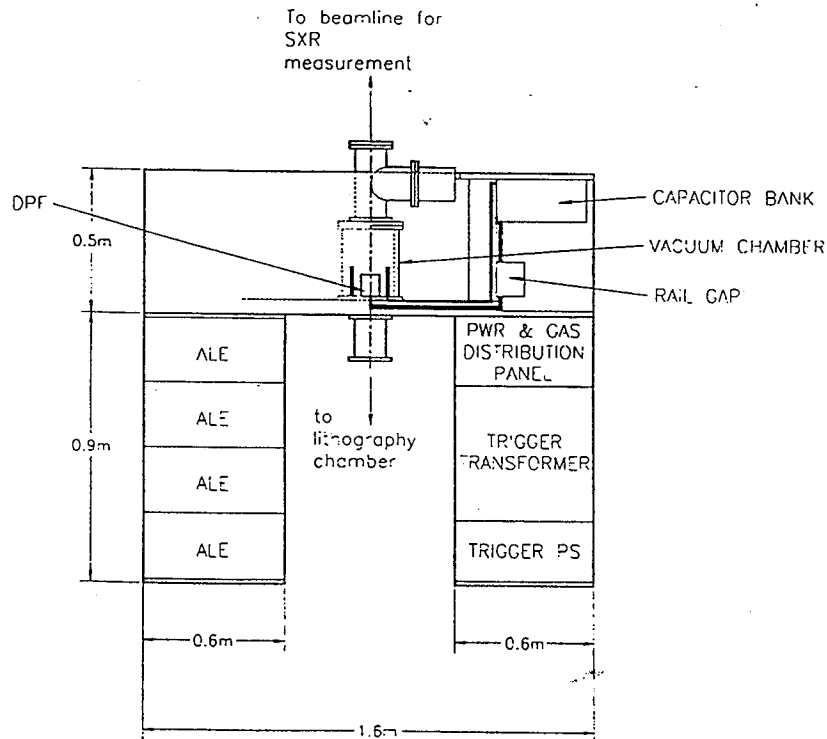


Figure 1 General overview of the NX2 apparatus

2.1 Electrical system

Both the NX1 and NX2 plasma focuses are driven by 30 μ F capacitor bank charged by ALE Systems model 802 high voltage capacitor chargers. The capacitor banks are connected to the focus via four switches. The main difference between the NX1 and NX2 electrical system is that the NX2 has a lower inductance so that higher currents are obtained with the same charging voltage with a shorter rise time. The lower inductance also means that more energy is coupled to the plasma. Table 1 summarizes the characteristics of the electrical systems. A schematic of the electrical system is shown in figure 2.

	Charging Voltage (kV)	Energy (kJ)	Repetition rate (Hz)	Current (kA)	Short circuit rise time or quarter period (μ s)
NX1	12	2.2	3*	280	1.5
NX2	11.5	2.0	20	510	1.0

Table 1 Summary of electrical characteristics

* limited by available charging power.

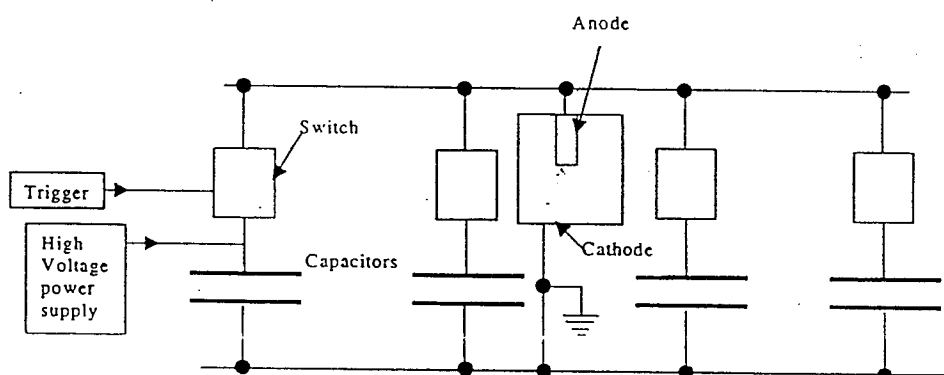


Figure 2. Schematic of electrical system

2.2 Focus chamber

Three chambers have been used with the NX1. The main difference between the three chambers is the lengths. The first chamber has a 3.5cm anode and the second chamber a 4.5cm long anode and the third a 5.5cm anode. In both cases the anode diameter is 3cm and the cathode is 5cm in diameter. Schematics of the NX1 and NX2 electrode configuration are shown in figure 3. Two anode lengths were tried with the NX2. The electrode dimensions are summarized in table 2.

An important difference between the NX1 and NX2 is that the NX2 electrodes are designed to be cooled by water. Water is circulated through the electrodes using two Bay Voltex RRS-1650-AC chillers with a total cooling capacity of 9.6kW.

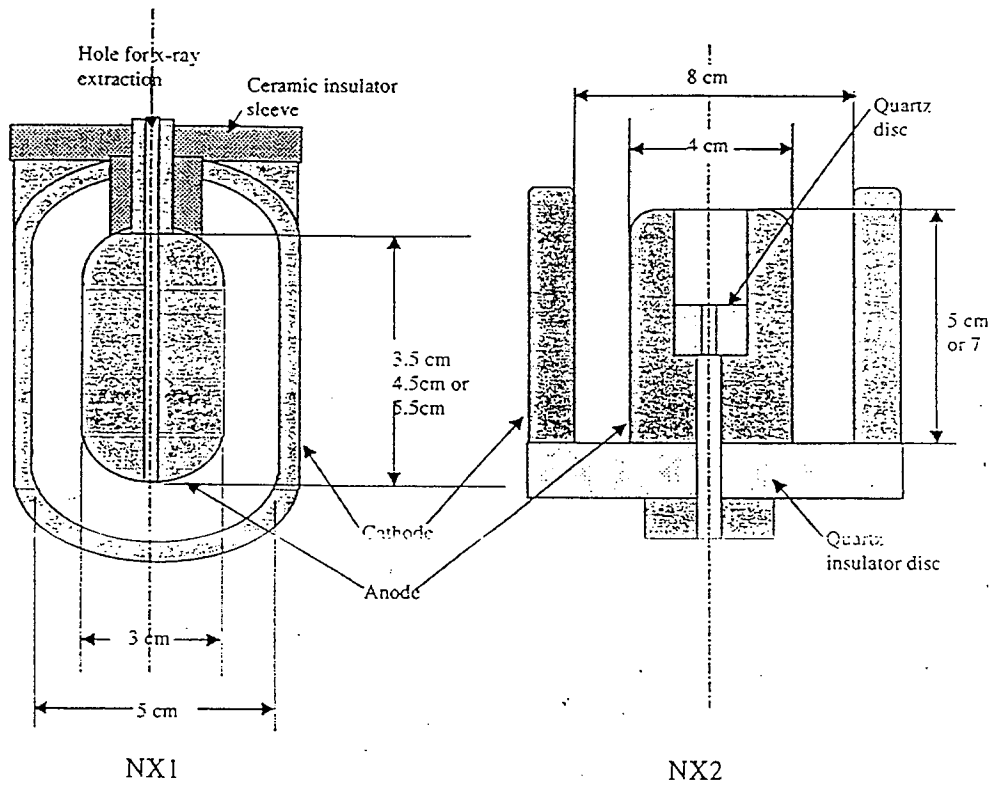


Figure 3. Schematic of focus electrode and chamber

	Anode diameter(cm)	Cathode diameter (cm)	Anode length (cm)	Electrode material	Insulator material
NX1	3	5	3.5, 4.5, 5.5	Copper	Ceramic
NX2	4	8	5, 7	Stainless steel	Quartz

Table 2 Summary of focus electrodes

3. EXPERIMENT

The diagnostics were 1mm^2 area $10\mu\text{m}$ thick PIN diodes¹⁰ and 3mm^2 photoconducting diamond (PCD). The filters used were $12\mu\text{m}$ mylar with $10\mu\text{m}$ Be and $24\mu\text{m}$ mylar with $10\mu\text{m}$ Be with the PIN diode on the NX1 and $4\mu\text{m}$ aluminum with the PCD and $12\mu\text{m}$ mylar with $4\mu\text{m}$ aluminum PIN diode and NX2. The setup used for the experiments is shown in figure 4. The x-ray measurement system is essentially the same for both the NX1 and the NX2. Figure 5 shows the sensitivity of the diodes with the $12\mu\text{m}$ mylar and $10\mu\text{m}$ beryllium filters.

Both the PCDs and the PIN diodes were used on both machines. In the case of the NX1, the x-ray was detected through the extraction hole through the anode. This means that there is also an electron beam traveling along the same path. The electrons are excluded by the application of a magnetic field to deflect the electrons and also by the $10\mu\text{m}$ beryllium which scatters the electrons. The energy of the electrons have been determined in a previous experiment¹¹

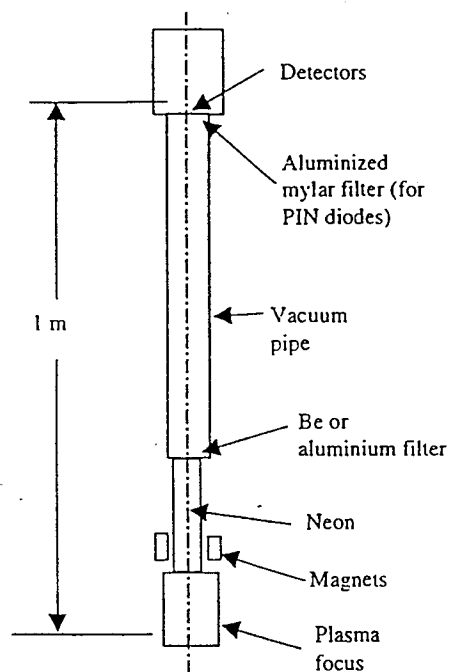


Figure 4 Experimental set up for soft x-ray measurement

The initial pressure of neon was varied and the optimum pressure was found for the various electrode lengths and for charging voltages of 10kV and 14kV. Most of the data points were repeated about 5-10 times for the NX1 and 20-200 times for the NX2.

For the NX2, A high repetition rate acquisition system consisting of a Tektronix TDS380 oscilloscope connected to a computer was used so that the x-ray for every shot up to a repetition rate of about 10 HZ could be obtained.

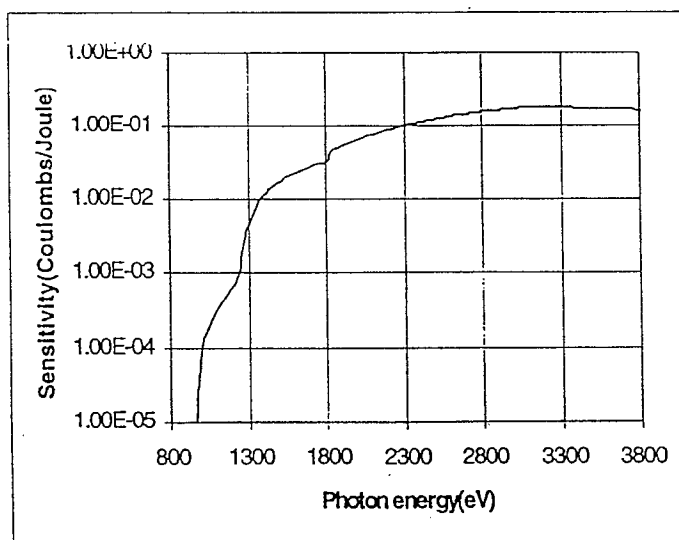


Figure 5 sensitivity of detectors

4. RESULTS

To obtain the x-ray yield from the PIN diode measurements, the area under the oscilloscope trace is obtained and the total amount of x-rays is calculated with the following equation.

$$Y_x = \frac{S(1.3keV) \times C}{T_{Ne}(1.3keV)T_{Be}(1.3keV)} \frac{\int Vdt}{R}$$

where S is the reciprocal sensitivity of the filtered pin diode (in Joules/Coulomb) at 1.3keV,
 T_{Ne} is the transmission of neon gas between the source and the beryllium filter
 T_{Be} is the transmission of the beryllium filter
R is the terminating resistance 50 ohms
V is the voltage across the terminating resistance and
C is the correction factor based on the spectrum.

From spectra obtained with a crystal spectrograph the soft x-ray energy is expected to be in mostly at 1keV and 1.3 keV with 65% in the 1keV region and 35% in the 1.3keV region¹². The yield is obtained using the calculated sensitivity S (1.3keV) of the detector with a correction factor C accounting for the spectrum. For comparison, a PCD (calibrated by AASC¹³) is also used for the yield measurement. The PCD has a flat sensitivity over the range of SXR spectrum considered. Hence interpretation of the yield is more reliable. The measurements using the two methods agree to within 20% on the NX2. All the results are adjusted to the PCD calibration for comparison.

The results from the x-ray yield measurements are shown in figure 6. Figure 6a shows that with the NX1, it is possible to get up to 5% conversion into soft x-ray from the capacitor bank energy and corresponding wall plug efficiency of about 4%. For the NX1 the highest x-ray yield and conversion efficiency is obtained with the 4.5cm anode at 12kV. The x-ray yield varies within 50% of the maximum when the pressure is within 20% of the optimum. The typical variation of the x-ray yield when other factors like neon pressure, charging voltage are kept constant is about $\pm 35\%$ of the average x-ray yield.

For the NX2, the x-ray yield measurements show that the 5cm electrode is best in terms of high x-ray yield and conversion efficiency. The pressure range can be 50% off the optimum for less than 50% change in the x-ray yield.

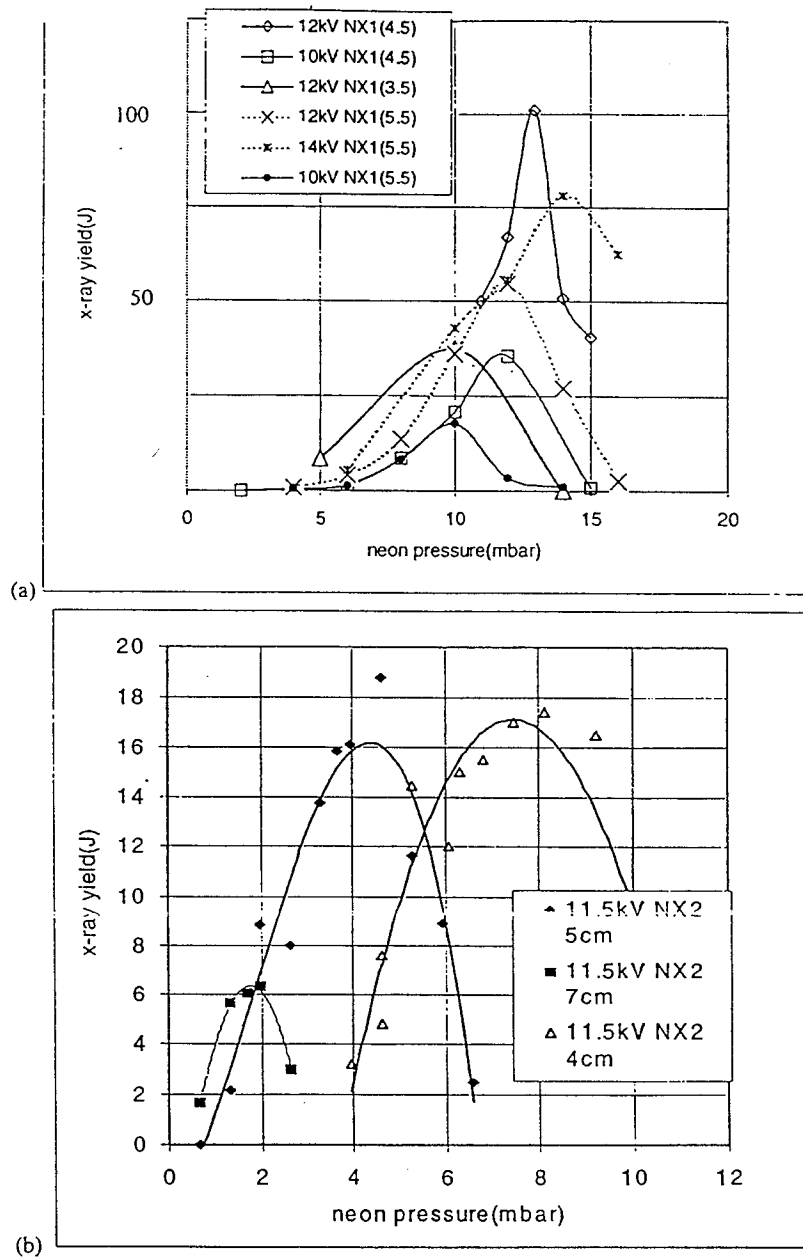


Figure 6. X-ray yield for different neon pressures for a) NX1 and b) NX2.

Figure 7 shows some representative oscilloscope current traces obtained using the NX1 with 4.5cm anode operated with a charging voltage of 10kV and the NX2 with the 5cm anode operated at 11.5kV with 4mbar neon. Some current dips to

as low as 60% of the peak current when there are multiple focus within a short time of each other. More typical dips drop the current to 80% of the maximum which is what the 1st dip associated with the 1st focus event in figure 7a. It can be seen that the energy transfer into the plasma is more efficient for the NX2 as the dip shown in figure 7b dips to about 65% of the peak current with only one focus event.

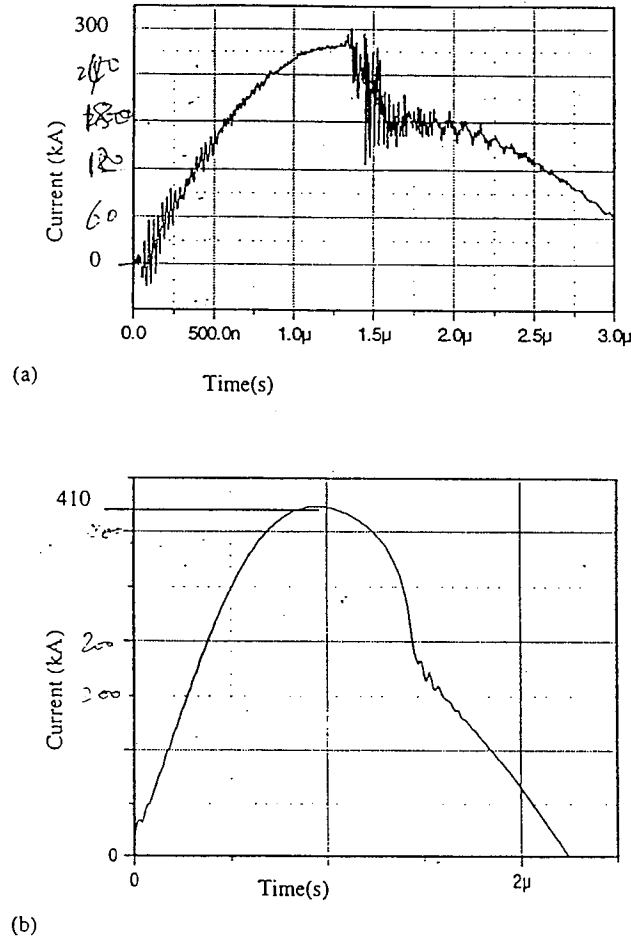


Figure 7 Some representative oscilloscope traces obtained from (a) the NX1 and (b) the NX2

5. DISCUSSION AND CONCLUSION

Figure 8 is a graph of time from current start to time of focus against pressure for (a) NX1 and (b) NX2. The best time for x-rays is later for 10 kV charging voltage than for 12kV. This means that the focus is running faster at 12kV. This could mean that the faster motion and thus temperature produces more x-rays only if there is sufficient current to maintain a high compression and density.

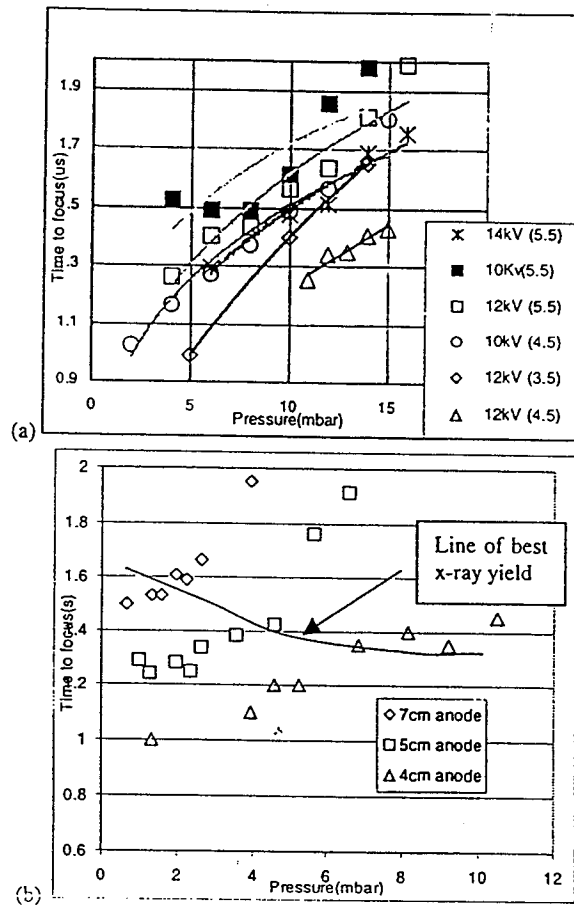


Figure 8 Graph of time to focus against neon pressure for (a) various configurations of the NX1, (b) various configurations of the NX2.

Table 3 shows the parameters for maximum x-ray yield for some of the configurations we tried. It can be seen that the best x-ray yield is at an average velocity of $3.6 \pm 0.2 \mu\text{scm}^{-1}$. With the shorter electrode, it is not possible to run the focus at a higher velocity as the focus would occur at a time too long before the natural current peak such that not enough of the capacitor bank energy has been converted to the magnetic field driving the plasma¹⁴. However if the anode is made too long and the velocity too high, several factors will cause the x-ray yield to be reduced. First of all, the neon K shell lines will not be possible anymore as the populations of the ions required would be reduced as all the neon becomes fully ionized. At high velocities, the plasma focus does not work well as the plasma becomes unstable and also due to the decoupling of the magnetic piston from the plasma sheath. The anode length also plays an important role in other processes like neutron production in deuterium focuses¹⁵ where neutron yield can vary by a factor of two when the anode length is 30% away from the optimum value. Due to the limitation in the highest voltage and therefore current (which is one way of increasing speed) we can use with our charger, a higher speed may require a lower neon pressure which also reduces the conversion efficiency.

Machine	Capacitor bank energy (kJ)	Current (kA)	Length / equivalent length* (cm)	Pressure (mbar)	T _{focus} (μs)	x-ray yield (J)	Speed (cmμs ⁻¹)
NX1	1.6	230	5.5/6	10	1.75	20	3.4
NX1	2.3	280	5.5/6	12	1.7	55	3.5
NX1	3.1	320	5.5/6	14	1.65	80	3.6
NX1	2.3	280	4.5/5	13	1.35	100	3.7
NX1	1.6	230	4.5/5	12	1.5	35	3.3
NX1	2.3	280	3.5/4	10	1.35	35	3.0
NX2	1.9	450	4	7	1.35	15	3.0
NX2	1.9	410	5	4	1.45	18	3.4
NX2	1.9	340	7	2	1.6	7	4.4

Table 3 Average speed of plasma.

*The equivalent length takes into account that the NX1 is curved so that the run down length is slightly longer.

From table 3 it is seen that for the NX2 with anode length down to 4cm, the focus time is still considerably greater than the short circuit rise time of the current. However the speed has decreased considerably with anode length. Thus it is clear that using a shorter anode cannot improve the NX2 x-ray yield. Using short anodes will bring with it additional problems. For example, we have observed that the quartz disk used to protect the inner surface of the 5cm anode tends to be more severely damaged than that in the 7cm anode. An electron beam and the plasma bombard the quartz disc in the anode so that if a shorter anode is used, the quartz disk will be placed closer to the high energy density plasma.

In the case of the NX2, the peak current is seen to be clearly dependent on the anode length, as the inductance of the focus is comparable to the inductance of the external circuit.

The results are promising. The NX1 chamber can be redesigned to incorporate cooling. By increasing the charging capacity, operation at just less than 10Hz will produce more than 1kW of SXR power, sufficient to expose a field in less than 2s on a 100mJcm⁻² resist, even if the transmission of the beamline is limited to 0.5. On the other hand, the NX2 can be redesigned to incorporate the materials and geometry of the NX1 to achieve the same yield per shot as the NX1.

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TIME-AVERAGED SPONTANEOUS POWER RADIATION IN PLASMA FOCUS*

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The time-averaged spontaneous radiation power and its spectrum are derived analytically. The collective mode is taken to be electron-cyclotron mode driven by the relativistic electron beam existing in the unstable and late phases of plasma focus. The infrared range radiation calculated is in agreement with experimental observation.

PACC: 5225P

I. INTRODUCTION

The relativistic electron beams (REB) have long been observed in the unstable and late phases of plasma focus.^[1-3] During the same time the infrared range radiation was observed.^[3] The plasma parameters are as follows: plasma density $n \sim 10^{19} \text{ cm}^{-3}$, magnetic field $\sim 500 - 1000 \text{ T}$, the REB density $n_b \ll n_{\text{core}}$ (core plasma density), and the velocity of the relativistic electrons ~ 0.5 to $0.9 c$, where c is the light speed.

We propose that the observed infrared range radiation is due to the REB driven electron cyclotron waves. Their frequencies are in the range of infrared with wavelength $\lambda \sim 10 \mu\text{m}$. Because the wavelengths are much shorter than the plasma scale length, we can treat the plasma as a uniform medium. The wave frequencies are much higher than the ion plasma frequency, so the ions provide a uniform background to ensure charge neutrality. By the same reason we ignore the changes of plasma parameters. A slab model is adopted. Because the REB energy is much larger than the core plasma temperature $\sim 1 \text{ keV}$, we approximate the core plasma to obeying the cold plasma theory. Since $n_b \ll n_{\text{core}}$, the waves are supported by the core plasma and driven by REB. Therefore, only the lowest order contribution of the power radiation is retained. The time-averaged total radiation power and its spectrum are derived analytically. The dominant contribution comes from the inner product of the self-consistent electric field fluctuation and the self-consistent current fluctuation.

The necessary formulations are presented in section II. The time-averaged radiation power and the power spectrum generated by the electron modes are derived in section III. Section IV is for discussion and conclusion.

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II. NECESSARY FORMULATIONS

The time-averaged radiation power emission from the plasma can be written in Fourier space $(\mathbf{k}, \omega)$

$$\langle P \rangle = - \lim_{T \rightarrow \infty} \frac{1}{T} \frac{2}{(2\pi)^4} \int d^3k \int_0^\infty d\omega \operatorname{Re}[\delta E^+(\mathbf{k}, \omega) \cdot \delta j(\mathbf{k}, \omega)], \quad (1)$$

where

$$\delta j(\mathbf{k}, \omega) = \boldsymbol{\sigma}^b \cdot \delta E(\mathbf{k}, \omega) \quad (2)$$

is the fluctuating part of REB currents driven by the self-consistent modes and $\boldsymbol{\sigma}^b$ is the conductivity tensor of REB and is related to the REB-induced susceptibility tensor χ^b by $\boldsymbol{\sigma}^b = -\frac{i\omega}{4\pi}\chi^b$. The waves are governed by the Maxwell equations with source current and plasma distributions. They give

$$\mathbf{D} \cdot \delta E = -\frac{4\pi i}{\omega} \delta j, \quad (3)$$

where $\mathbf{D}$ is the dispersion tensor,

$$\mathbf{D} = n^2 \left[\frac{\mathbf{k}\mathbf{k}}{k^2} - 1 \right] + 1 + \chi^{\text{core}} + \chi^b. \quad (4)$$

The core plasma dielectric tensor can be written as^[4]

$$\mathbf{D}^{\text{core}} = \begin{bmatrix} \epsilon_{11} - n^2 \cos^2 \theta & \epsilon_{12} & n^2 \sin \theta \cos \theta \\ -\epsilon_{12} & \epsilon_{22} - n^2 & 0 \\ n^2 \sin \theta \cos \theta & 0 & \epsilon_{33} - n^2 \sin^2 \theta \end{bmatrix}, \quad (5)$$

where $\sin \theta = k_\perp / k$ and $\cos \theta = k_\parallel / k$.

The susceptibility of REB electrons can be expressed as^[5]

$$\begin{aligned} \chi^b = & 2\pi \frac{\omega_{pb}^2}{\omega^2} \int_{-\infty}^{\infty} du_\parallel \int_0^\infty du_\perp \frac{u_\parallel}{\gamma} \left(u_\perp \frac{\partial}{\partial u_\parallel} - u_\parallel \frac{\partial}{\partial u_\perp} \right) F(u_\perp, u_\parallel) \hat{z}\hat{z} \\ & + 2\pi \frac{\omega_{pb}^2}{\omega^2} \int_{-\infty}^{\infty} du_\parallel \int_0^\infty du_\perp \left[\omega \frac{\partial}{\partial u_\perp} + \frac{k_\parallel}{\gamma} \left(u_\perp \frac{\partial}{\partial u_\parallel} - u_\parallel \frac{\partial}{\partial u_\perp} \right) \right] \\ & \cdot F(u_\perp, u_\parallel) \sum_{m=-\infty}^{\infty} \frac{T^{(m)}}{\gamma\omega - m\Omega - k_\parallel u_\parallel}, \end{aligned} \quad (6)$$

where

$$T^{(m)} = \begin{bmatrix} \frac{m^2}{k_\perp^2} \Omega^2 J_m^2(\lambda) & i \frac{m\Omega^2}{k_\perp^2} \lambda J_m(\lambda) J'_m(\lambda) & u_\parallel \frac{m\Omega}{k_\perp} J_m^2(\lambda) \\ -i \frac{m\Omega^2}{k_\perp^2} \lambda J_m(\lambda) J'_m(\lambda) & \frac{\Omega^2}{k_\perp^2} \lambda^2 J_m^2(\lambda) & -iu_\parallel \frac{\Omega}{k_\perp} \lambda J_m(\lambda) J'_m(\lambda) \\ u_\parallel \frac{m\Omega}{k_\perp} J_m^2(\lambda) & iu_\parallel \frac{\Omega}{k_\perp} \lambda J_m(\lambda) J'_m(\lambda) & u_\parallel^2 J_m^2(\lambda) \end{bmatrix}, \quad (7)$$

ω_{pb} is the REB plasma frequency, $\lambda \equiv k_{\perp} u_{\perp} / \Omega$, $\gamma = (1 + u^2/c^2)^{1/2} = (1 - v^2/c^2)^{-1/2}$ is the relativistic factor, $u = \gamma v$, and $F(u_{\perp}, u_{\parallel})$ is the velocity space distribution function of REB. We noticed that the second term of Eq. (6) is the nonadiabatic part.

Because of $N_b \ll N_{core}$, only the lowest order contribution of REB is considered. Namely, the wave is supported by the core plasma and driven by the excessive free energy of REB. Hence, we are interested in the nonadiabatic part of χ^b .

III. DERIVATION OF THE TIME-AVERAGED RADIATION POWER

To calculate the integrand of Eq. (1), we have to use Eq. (3) to get δE in terms of δj_s , namely,

$$\delta E = -\frac{4\pi i}{\omega} \mathbf{D}^{-1} \cdot \delta j_s = -\frac{4\pi i}{\omega} \frac{\mathbf{D}^c}{|\mathbf{D}|} \cdot \delta j_s, \quad (8)$$

where $|\mathbf{D}|$ is the determinant of dispersion tensor and $\mathbf{D}^c$ is the comatrix of $\mathbf{D}$. From Eqs. (2) and (8) we have

$$\text{Re}[\delta E^+ \cdot \delta j] = \text{Re}[\delta E^+ \cdot \sigma^b \cdot \delta E] = \left(\frac{4\pi}{\omega}\right)^2 \text{Re}[|\mathbf{D}|^{-2} \delta j_s^+ \cdot \mathbf{D}^{c+} \cdot \sigma^b \cdot \mathbf{D}^c \cdot \delta j_s]. \quad (9)$$

Since we only retain the lowest order terms, we ignore the REB contributions in $\mathbf{D}^c$, which can be written in a dyadic form

$$\mathbf{D}^c = |\text{Tr} \mathbf{D}^c| a(\mathbf{k}, \omega) a^+(\mathbf{k}, \omega) \quad (10)$$

with

$$a^T = -i \left[\frac{D_{22}^c}{|\text{Tr} \mathbf{D}^c|} \right]^{\frac{1}{2}} \left(\frac{\epsilon_{22} - n^2}{\epsilon_{12}}, 1, \frac{(\epsilon_{22} - n^2) n^2 \sin \theta \cos \theta}{\epsilon_{12} (\epsilon_{33} - n^2 \sin^2 \theta)} \right), \quad (11)$$

where we have used the core plasma dispersion relation in the above derivations.

Substituting Eq. (10) into Eq. (9), we get

$$\text{Re}[\delta E^+ \cdot \delta j] = \left(\frac{4\pi}{\omega}\right)^2 \frac{|\text{Tr} \mathbf{D}^c|^2}{|\mathbf{D}|^2} \text{Re}[a^+ \cdot \sigma^b \cdot a] |a^+ \cdot (\delta j_s, \delta j_s^+) \cdot a|. \quad (12)$$

From Eq. (10) we obtain

$$\text{Re}[a^+ \cdot \sigma^b \cdot a] = \frac{\omega}{4\pi} \frac{G}{|\text{Tr} \mathbf{D}^c|}, \quad (13)$$

where

$$G \equiv D_{11}^c \text{Im} \chi_{11}^b + D_{22}^c \text{Im} \chi_{22}^b + D_{33}^c \text{Im} \chi_{33}^b + 2[D_{13}^c \text{Im} \chi_{13}^b + D_{12}^c \text{Re} \chi_{12}^b + D_{23}^c \text{Re} \chi_{23}^b]. \quad (14)$$

By introducing the REB distribution function $F(u_{\perp}, u_{\parallel})$, the source current j_s may be written as

$$\delta j_s(\mathbf{k}, \omega) = -e N_b \lim_{T \rightarrow \infty} \int_{-T/2}^{T/2} dt \int d^3 u F(u_{\perp}, u_{\parallel}) v(t) \exp[i\omega t - i\mathbf{k} \cdot \mathbf{x}(t)], \quad (15)$$

where $\mathbf{x}(t)$ is the particle position at time t given by

$$\mathbf{x}(t) = \mathbf{x}(0) - \frac{\gamma v_{\perp}}{\Omega} \sin(\theta - \frac{\Omega}{\gamma} t) + k_{\parallel} v_{\parallel} t. \quad (16)$$

Using Bessel function expansion, we obtain

$$\delta j_s \delta j_s^+ = 8\pi^3 e^2 N_b \sum_{m=-\infty}^{\infty} \int du_{\parallel} \int du_{\perp} u_{\perp} j_m j_m^+ \gamma^2 \delta^2(\gamma\omega - m\Omega - k_{\parallel} u_{\parallel}) F(u_{\perp}, u_{\parallel}), \quad (17)$$

where

$$j_m^T = \left[\frac{mv_{\perp}}{\lambda} J_m(\lambda), i v_{\perp} J_m'(\lambda), v_{\parallel} J_m(\lambda) \right]. \quad (18)$$

And

$$\begin{aligned} a^+ \cdot (\delta j_s, \delta j_s^+) \cdot a &= 4\pi^2 e^2 N_b \lim_{T \rightarrow \infty} \sum_{m=-\infty}^{\infty} \int du_{\parallel} \int du_{\perp} u_{\perp} F(u_{\perp}, u_{\parallel}) \\ &\times \frac{c^2}{\gamma^2} \left| \frac{D_{22}^c}{\text{Tr} \mathbf{D}^c} \right| Q_m^2 \gamma^2 \delta(\gamma\omega - m\Omega - k_{\parallel} u_{\parallel}), \end{aligned} \quad (19)$$

where

$$Q_m \equiv \left[(1 - n^2) \left(\frac{\omega^2 - \Omega^2}{\omega_p^2} \right) - 1 \right] \left[\frac{m}{n \sin \theta} + \frac{\omega}{\Omega} \frac{n^2 \sin \theta \cos \theta}{1 - \omega_p^2 / \omega^2 - n^2 \sin^2 \theta} \frac{u_{\parallel}}{c} \right] J_m(\lambda) + \frac{u_{\perp}}{c} J_m'(\lambda). \quad (20)$$

To sum up, Eqs. (1), (12) - (14), (19) and (20) give rise to the expression of the time-averaged radiation power

$$\langle P \rangle = -\frac{2c^2 e^2 N_b}{\pi} \int d^3 k \int d\omega \frac{|D_{22}^c| G}{\omega |\mathbf{D}|^2} \sum_{m=-\infty}^{\infty} \int du_{\parallel} \int du_{\perp} u_{\perp} F(u_{\perp}, u_{\parallel}) Q_m^2 \delta(\gamma\omega - m\Omega - k_{\parallel} u_{\parallel}). \quad (21)$$

To evaluate $|\mathbf{D}|^{-2}$, we assume $|\text{Im} \mathbf{D}|^2 \ll |\text{Re} \mathbf{D}|^2$ (this is justified for $N_b \ll N_{\text{core}}$). With δ -function approximation, we have the following equation:

$$\begin{aligned} \frac{1}{|\mathbf{D}|^2} &= \frac{1}{|\text{Re} \mathbf{D}|^2 + |\text{Im} \mathbf{D}|^2} \approx \frac{\pi}{|\text{Im} \mathbf{D}|} \delta[|\text{Re} \mathbf{D}|] \\ &= \frac{\pi}{|\text{Im} \mathbf{D}|} \sum_i \left| \frac{\partial^2 \text{Re} \mathbf{D}}{\partial n^2} \right|^{-1} \delta(n^2 - n_i^2), \end{aligned} \quad (22)$$

where n_i^2 is the solution of the dispersion relation $|\text{Re} \mathbf{D}| = 0$. For the current problems, we are interested in the collective modes which are mainly governed by the core plasma, i.e., $|\text{Re} \mathbf{D}| \approx |\mathbf{D}^{\text{core}}| = 0$. Up to the lowest order, we need to keep only the terms linear in χ^b for $|\text{Im} \mathbf{D}|$, which gives the result

$$|\text{Im} \mathbf{D}| = D_{11}^c \text{Im} \chi_{11}^b + D_{22}^c \text{Im} \chi_{22}^b + D_{33}^c \text{Im} \chi_{33}^b + 2[D_{13}^c \text{Im} \chi_{13}^b + D_{12}^c \text{Re} \chi_{12}^b + D_{23}^c \text{Re} \chi_{23}^b]. \quad (23)$$

The problem is greatly simplified by realizing $|\text{Im} \mathbf{D}| = G$ from Eqs. (14) and (23).

Substituting Eqs. (14), (23) into Eq. (21) and transforming k -space integral to the n -space one, we have

$$\begin{aligned} \langle P \rangle = & -\frac{2\pi e^2 N_b}{c} \sum_i \int_0^\infty dn n^2 \int_0^\pi \sin\theta d\theta \int_{-\infty}^\infty d\omega \omega^2 \delta(n^2 - n_i^2) A(n^2) \\ & \times \sum_{m=-\infty}^\infty \int du_{\parallel} \int u_{\perp} du_{\perp} F(u_{\perp}, u_{\parallel}) Q_m^2 \delta(\gamma\omega - m\Omega - k_{\parallel} u_{\parallel}), \end{aligned} \quad (24)$$

where

$$A(n^2) = \frac{|\epsilon_{11}\epsilon_{33} - n^2(\epsilon_{11}\sin^2\theta + \epsilon_{33}\cos^2\theta)|}{|2n^2(\epsilon_{11}\sin^2\theta + \epsilon_{33}\cos^2\theta) - [\epsilon_{11}\epsilon_{33}(1 + \cos^2\theta) + (\epsilon_{11}^2 - |\epsilon_{12}|^2)\sin^2\theta]|}.$$

The time-averaged power spectrum is defined as

$$\eta(\mathbf{k}, \omega) = \frac{d^2 \langle P \rangle}{d\omega d\Omega_k}, \quad (25)$$

where Ω_k is the k -space solid angle. Therefore,

$$\begin{aligned} \eta(\mathbf{k}, \omega) = & -\frac{e^2 N_b}{C} \left\{ \sum_i \int_0^\infty dn^2 [n\omega^2 \delta(n^2 - n_i^2) A(n^2)] \right\} \\ & \times \sum_{m=-\infty}^\infty \int du_{\parallel} \int u_{\perp} du_{\perp} [u_{\perp} F(u_{\perp}, u_{\parallel}) Q_m^2 \delta(\gamma\omega - m\Omega - k_{\parallel} u_{\parallel})]. \end{aligned} \quad (26)$$

Equations (24) and (26) are our main results. They are possible to be solved numerically if the modes of fluctuation and the REB distribution are given.

Now we are going to explore analytically the intrinsic properties of the relativistic resonance and the high frequency collective modes, thus further simplify Eqs. (24) and (26). Furthermore we have the relation

$$\delta(\gamma\omega - m\Omega - k_{\parallel} u_{\parallel}) = \frac{\delta(u_{\perp} - U_{\perp})}{\left| \frac{\partial}{\partial u_{\perp}} (\gamma\omega - m\Omega - k_{\parallel} u_{\parallel}) \right|} = \left| \frac{\gamma c^2}{2\omega u_{\perp}} \right| \delta(u_{\perp} - U_{\perp}), \quad (27)$$

where $U_{\perp}$ is the solution of the relativistic resonance condition $\gamma\omega - m\Omega - k_{\parallel} u_{\parallel} = 0$.

Substituting Eq. (27) into Eq. (26) and carrying out the integration of n^2 and $u_{\perp}$, we have

$$\begin{aligned} \eta(\mathbf{k}, \omega) = & -\frac{e^2 c N_b \omega}{2} \sum_i \left\{ n_i A(n_i^2) \right. \\ & \times \sum_{m=-\infty}^\infty \int_{U_{\parallel-}}^{U_{\parallel+}} du_{\parallel} F[U_{\perp}(u_{\parallel}, n_i, \theta), u_{\parallel}] Q_m^2 [U_{\perp}(u_{\parallel}, n_i, \theta), u_{\parallel}, n_i] \left. \right\}. \end{aligned} \quad (28)$$

One can use Altar-Appleton-Hartree dispersion relation for n_i . They are^[4]

$$n_{\pm}^2 = 1 - \frac{2\omega_p^2(\omega^2 - \omega_p^2)/\omega^2}{2(\omega^2 - \omega_p^2) - \Omega^2 \sin^2\theta \pm \Omega\Delta}, \quad (29)$$

where “+” for ordinary mode, “-” for extraordinary mode, and

$$\Delta \equiv [\Omega^2 \sin^4\theta + 4\omega^{-2}(\omega^2 - \omega_p^2)^2 \cos^2\theta]^{1/2}.$$

In plasma focus the direction of REB is mainly perpendicular to the magnetic field. For illustration we let

$$F(u_{\perp}, u_{\parallel}) = \frac{1}{\pi\alpha_{\perp}^2} \delta(u_{\parallel}) e^{-(u_{\perp} - U_{\perp 0})^2 / \alpha_{\perp}^2}, \quad (30)$$

where $\alpha_{\perp}$ is thermal velocity perpendicular to the magnetic field, $U_{\perp 0}$ is the mean flow velocity of REB. For simplicity, we take $m = -1$ and that the wave is in an extraordinary mode propagating perpendicular to the ambient magnetic field (i.e., $\theta = \pi/2$). We further assume $|\epsilon_{33}| \ll \Omega^2/\omega^2$ and $\lambda \ll 1$. Hence Eq. (28) gives a very simple result

$$\eta_x(k_{\perp}, \omega) \approx -\frac{e^2 c N_b \omega}{8\pi\alpha_{\perp}^2} (\Omega^2/\omega^2 - 1)(1 + \omega/\Omega)^2. \quad (31)$$

For an ordinary mode we find that only the quasi-transverse wave has the contribution

$$\eta_0(k, \omega) \approx -\frac{e^2 c N_b \omega}{8\pi\alpha_{\perp}^2} (\Omega^2/\omega^2 - 1) \epsilon_{33}^{3/2} (1 + \Omega/\omega)^2 \cos^2 \theta. \quad (32)$$

In general, the longitudinal modes propagate mainly along the magnetic field (B_{θ} direction in plasma focus). The radiation is hard to be detected outside the plasma.

From Eqs. (31), (32) we know that the radiation power in perpendicular direction is mainly contributed by the extraordinary quasi-transverse wave. The order of magnitude is about $e^2 c N_b \omega / 8\pi\alpha_{\perp}^2$.

In order to compare with the experimental measurements, we evaluate

$$\left| \frac{d^2 p}{d\lambda_w d\Omega_k} \right| = \left| \eta \frac{d\omega}{d\lambda_w} \right| \approx \frac{2\pi c^2}{8\pi\alpha_{\perp}^2} \frac{e^2 \omega}{\lambda_w^2} \Big|_{\text{CGS}} N_b \times 10^{-11} \text{ W}/\mu\text{m.sterad}. \quad (33)$$

Taking $c^2/\alpha_{\perp}^2 \approx 2$, $\omega \approx 10^{14} \text{ s}^{-1}$, the wavelength $\lambda_w \approx 10 \mu\text{m}$ and using the experimental result^[6], the total relativistic electrons $N_b \approx 2 \times 10^{12}$, we obtain

$$\left| \frac{d^2 p}{d\lambda_w d\Omega_k} \right| \approx 100 \text{ W}/\mu\text{m.sterad}. \quad (34)$$

It is one order of magnitude larger than the experimental observation^[3] $\sim 10 \text{ W}/\mu\text{m.sterad}$. In fact, both REB and the magnetic field B_{θ} are inhomogeneous. REB is peaked at the axis, where $B_{\theta} = 0$. Only the outer region of the plasma has the contribution to the radiation. Hence the radiation should reduce. In order to evaluate this effect we may assume that REB has the following profile

$$n_b = n_{b0} (1 - r^2/a^2)^2,$$

and the magnetic field is produced by the uniform plasma electrons: $B_{\theta} = 2\pi r e n v_{th}/c$. Now the radiation power in Eq. (33) should be multiplied by a coefficient G determined by the following expression

$$G = \int_{r/a}^1 (1-x^2)^2 (\Omega_0^2 x^2 / \omega^2 - 1) (1 + \omega / \Omega_0 x)^2 x dx, \quad (35)$$

where $\Omega_0 = \Omega|_{r=a}$, r should be larger than the critical value r_c , at which $\Omega^2 / \omega^2 = \epsilon_{33}$. If r/a is taken to be 0.6–0.8, G would be $\sim 0.2-0.1$. Then the radiation power is in the same order as the experimental observation.

IV. DISCUSSION AND CONCLUSION

We have derived the time-averaged radiation power and its spectrum. In this work the lowest order contribution of the self-consistent modes of radiation is retained. The main result is presented in Eqs. (24), (26) and (28). Due to the lowest order cancellation of $\text{Re}[\mathbf{a}^+ \cdot \boldsymbol{\sigma}_b \cdot \mathbf{a}]$ and $|\mathbf{D}|^{-2}$, the problem is greatly simplified. We also would like to point out that we have neglected the wave amplification. Otherwise, the time-averaged power $\langle P \rangle$ as well as the power spectrum η obtained in Eqs. (24) and (26) should be multiplied by a factor of $e^{2\omega_i \tau}$, where ω_i is the actual growth rate of the wave and τ is its saturation time. Both of them should be evaluated nonlinearly. This is out of the scope of this paper.

As mentioned at the end of the last section, our theory predicts an order of magnitude larger in radiation power for the uniform REB and magnetic field. When the inhomogeneity of REB and magnetic field is taken into consideration, the averaged radiation power is greatly reduced to the same order as that observed. Therefore the mechanism for the infrared radiation in plasma focus proposed here is reasonable.

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IN VITRO LASER LIGHT DISTRIBUTION IN HUMAN LUNG TISSUES AT 406.7 NM USING ISOTROPIC FIBRE-OPTIC PROBE

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A small isotropic fibre-optic probe together with an accurate positioning system was used to measure the fluence rates in human lung tissues *in vitro* irradiated by collimated beam of a Kr^+ laser at the 406.7 nm. The 2-D (fluence-depth, fluence-lateral) and 3-D profiles as well as contour plots of light distributions in normal and cancerous tissues were generated and analysed. Different profiles were obtained due to the different optical parameters between the normal and cancerous tissues. By comparing the measured fluence distributions with Monte Carlo simulations, the optical parameters of human lung tissues at 406.7 nm were estimated as: (1) $\mu_a \sim 4.83 - 5.08 \text{ mm}^{-1}$, $\mu'_s \sim 6.35 - 7.31 \text{ mm}^{-1}$ and $\mu_{\text{eff}} \sim 12.73 - 13.74 \text{ mm}^{-1}$ for the normal tissue; and (2) $\mu_a \sim 1.24 - 1.83 \text{ mm}^{-1}$, $\mu'_s \sim 3.21 - 3.85 \text{ mm}^{-1}$ and $\mu_{\text{eff}} \sim 4.07 - 5.58 \text{ mm}^{-1}$ for the cancerous tissue.

INTRODUCTION

Light distribution in tissues is of great interest in many areas of medicine and biology, such as in photodynamic diagnosis (PDD), photodynamic therapy (PDT), and photothermal therapy (PTT)¹⁻³. The determination of fluence rates in the blue-violet range is essential for establishing dosimetry in PDD in human targeted tissues. In addition, the measurements of tissue optical properties, such as the absorption coefficient, μ_a , the scattering coefficient, μ_s , the anisotropy factor, g , and the refractive index, n , are often required for proper design of therapeutic or diagnostic applications of light in medicine. To our knowledge, very few complete-set data on the optical properties of human lung tissues have been reported in the literature⁴⁻⁶. In this study, we carried out *in vitro* measurements of light distributions in normal and cancerous human lung tissues characterised by histology in order to determine the optical parameters at the 406.7 nm of a Kr^+ laser.

MATERIALS AND METHODS

The samples used in this experiment were obtained immediately after lung resection from a lung cancer patient. The tumour type was confirmed by pathological examination as being squamous carcinoma. The sample was rinsed briefly in saline to remove excess blood before measurements. The sizes of normal and cancerous lung tissues are roughly 5.2 cm by 3.6 cm by 1.1 cm and 5.1 cm by 4.5 cm by 1.1 cm, respectively.

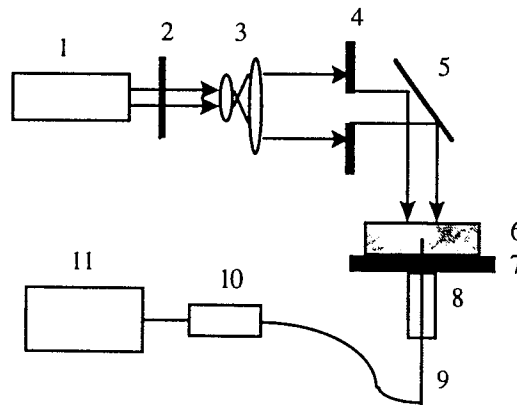


Fig. 1 Experimental setup for the measurement of light distribution in human lung tissue. 1. Kr^+ laser 2. variable attenuator 3. beam expander 4. iris 5. reflection mirror 6. tissue 7. translation stage 8. micrometer 9. fibre-optic 10. photomultiplier tube 11. photometer

The experimental setup for the measurements of light distribution in the tissue was shown in Fig. 1. A Kr^+ laser (Model 3500, Lexel Laser, Inc, USA) operating at the 406.7 nm was used as the irradiation source. The laser beam passed through an variable attenuator and was expanded and collimated by an inverse telescopic system, then was deflected perpendicularly onto the tissue surface via a reflection mirror. The laser beam diameter incident on the tissue was controlled through an iris diaphragm. The irradiance power and the beam diameter of laser were selected as 22 mW/cm^2 and 4.5 mm respectively in this study. The tissue holder was mounted onto a translation stage with resolution of 0.01 mm. Attached to the stage is a micrometer with a needle containing an isotropic fibre-optic probe of $800 \mu\text{m}$ in diameter mounted on a $400 \mu\text{m}$ optical fibre. The isotropic probe collected light equally from all directions (the anisotropy of the probe was less than $\pm 10\%$ from the mean value within an angular field of $\pm 160^\circ$ (see Fig. 2)), and therefore it measured the total fluence rate in its tissue site. The output of the isotropic fibre-optic probe was fed into a Photomultiplier Tube (PMT) and read out by an Oriel 7070 Photometer. At first, the needle tip was positioned in the centre of light spot at the back surface of the tissue, then it

was injected into the tissue from the base of the stage until the spherical tip near the surface. Then the needle was drawn back 5 mm. Thus the probe was located directly under the centre of light spot at this initial position. By translating the stage in steps of 0.1 mm, the lateral profile of the light distribution in the tissue at the determined depth at a 1 mm diameter can be obtained. On completion of this data

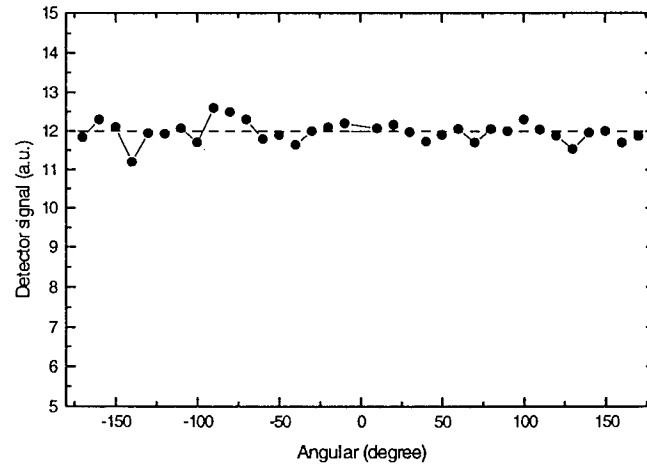


Fig. 2 The anisotropy response of an isotropic fibre-optic probe with diameter of 800 μm .

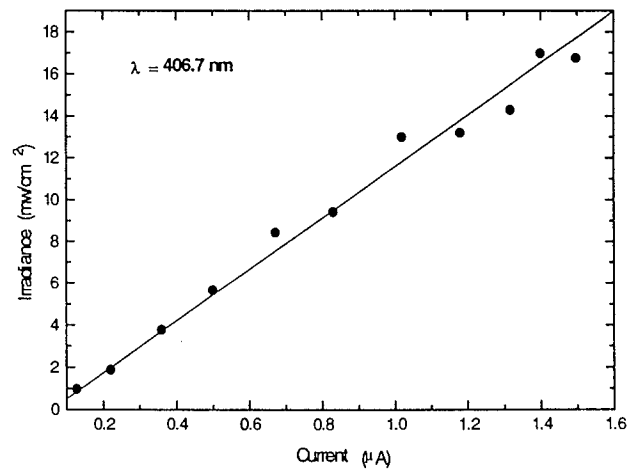


Fig. 3 The calibration curve of the detection system.

set, the spherical tip was withdrawn by 0.02 mm to a new tissue depth and data collection repeated. From the obtained data of light fluence rates with respect to the tissue depth and the lateral distance for the fixed beam diameter, the profiles of the 2-D and 3-D light distributions in the tissue can be determined. The general position

error of the probe in the tissue was not more than 0.01 mm. The probe was calibrated first in distilled water by measuring the response to a collimated light with known power density. The calibration curve of the detection system was shown in Fig. 3.

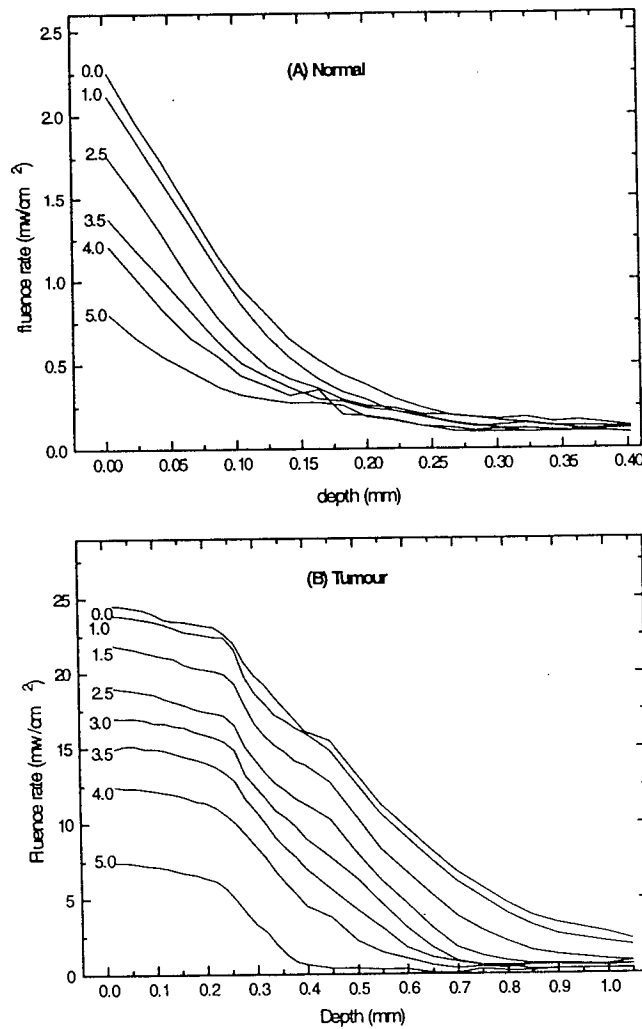


Fig. 4 The fluence rate versus tissue depth at different lateral distance in human lung tissues with an irradiance of 22 mW/cm² and beam diameter of 4.5 mm of the 406.7 nm of a Kr⁺ laser.

RESULTS AND DISCUSSION

Fig. 4 shows the measured fluence rate distributions as a function of tissue depth at different lateral distances from the incident beam in normal and cancerous

human lung tissues. It can be seen that the fluence rate (24.8 mW/cm^2) near the surface of tumour tissue (Fig. 4(B)) is slightly higher than the incident light (22 mW/cm^2), while the fluence rate (2.3 mW/cm^2) in normal tissue (Fig. 4(A)) is much lower than the incident fluence rate. The result indicates that the normal tissue tends

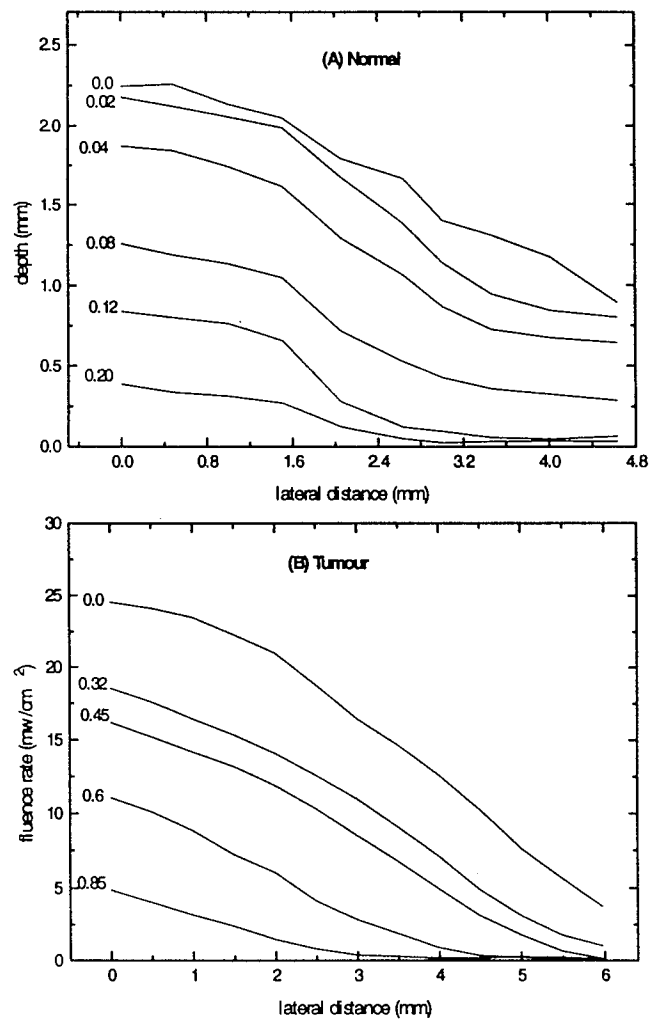


Fig. 5 The fluence rate versus lateral distance at different tissue depth in human lung tissues with an irradiance of 22 mW/cm^2 and beam diameter of 4.5 mm of the 406.7 nm of a Kr^+ laser.

to have a greater absorption characteristics as compared to the cancerous tissue at 413.1 nm . This may mainly be due to the great differences in the oxygenation level and the volume of blood between the normal and cancerous tissues⁷. From Fig. 4, it can also be found that the light attenuation rates between the normal and cancerous

tissues were different. When tissue depth is less than 0.25 mm in the tumour tissue, the fluence rate drops slowly. When the depth is larger than 0.25 mm, the fluence rate attenuates approximately with an exponential dependence. For the normal tissue, the fluence rate decays rapidly from the beginning of tissue surface. The similar trends of fluence rate distributions in normal and cancerous tissues at different lateral distances (1.0 to 5.0 mm) can be found compared to the light distribution at the central axis of incident beam.

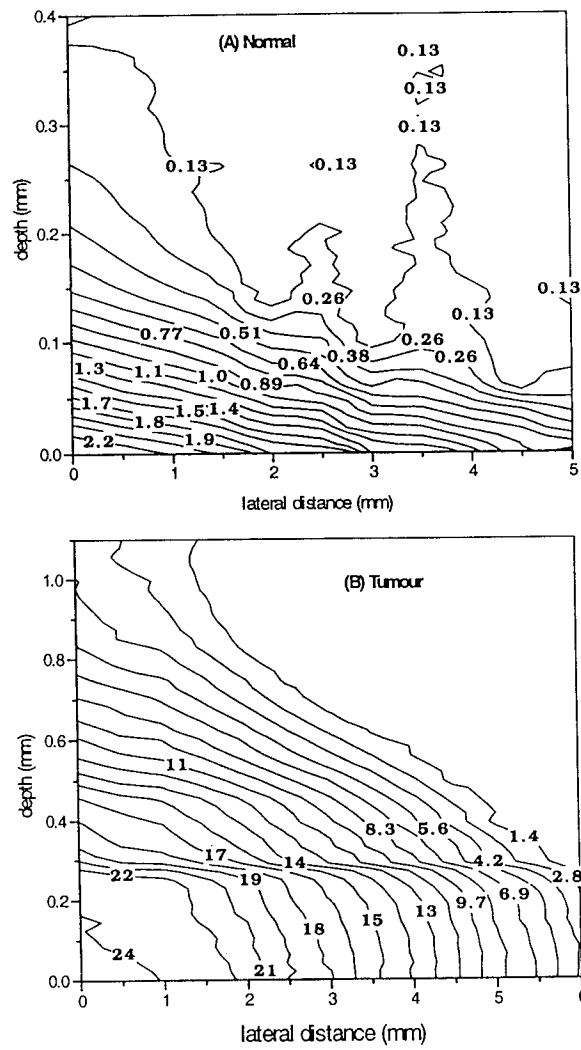


Fig. 6 The contour plot of fluence rate distribution in human lung tissues with an irradiance of 22 mW/cm^2 and beam diameter of 4.5 mm of the 406.7 nm of a Kr^+ laser.

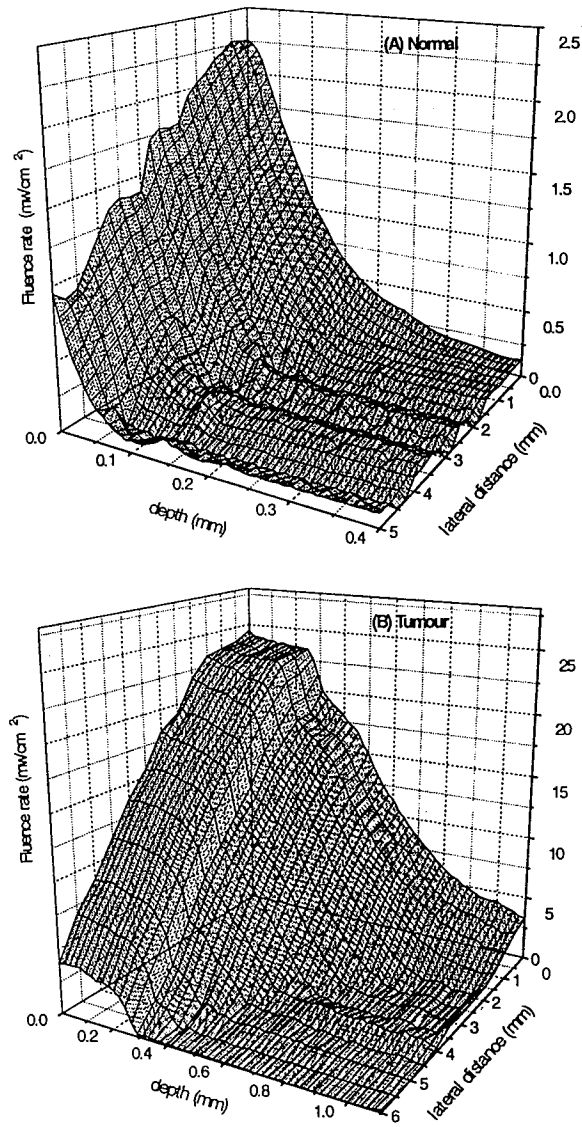


Fig. 7 The 3-D fluence rate distribution in human lung tissues with an irradiance of 22 mW/cm^2 and beam diameter of 4.5 mm of the 406.7 nm of a Kr^+ laser.

The lateral profiles at different depths are shown in Fig. 5. These fluence rate distributions in normal and tumour tissues showed a similar trend in the decrease of the fluence rate as the lateral distance was increased as well as when the tissue depth was increased. Deep and lateral spread of the fluence rate distributions are

observed in normal and cancerous tissues. This means that the scattering in normal and cancerous tissues extends the light fluence rate beyond the lateral dimensions of the incidence irradiance. The magnitude of these effects depends strongly on the scattering and absorption properties of lung tissues as well as the diameter of the laser beam⁸.

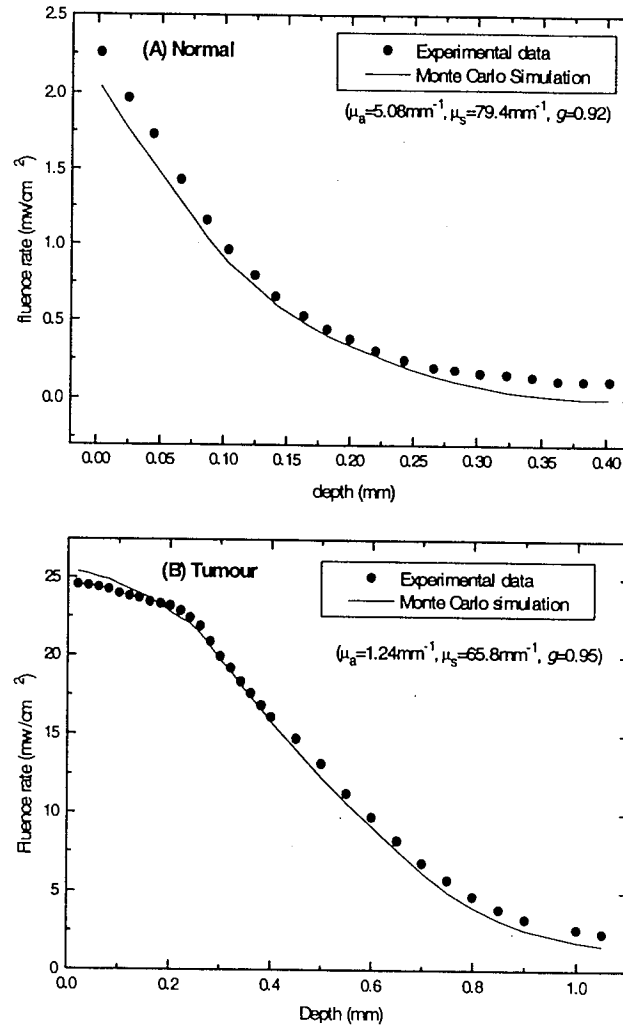


Fig. 8 Comparison of fluence rate distributions between the experimental data and the Monte Carlo calculations.

Fig. 6 represents the contour plots of fluence rate with respect to the tissue depth and lateral distance in normal and cancerous lung tissues. The values indicated

in the graphs account for the fluence rates at a particular tissue depth and lateral distance. One notes that the relative spacing of the contours give an indication of the decay gradient of the fluence rate in the tissue. It can be seen that in the lateral displacement region within the beam radius of 2.25 mm, the changes of fluence rates in normal and cancerous tissues are much flatter compared to those of fluence rates in greater than 2.3 mm lateral displacement, but the decay gradient of fluence rate is steeper in the normal tissue compared to that of cancerous tissues. The presence of some "loop" indicates the inhomogeneity in normal tissue (Fig. 6(A)). The discontinuity at tissue depth of 0.25 mm and the lateral distances of 0 to 6 mm also gives evidence of inhomogeneity in the cancerous tissue (Fig. 6(B)). From these two graphs, it can also be observed that the incident light beam is rapidly diffused in all directions in the tissue despite the use of a collimated beam, and the light distribution in the tissues is not homogeneous because of light scattering. The typical spherical form of the iso-fluence curves for small beam diameter⁹ was not found in both of normal and cancerous human lung tissues in this study.

The 3-D surface profiles of fluence rate distributions in normal and cancerous human lung tissues as a function of the tissue depth and lateral distance are shown in Fig. 7. The great differences of fluence rate distributions between the normal and cancerous tissues are clearly displayed, and the sites of small peaks and pits in the normal and cancerous tissues can also be found in these two 3-D plots. It should be noted that the detection of these inhomogeneity depends on the diameter of beam and the size of inhomogeneity in the tissue.

With the experimental values of the irradiance of 22 mW/cm² and beam diameter of 4.5 mm, Monte Carlo simulations^{9,10} were performed to generate the fluence distributions in tissues. In each simulation, 1,000,000 photons were launched. The refractive indices n of normal and cancerous tissues used in the Monte Carlo simulations were obtained by the total internal reflection method¹¹. By varying the parameters such as μ_a , μ_s and g , the results from the simulations were analysed and compared to the experimental data. The aim was to try to fit the simulation data with the experimental data. Fig. 8 gives the example of best fittings between the experimental fluence rates and the Monte Carlo calculations.

The fundamental optical parameters (μ_a , μ_s , g) derived from the best fittings are summarised in Table I. As a consequence, some other parameters, such as the effective attenuation coefficient, μ_{eff} , the effective penetration depth, δ_{eff} , can be determined according to the formulas⁴:

$$\mu_{\text{eff}} = \sqrt{3\mu_a(\mu_a + \mu'_s)}$$

$$\delta_{\text{eff}} = \frac{1}{\mu_{\text{eff}}}$$

and

$$\mu'_s = \mu_s(1 - g).$$

Table I: The derived optical parameters of human lung tissues at 406.7 nm using Monte Carlo simulations.

	Normal Tissue	Squamous Carcinoma
μ_a (mm ⁻¹)	4.83-5.08	1.24-1.83
μ_s (mm ⁻¹)	79.4-91.4	64.2-77
$\mu'_s = \mu_s(1 - g)$	6.35-7.31	3.21-3.85
g	0.92	0.95
n	1.408	1.411
μ_{eff} (mm ⁻¹)	12.73-13.74	4.07-5.58
δ_{eff} (mm)	0.07-0.08	0.18-0.25

As can be seen in Table I, the absorption coefficient of normal tissue is much greater than that of cancerous tissue. The light penetration depth δ_{eff} at 406.7 nm for normal tissue is in the range of 0.07–0.08 mm, while the δ_{eff} for tumour tissue is in the range of 0.18–0.25 mm.

CONCLUSION

In this study we have demonstrated that the spatial distribution of light fluence rate in a tissue can be directly measured using the isotropic fibre-optic probe technique. The comparison of the 3D surface profiles as well as the contour plots can yield information on tissue optical characteristics. The optical properties of human tissues can be estimated by comparing the measured fluence rate distribution with the Monte Carlo calculations. This further demonstrates that the Monte Carlo simulation can, to a certain extent, effectively model the response of tissues to laser irradiation. In addition, various parameters for laser dosimetry, such as effective attenuation coefficient, light penetration depth, can also be deduced based on this technique. These values would be very useful for diagnostic and therapeutic applications of lasers in determining the optimum depth at which laser irradiation is effective without causing any undesirable effects.

ACKNOWLEDGEMENTS

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DYNAMICS OF A SPARK PRODUCED BLAST WAVE

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The expansion of a spark produced plasma was studied with a simple model and compared to experiments. The model and experiments were performed using a 11.2 nF capacitor bank charged up to 10 kV corresponding to a total energy of 0.6 J. The nanosecond shadow pictures revealed detail structure of the shock waves, giving trajectory, speed and blast wave pressure ratios. Conversions of energy into motion and light wave were estimated.

INTRODUCTION

A blast wave is produced by depositing energy very quickly into a small volume. The blast moves initially at very high speeds and slows down in the long time scale limit to the sound speed. In this paper, we study the dynamics of the shock wave produced after electrical spark with a model and experiment.

Blast waves can be produced for example, by electrical discharges (e.g lightning), high power lasers, and explosives.

THEORY

When energy is deposited very quickly into a small region, a hot plasma can be produced. The pressure associated with the high temperature results in a fast expansion at speeds greater than the sound speed in the surrounding gas. This produces

a shock wave sweeping up gas as it propagates. After some time, depending on the amount of surrounding gas, the blast wave slows down to the sound speed. As the Mach number decreases towards 1 no additional mass will be swept up.

It is possible to obtain the shock front velocities using simple models¹. Without going into details about mechanisms, if we assume that all the mass is swept up by the shock layer (this is applicable for a strong shock) and give the shock mass the absorbed energy, it is possible to estimate the speed using

$$\frac{1}{2}mv^2 = E_{abs} \quad (1)$$

where E_{abs} is the amount of energy transferred to the motion of the plasma (some of the energy is converted directly to light but the amount is negligible), and m is the mass of the gas swept up (m_g) such that for an expanding sphere,

$$m_g = \frac{4}{3}\pi r^3 \rho_0 \quad (2)$$

and for an expanding cylinder,

$$m_g = \pi r^2 l \rho_0 \quad (3)$$

where r is the radius of the sphere or cylinder and l the length.

The speed used should be the root mean square of the whole expansion. If we use the shock front for comparison we must keep in mind that the front will travel faster than the rest of the mass. An important parameter, the energy transferred, absorbed or released can be estimated from the experiments and the snowplow model. The velocity can be obtained from the experiments by measuring the radius for two slightly different times at high Mach numbers. The swept-up mass m_g is obtained from Eq. (2) and substituted for the mass in Eq. (1) from which the energy absorbed E_{abs} is thus obtained. The calculation was performed using a spreadsheet by dumping all the energy into a specified volume of gas, then calculating with small increments in time Δt the speed v using Eq. (1), followed by the radius using $r = r + v\Delta t$, followed by the swept-up mass using Eq. (2) and repeating.

EXPERIMENT

The experiment was performed using a 11.2 nF capacitor bank charged up to 10 kV corresponding to a total energy of 0.6 J. The expansion of the plasma was monitored by a nanosecond shadowgraphic system using a 1 ns nitrogen as a probe beam². Fig. 1 shows the set up for the experiment. Plasma light is excluded through the use of the iris and an interference filter. The results were taken over a large number of shots whilst varying the time delay between the probe and the discharge using electronic delay units. The time between the discharge and the time of the snap shot is measured using a fast oscilloscope with photodiodes. The photodiodes are also

used to obtain estimates of the total light energy emitted by the spark. The pictures are taken on a Pulnix 6EX CCD camera connected to a Matrox Magic frame grabber card. The frame grabber card generates the signal which triggers a high voltage pulse unit which in turn triggers the spark gap.

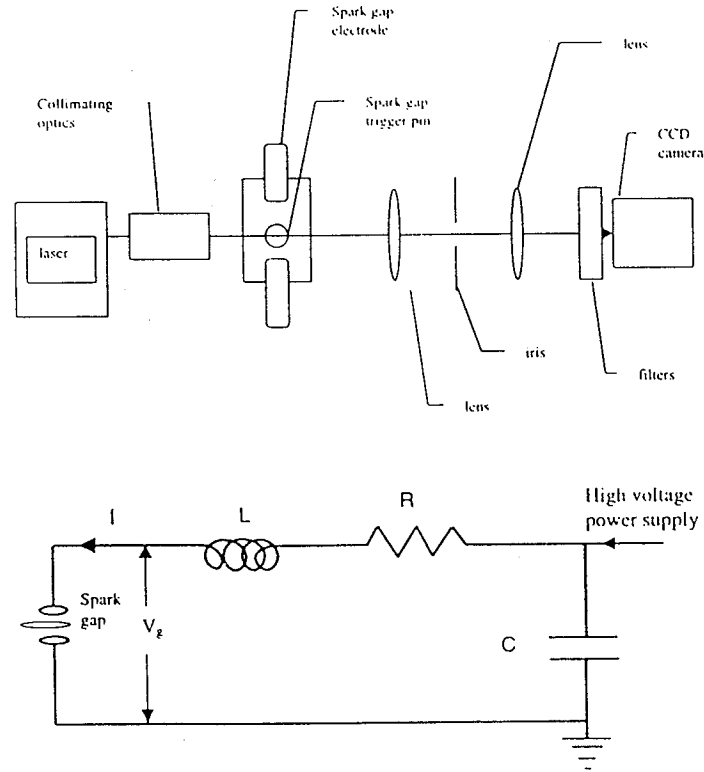


Fig. 1 Experimental set up.

RESULTS

Nanosecond shadow pictures obtained on the CCD from the experiment are shown in Fig. 2. The radius of the expansion was obtained from the edge visible in the shadowgraphs. Graphs of radius against time are plotted. A smooth curve is fitted and the velocity obtained by differentiating. This is plotted against time as well. Given the velocity or Mach number curve, shock wave theory was used to calculate many other parameters e.g. the shock strength or pressure ratio.

$$y = \frac{P_1}{P_2} = M^2(1 + \mu) - \mu \quad (4)$$

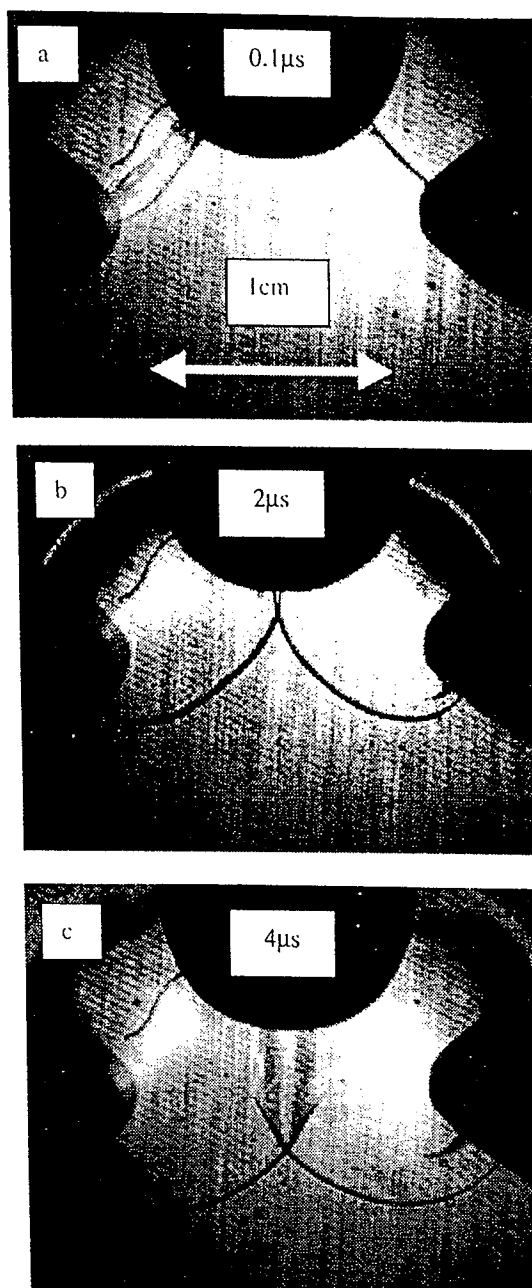


Fig. 2 Some typical nanosecond shadow pictures of the expansion taken at various times (note that the last two are at different magnification).

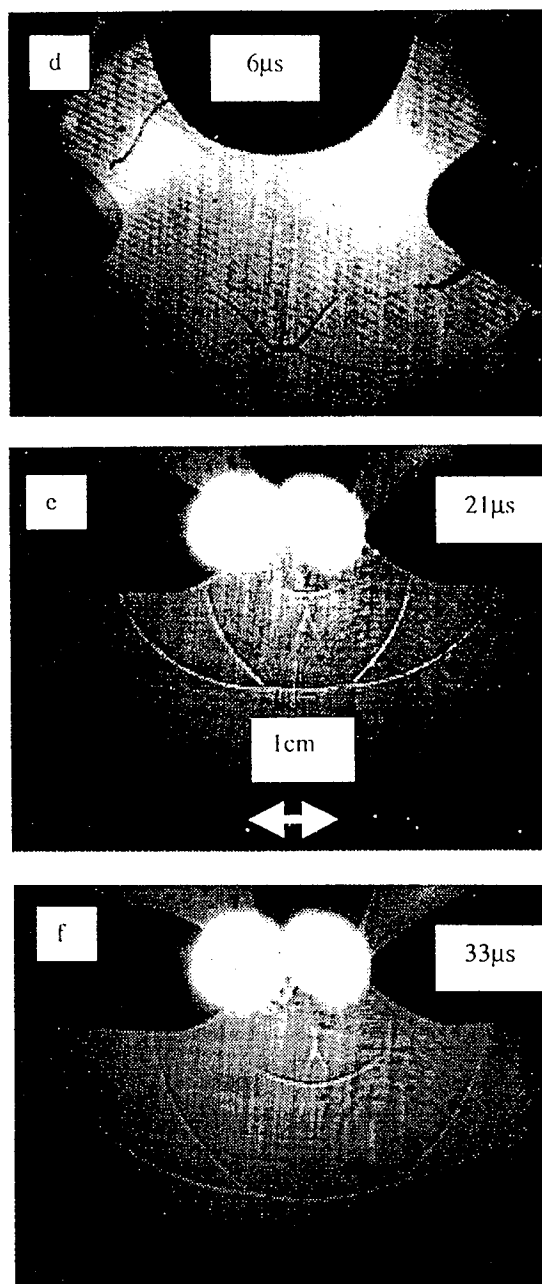
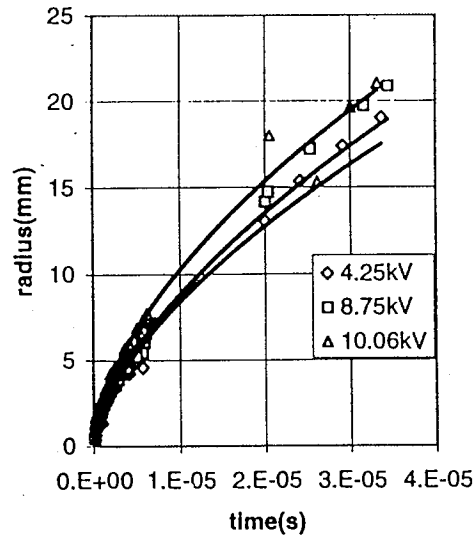


Fig. 2 continued.

where μ is a constant depending on the specific heat capacity ratio, the latter being 1.4 for air.

The graphs of radius against time, velocity against time and pressure ratio plotted against radius of expansion are shown in Fig. 3.



Graph of velocity (m/s) against time (s)

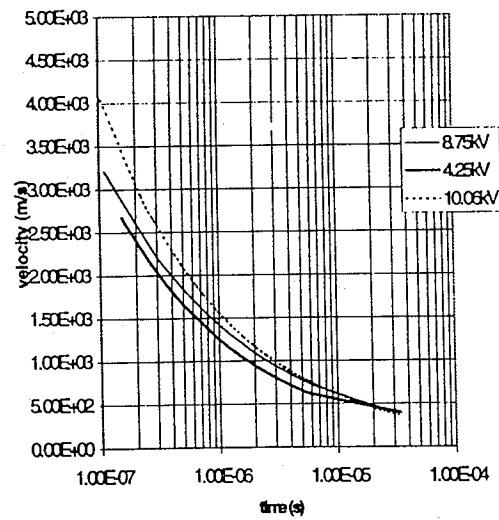


Fig. 3 Typical radius against time, velocity against time graphs and pressure ratio plotted against radius of expansion.

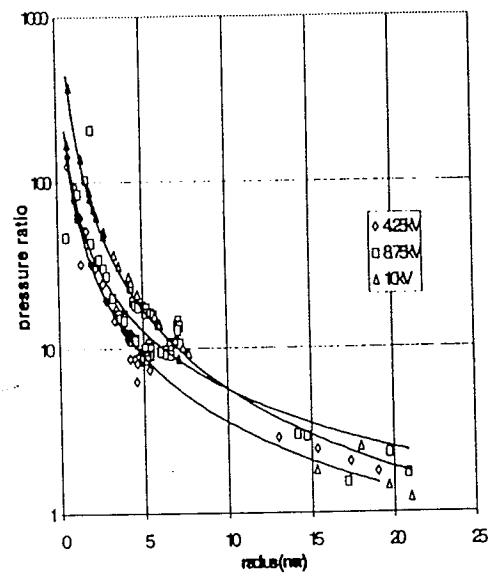


Fig. 3 continued.

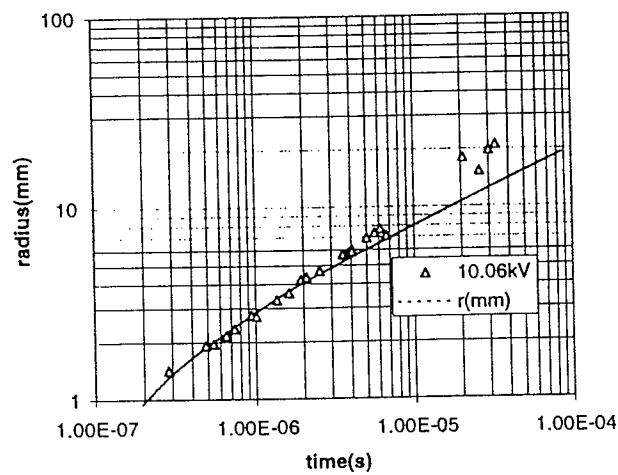


Fig. 4 Typical result from the model (using 130 mJ kinetic energy and atmospheric air) compared with the experimental radius against time curve for 10 kV charging voltage.

Fig. 4 is a typical result from the snowplow model. By comparing results from the snowplow model with the experiments we estimate an upper limit of the amount

of energy converted to kinetic energy. Table I shows a summary of these results.

Table I: Some experimental parameters.

Charging voltage (kV)	4.25	8..75	10.1
Capacitor energy ($E = CV^2/2$) (mJ)	90	360	560
Energy converted to motion (mJ)	45	60	130
Energy converted to light (mJ)	2.3	9.4	14.5

The current was measured using a magnetic probe and found to be 0.27 kA per kV of charging voltage³.

DISCUSSION AND CONCLUSION

Since the model is one dimensional, it is impossible to reproduce the detailed structure observed in the experiments. However it is possible to reproduce the position of the shock front and velocities from the model. The snowplow model allows us to immediately see that the speed of expansion is controlled only by the amount of energy transferred to the plasma. It also allows the actual energy absorbed to be estimated. The model breaks down when the blast wave continues even at sound speed. In fact the model breaks down even for weak shocks below Mach 3 as shown in Fig. 4. In this regime, the wave does not accumulate mass.

It is interesting to note from Table I that the fraction of energy transferred to the motion increases for the low voltage spark. This is due to a significant increase in the resistive phase of the spark for decreasing electric field. A formula for the resistive phase duration⁴ can be used to show this. For 10 kV, the characteristic time duration is 35 ns and for the 4 kV spark, it is 110 ns, which is already comparable to the period of the discharge.

Several interesting effects can also be observed in the intersection region of the two shock fronts. For example in Fig. 2(c) the shock has just intersected. In Fig. 2(d), it can be seen that the shock which has intersected and is travelling inside the low density region is travelling faster than the shock moving into atmosphere. A planar region can also be seen between the two spherical fronts. At 20 μ s, the planar front has already caught up with the two spherical fronts. Also the low density front from the intersecting shock has become visible as it sweeps up material left behind by the first shock front. The bright blobs straddling the gaps are due to the emission of light from the plasma channel at the same wavelength as the laser light. The data obtained from the dynamics study may be scaled to lightning discharges. The pressure ratios in particular may be used to estimate blast wave effects of lightning stroke. This is the subject of another paper⁵.

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**FINAL MEETING REPORT OF THE CRP ON "DEVELOPMENT OF PLASMA
HEATING AND DIAGNOSTIC SYSTEMS IN INSTITUTES IN DEVELOPING
COUNTRIES USING MIDDLE- AND SMALL- SCALE PLASMA DEVICES "**

IAEA-HQ, Vienna, Austria, 15 - 17 DECEMBER 1997

Single shot 3 kJ Plasma Focus and Beyond, Invited paper,
Int. Atomic Energy Agency (IAEA), was incorporated as part of this report

Abstract

Mindful that nuclear fusion is a most attractive long term energy option for mankind, this present CRP has substantially contributed to promote fusion-oriented research by supporting small and middle-scale plasma experiments in developing countries aimed at enlarging existing data base and at the development of technological spin-offs. A three-prong approach was adopted to develop methods of plasma heating and diagnostics, linked by theory.

In plasma heating, long-pulse experiments in small tokamaks in Prague, Ankara, Cairo and INPE (Brazil) were supported, as are short pulse dense plasma focus experiments in Cairo and Singapore. This support from IAEA has increased the confidence and national stature as well as the international collaboration of our CRP groups. The established CASTOR tokamak continues to show the effectiveness of small machines in contributing to data base whilst providing training of valuable high-level manpower. Results of the Cairo plasma focus and the benchmarking of the UNU/ICTP plasma focus within this CRP has benefitted the network of small plasma focus in ten countries, not least in the aspect of IAEA recognition.

Development of diagnostics complement the plasma heating programmes. These include electric and magnetic probe arrays with data acquisition systems, spectroscopy, radiation yield measurements and a non-perturbing neutral lithium beam technique. Theoretical consideration of statistical behaviour of the macroscopic plasma motion was used in order to develop new methods of plasma diagnostics including a way to infer information about turbulent plasma motion from electromagnetic wave scattering.

A natural and encouraging outcome of this CRP are the technological applications that have emerged from the various experiments. These include the use of low density plasmas for surface coating and modification, and of high density plasmas as an intense Soft X-ray source for microelectronics lithography. Plasma materials processing is already a cornerstone in wafer and microelectronics fabrication and in advanced materials for industrial uses. These plasma processes generate trillion dollar turnovers. This CRP has contributed substantially to the development of such plasma-based technology within our CRP.

I. INTRODUCTION

Nuclear fusion is one of the most attractive long term energy options for mankind, with practically unlimited fuel reserves and attractive environmental features. Present trends in international fusion research point to a globalization of efforts towards the development of nuclear fusion reactors, centered around a few major experimental devices. These activities, however, involve only a limited number of Member States of the IAEA with sufficient economic resources and technological development, due to the extreme complexity and high cost of these large scale fusion experiments. For the same reasons, Member States with limited resources and particularly developing Member States, have a marginal or negligible participation in these activities.

This situation is presently creating a widening gap in fusion research around the world, which should be reversed if fusion energy is to become a global commodity in a long term scenario when every country should be capable of operating fusion reactors as centralized power sources.

The present CRP of the IAEA is a positive step in this direction. In particular, it is considered that:

- * small and middle scale plasma experiments can substantially contribute to promote fusion-oriented research in developing countries, in order to produce the human resources and the technological infrastructure that will be required in the long term for local operation of nuclear fusion power reactors.
- * small and middle-scale plasma devices are ideally suited to developing Member States because of their relative technological simplicity, cost effectiveness and short turn-around time.
- * These activities can also be of relevance for major international experiments, by enlarging the existing data base and by doing supporting work in insufficiently studied topics that can be addressed with small and middle size machines, as well as by theoretical and computational studies.

- * Technological spin-offs of fusion and plasma research may also contribute to improve the industrial growth of developing Member States.

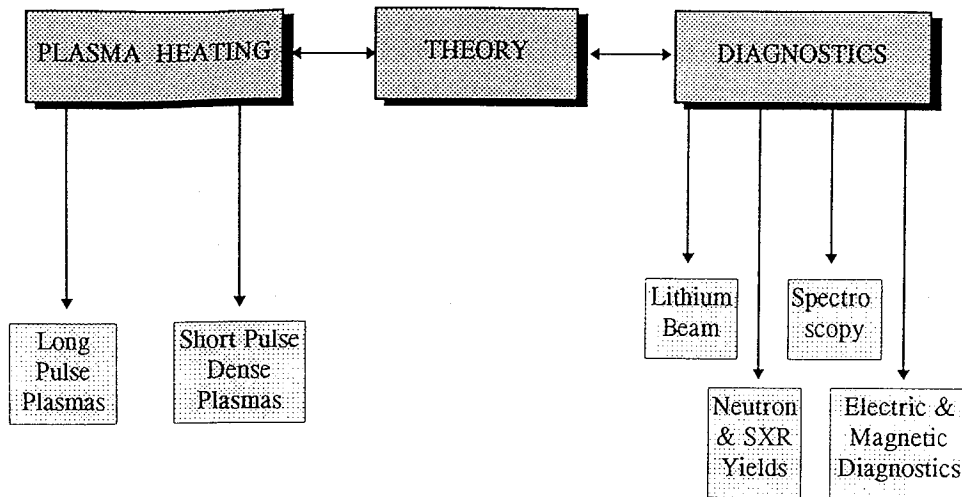
It should be pointed out that this CRP meeting was particularly fruitful in terms of direct discussions on additional coordinated cooperation activities among the participating members. Specific topics in this connection include plasma focus research, cooperation in plasma applications and a hands-on training course on Tokamak research.

II. OBJECTIVES OF THE CRP

- * To promote coordinated cooperation in fusion research and its technological spin-offs among IAEA developing Member States.
- * To carry out fusion oriented plasma physics research using small and middle-scale devices.
- * To promote the growth of fusion research activities and plasma technological applications in developing Member States.
- * To contribute to the international progress in fusion research by enlarging the existing data base and by doing supporting work in insufficiently studied topics as well as by theoretical and computational studies.
- * To promote international cooperation in fusion research and its technological spin-offs among IAEA's Member States.

III. ORGANIZATION OF THE CRP

The general organization of the CRP is illustrated in the attached diagram. The activities are divided into plasma heating and plasma diagnostics. Theory and applications relevant to these activities have been included.



IV. Summary of main results of the project

V.

IV.1 Plasma Heating

Work on plasma heating is divided into long pulse plasmas and short pulse dense plasmas.

IV.1.1 Long Pulse Plasmas

This part of CRP is related to the confinement and heating of low density plasmas, mostly in toroidal configurations. Results from a few experimental devices (either in the operation, commissioning, construction or design phases) are presented.

- * The CASTOR tokamak is a routinely operating device in IPP Prague. Systematic measurements of plasma fluctuations have demonstrated the similar character of turbulent structures existing in a small-scale experiment like CASTOR and in a large machines like ASDEX. It may indicate an universal nature of the edge turbulence in tokamaks.

- * Theoretical studies and computational experiments are performed at the Turkish Atomic Energy Authority (Ankara) on improvement of the spherical tokamak concept (including the spherical pinch) using magnetically driven multiple plasma guns. The analytical and numerical models for current drive are being developed, based on magnetic helicity injection on the relaxation state and the bootstrap currents. In addition, the complex current drive mechanism produced by helical currents with different pitches are studied. Furthermore, the overall system parameters are investigated from the viewpoint of an alternative small scale fusion reactor design.
- * The small tokamak EGYPTOR is under construction in the Plasma Physics and Nuclear Fusion Dept. of Atomic Energy Authority, (Cairo). The individual parts of the device have already been tested and the whole system will operate within two months.
- * A small, low aspect ratio ($A=1.5$) tokamak ETE is being built at INPE (Brazil) and will be operational within two years. The major objective of this experiment is to study the stability of high β , compact, naturally elongated, high current tokamak plasmas.

IV.1.2 Short Pulse Dense Plasmas

The plasma focus (PF) is identified as an ideal small scale device for study of short pulse dense fusion plasmas. The work of this CRP includes specifically PF research in Cairo and Singapore, and more generally benchmarking the 10-machine network of 3 kJ PF devices actively operating in 9 countries for optimum neutron and soft x-ray yields. The work in Cairo on the 4 kJ and 20 kJ devices demonstrates interesting regimes of operation including plasma current rotation. It also indicates the importance of shock wave and piston structures to the radiation yield. These results may throw light on the mechanism of force-field decoupling from the flow-field as suggested by shadowgraphic studies in Kuala Lumpur and Singapore. Suppressing this decoupling mechanism will lead to a speed enhancement effect raising fusion neutron yield from I^4 (I is the current) to I^8 scaling. Such a yield enhancement mechanism could lower the break-even energy from ~ 300 MJ to below ~ 15 MJ. This is a major result of the collaborative work of Cairo and Singapore groups within the framework of this CRP. The benchmarking of the 3 kJ PF (the UNU/ ICTP PFF) will enable a systematic compilation and correlation on the diverse results of the network of the UNU/ICTP PFF. This will add significantly to the data base of pulsed dense plasmas.

The experimental results have shown that the plasma sheath in the axial phase is restricted when applying magnetic field of intensity 3.8 kG along the coaxial electrode and the plasma sheath velocity decreases by 20%, where a plasma sheath gained a rotational energy.

Measurements of the focused electron temperature decreases from 2.2 keV to 0.8 keV, while the expanded T_e decreases 2.6 times and its density increases by 9 times. This indicated that the expanded plasma motion is restricted by radial component of the applied B_z . Then the plasma is contained in the expansion chamber.

The measurements of the plasma sheath dynamics on presence of transverse magnetic field indicated that the plasma is contained by this field.

The traces of B_z and I_z showed that FWHM of these signals decreased and they become more stable? In presence of B_z and B_r .

IV.2 Diagnostics

Development of diagnostics for the determination of plasma parameters has been one of the major topics within this CRP. Hence efforts have been made to develop electric and magnetic probe arrays together with an appropriate data acquisition system and software to investigate plasma fluctuations in the CASTOR tokamak with a sufficient spatial and temporal resolution. A microwave reflectometer of 35 GHz was also developed for that device to study density fluctuations in the core plasma. Furthermore, a quite novel concept of the single Langmuir probe, so called Double-Pin-Plate probe, was proposed and tested. Such arrangement allows to measure the electron temperature in turbulent and magnetized plasmas with the temporal resolution better than 1 ms.

Optical emission spectroscopy and Langmuir probes were used to determine the plasma species and the electron density and temperature as well as to calculate the relative concentration of heavy species in glow discharge plasmas for formation of TiN coatings. The goal of this study was to determine the dominant plasma species contributing to the TiN film formation. Plasma spectroscopy has also been used for studies of a magnetized z-pinch. In the plasma focus devices, a series of suitable diagnostics have been applied: miniature Rogowski coil, magnetic probes, shadowgraphy, neutron yield, neutron TOF, soft X-ray yield and spectroscopy.

On the other hand, as an example of a more specialized diagnostics for probing of plasma without perturbation, a neutral lithium beam has been developed. A neutral lithium beam of about $40 \mu\text{A}/\text{cm}^2$ equivalent current of 2 keV is ready to be applied to diagnose both hot and cold plasmas. The plasma immersion ion implantation (PIII)

system have been developed and its microwave produced plasma will be used as a target plasma for FNLB probing. This experiment combining both advanced surface modification techniques and novel diagnostics will be carried out soon and will provide important information on the plasma response to high voltage pulses (-10 to -20 kV, 10 μs ?, 20 Hz) applied to the samples immersed in the plasma.

Meanwhile, project of FNLB for the ETE tokamak is underway. The Li beam source has been improved and higher voltage power supplies (10 kV and 3 kV) have been built or purchased recently and the diagnostic set-up for edge density and its fluctuations measurements is been decided.

IV.3 Theory

Kinetic behaviour of solitons in Nonlinear Schrodinger Equation has been analyzed . Boltzmann type kinetic equation has been constructed and it is shown that kinetic behaviour of solitons are principally differ from kinetic properties of both particles and usual waves. In the case when processes with momentum exchange takes place diffusion coefficient is the sum of two terms deal with the shifts of positions and momentum exchange. Relaxation process in soliton gas two steps: chaotization in real space and usual thermalization New kinetic properties have to be taken into account. in the explanation of Langmuir turbulence. Possibility of irradiation dose measurement using soliton propagation in optical fibres and magnets has been considered. Fluctuation spectra in magnetized plasma in the presense of field like turbulent excitation has been investigated. Large and small correlation length scales comparing with the fluctuation wave length are considered. Typical tokamak coherent scattering spectra is analyzed and new possibilities to interpret information from laboratory and space plasma are shown. Waves scattering in gyrotropic turbulent media have been considered in order to measure the spirality of the media. The model for measurement of the cross-section has been proposed.

The nonlinear interaction of intense electromagnetic radiation with hot plasma related to fusion is investigated analytically. Ponderomotive and striction nonlinearities cause wave modulation

with the formation of solitons and cavitons in the hot plasma. Relativistic Vlasov equation with the appropriate Maxwell-Boltzmann-Jüttner distribution for the unperturbed plasma thermal equilibrium is state is considered. Ultrasuperluminal electromagnetic radiation is found to exist in the ultrarelativistically hot plasmas. The superluminal radiations undergo no Landau damping and the radiation energy propagation velocity is close to the speed of light. Kinetic theory of the rotating plasma related to fusion and some astrophysical objects is developed. Nonlinear modes in the electron-positron plasmas are studied and possible generation of strong ambipolar field is found for particle acceleration through plasma wakes.

Trajectories of ions have been calculated under conditions similar to those in the edge of plasmas of tokamaks. The model assumes the spatial modulation of electric field, which might be an approximation of electrostatic structures seen in experiment. It was found that for a sufficiently high $E \times B$ force the ion trajectories are chaotic. This effect is significant namely for heavy ions.

The statistical behaviour of the macroscopic motion in a plasma has been considered in order to develop new methods for plasma diagnostics. Kinetic properties of Langmuir solitons described by the nonlinear Schrödinger equation have been studied. It has been shown that kinetic properties of a soliton gas principally differ from the kinetic properties of usual particles and have two steps: chaotization in real space and usual thermalization. Renormalization of plasma density and its electrical susceptibility due to macroscopic turbulent-like motion were found. Proposals for new possibilities of plasma diagnostics have been made. In particular, ways to infer information about the turbulent plasma motion from electromagnetic wave scattering were found.

The nonlinear propagation of intense electromagnetic radiation in a hot plasma related to fusion was investigated. The nonlinear evolution of the fast wave is either periodic or it forms modulation envelopes (solitons, cavitons, etc.). Ultra-superluminal electromagnetic radiation was found to exist in ultrarelativistically hot plasmas. The frequency and wavelength of the radiation are bound by some characteristic frequency and wavelength which are determined by the plasma density and its temperature. The superluminal radiation undergoes no Landau damping and its group velocity is very close to the speed of light.

IV.4 Applications

The application of low density plasmas for production of surface coatings and surface modification by means of CVD plasma techniques has been investigated. In particular, TiN, TiC and TiCN coatings have been produced. These coatings are relevant for protection of selected plasma interactive components in fusion reactors as well as for production of hydrogen diffusion barriers. In addition, they find application as hard protective coatings for industrial use.

The experiment of TiN formation was successfully completed. It was determined that Ti atoms and N₂ metastables in the first excited level constitute the dominant species contributing to that supply of titanium and nitrogen to the substrate surface. On this base, it is concluded that these two species may play a dominant role in the TiN film formation.

In connection with the present research in plasma nitriding, the plasma reactor has been improved by incorporating a mechanical booster pump and a quadrupole mass spectrometer for identification of plasma species, which will be used together OES. Work is in progress at the moment to reduce oxygen impurity concentration inside the vacuum processing chamber by using a Ti getter.

In addition, new research work has started to study the plasma processes responsible for plasma nitriding under conventional radical nitriding conditions. Present activities in this connection are concentrated in setting up the proper experimental conditions for this research work.

As an example of regional cooperation among member states on technological spin-off of fusion research a regional training course on plasma processing at the Latin America level is under organization at the moment for execution in the period 1998-2002. Preliminary ideas concerning this course was discussed at the first CRP meeting between Argentine and Brazilian participants and it will be implemented under the sponsorship of the Argentina Atomic Energy Commission together with the Japan International Cooperation Agency.

Other applications developed within this CRP make use of the intense soft X-ray (SXR) yield of the plasma focus operated with noble gases. A high repetition rate plasma focus

has been developed to provide a sufficiently bright (~ 300 W) point SXR source with an excellent wavelength range (0.5 - 1.4 nm) for lithography applications for the microelectronics industry. Plasma focus radiation will also be used for medical imaging applications with improved imaging quality in terms of contrast and spatial resolution.

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HIGH REPETITION HIGH PERFORMANCE PLASMA FOCUS AS A POWERFUL RADIATION SOURCE

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ABSTRACT

Basic operational characteristics of the plasma focus are considered from design perspectives to develop powerful radiation sources. Using these ideas we have developed two Compact Plasma Focus (CPF) devices operating in neon with high performance and high repetition rate capacity for use as an intense Soft X-ray (SXR) source for microelectronics lithography. The NX1 is a four-module system with a peak current of 320 kA when the capacitor bank ($7.8\mu\text{F} \times 4$) is charged to 14 kV. It produces 100 J of SXR per shot (4% wall-plug efficiency) giving at 3 Hz, 300 W of average SXR power into 4π . The NX2 is also a four-module system. Each module uses a rail-gap switching 12 capacitors each with a capacity of $0.6\mu\text{F}$. The NX2 operates with peak currents of 400 kA at 11.5 kV into water-cooled electrodes at repetition rates up to 16 Hz to produce 300 W SXR in burst durations of several minutes. SXR lithographs are taken from both machines to demonstrate that sufficient SXR flux is generated for an exposure with only 300 shots. In addition flash electron lithographs are also obtained requiring only 10 shots per exposure. Such high performance compact machines may be improved to yield over 1 kW of SXR, enabling sufficient exposure throughput to be of interest to wafer industry. In deuterium the neutron yield could be over 10^{10} neutrons per sec over prolonged bursts of minutes.

INTRODUCTION

For Mather's type plasma focus operation it is observed experimentally [1,2] that the quantity designated as the drive parameter $1/S = (I/a)/\rho^{1/2}$ (where I is the driving current and ρ the operational gas density), a measure of speed, both axial and radial, has an optimum value for each gas of operation. Thus for deuterium the average axial speed for optimum neutron yield appears to be just below 6 cm/ μsec corresponding to a peak axial speed of 9-10 cm/ μsec and a peak radial speed of some 25 cm/ μsec as the plasma focus radial shock goes on axis. That the optimum speed should be so low for optimum neutron yield is surprising since one would expect from D-D fusion cross-section consideration that the fusion yield should be enhanced by an increase in speed which should boost the focus ions above the 1 keV observed for focus operation at the above mentioned optimum speeds. The speed limitation may be due to a force-field flow-field decoupling effect [1]. An effort to achieve yield enhancement by breaking through the speed limit has been made [3].

Operating in noble gases for the generation of soft x-ray (SXR) an optimum speed may be more readily understood. For example in neon the compressed plasma in the focus should have a temperature of some 400 eV if the radiation is required to be predominantly in the 0.8-1.4 nm for the purpose of microelectronics lithography. We have used a model computing plasma dynamics in the axial, radial, and radial reflected shock phases, incorporating a quasi-equilibrium radiative phase [4,5,6] to examine for example the optimum axial speed required to set the stage for optimum radiation in the 0.8-1.4 nm range. This model is used to correlate with experimental results which indicate an optimum average axial speed of 4.5 cm/ μsec .

It is important to note that the optimum speed for each of deuterium and neon operation remains nearly constant for the range of machines surveyed. This is particularly remarkable for deuterium operation where a value of S nearly constant at 90 kA/torr^{1/2}, corresponding to a peak axial speed of just less than 10 cm/ μsec , is tabulated [1]

over a wide range of machines from training machines of 3 kJ /2/ to machines of 300kJ. This means that for each gas the plasma temperatures in each of the dynamic phases, and by inference also in the compressed radiative phase, are identical for all machines, big and small, when optimized.

We next note that the quantity S is dependent on $D=(I/a)$ linearly whilst it depends only on the half power of p . Note also that over a two decade range of stored energy the optimized operational pressure has a range of only 2 /1/. Thus in a relative sense the density ρ and hence the quantity D may in the first approximation be considered also as constant when comparing different machines, all optimized. This clearly agrees with the design tendency to increase the anode radius proportionally with the available drive current. But there is also a fundamental significance.

For each gas, since we are dealing with the same compressed temperature and essentially the same density, radiation yield will depend on the product of compressed plasma volume and lifetime. Again since we are dealing with the same dynamical speeds and compressed temperatures any reasonable modelling /4,7,14/ will show that each dimension of the pinched plasma is proportional to the anode radius, as is the lifetime of the compressed plasma. Thus radiation yield is proportional to a^4 . And since D is essentially constant for each gas, radiation yield, at least for neutrons and SXR, is proportional to I^4 . Such a scaling is energetically possible since whenever energy is taken from the circuit by the plasma such an energy extraction will reflect in a lowering of the current. Such a self-regulating mechanism will self-consistently limit the extraction of energy from the circuit.

Thus for a given stored energy, yield performance is related to current. Circuit inductance needs to be minimized. Our modelling also indicates the importance of minimizing the ratio of generator impedance to total impedance for efficient transfer of energy to the plasma pinch. Practically this is again accomplished by minimizing all the inductances from the capacitor bank through the switches right up to the collector flanges of the plasma focus head. Thus improving circuit performance should improve yield performance.

For applications, whilst the peak rates of yield may have significance for some time-resolved experiments, for other applications such as SXR lithography for microelectronics application there is a need for high average yield rates sustained over at least a duration of minutes, even for demonstration purposes. Thus ability to operate at high repetition rates in a prolonged burst is necessary.

The length of the anode is also of crucial importance /2,7/. Computation and experience agree that a strong focus with optimum energy coupled into the focus pinch so as to emit intense radiation, is achieved when the radial compression starts (end of axial phase) at a time t_{ax} where t_{ax} is equal to t_r , t_r being a hypothetical risetime of the capacitor bank with a value between the short-circuited risetime and the risetime of the circuit loaded hypothetically with the full axial load. As a rule of thumb the short-circuited risetime may be used for a first estimate of the optimum anode length.

Thus for the deuterium focus with an optimum average axial speed of say 5.5 cm/ μ sec the anode length should be 5.5 cm per μ sec short-circuited bank risetime. For the neon focus taking the optimum average axial speed to be 4.5 cm/ μ sec would give us an indicative optimum anode length of 4.5cm for every μ sec of shortcircuited bank risetime.

What about the value of $D=(I/a)$? From a survey of experiments it is found that the current per unit anode radius has a design range of 150-220 kA/cm, for optimum neutron yield. We have used this range also as an indicative design range for our SXR facilities.

Based on the above considerations we have developed two high repetition rate compact plasma focus facilities, the NX1 and the NX2 to be powerful SXR sources for microelectronics lithography /8,9,10/.

We note that the requirements for a point SXR lithography source may be expressed as follows: point source dimension less than 1 mm (focussed plasma viewed end-on) with emission in the wavelength range 0.8-1.4nm, and average SXR power of 1 kW at source over 4π delivered over a prolonged burst. This last requirement indicates what is needed from industrial wafer throughput considerations. For a resist with 100mJ/cm² sensitivity

exposed at a distance which cannot be less than 30cm /9/ from the point source, 1kW will deliver the required 100 mJ/cm² in 2 sec assuming beamline transmission ratio of 0.5. A 2 sec exposure time per field may be sufficient for industrial wafer throughput purposes. For demonstration purposes even a 100W source is useful.

Other practical design features include compact footprint with ample space for a stepper to be integrated eventually into the facility.

2. APPARATUS

The plasma focus soft x-ray sources used in these experiments are low energy ~2kJ plasma focus operated in neon. A general view of the NX2 is shown in Fig 1. The design enables measurement of SXR yield at the same time as lithographic exposure is made. The footprint of the machine is 1.6 m x 1.6 m. There is a clear

space for the integrated development of a stepper. The system is completely shielded against electromagnetic radiation.

2.1 Electrical system

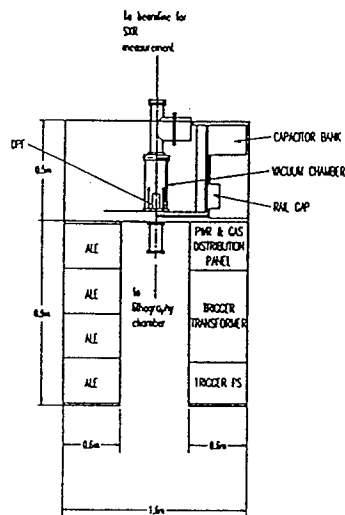
Both the NX1 and NX2 plasma focuses are driven by 30μF capacitor bank charged by ALE Systems model 802 high voltage capacitor chargers. The capacitor banks are connected to the focus via four switches (pseudo spark switches for the NX1 and rail gap switches for the NX2). Table 1 summarizes the characteristics of the electrical systems. A schematic of the electrical system is shown in Fig 2.

	Charging Voltage (kV)	Energy (kJ)	Repetition rate (Hz)	Current (kA)	Short circuit rise time or quarter period (μs)
NX1	12	2.2	3*	280	1.5
NX2	11.5	1.9	16	400	1.0

Table 1 Summary of electrical characteristics * limited by available charging power.

2.2 Focus chamber

Three chambers have been used in the NX1 (see Fig 3) with oxygen-free copper anode lengths 3.5, 4.5 and 5.5 cm respectively. Three anode lengths were tried with the NX2. The electrode dimensions are summarized in table 2. The NX2 stainless steel electrodes are cooled by water circulated through the electrodes using two Bay Vortex RRS-1650-AC chillers with a total cooling capacity of 9.6kW



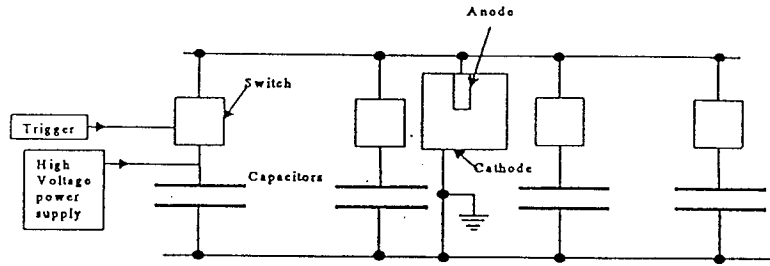


Figure 2. Schematic of electrical system

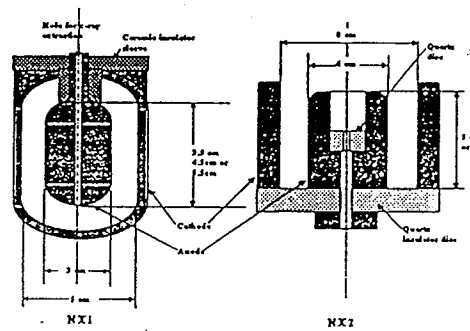


Figure 3. Schematic of focus electrodes and chamber

	Anode diameter(cm)	Cathode diameter (cm)	Anode length (cm)	Electrode material	Insulator material
NX1	3	5	3.5, 4.5, 5.5	Copper	Ceramic
NX2	4	8	5, 7	Stainless steel	Quartz

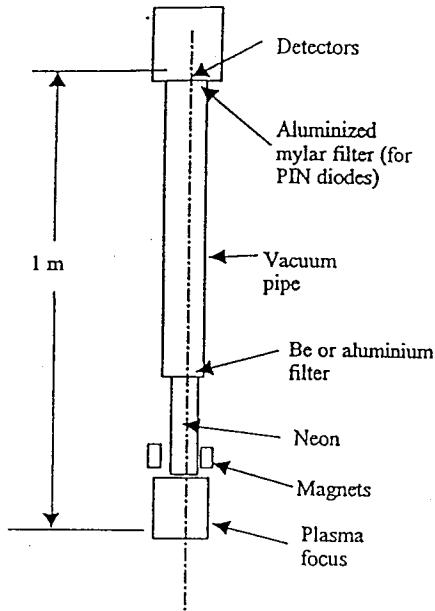
Table 2 Summary of focus electrodes

3. EXPERIMENT

The diagnostics were 1mm^2 area $10\mu\text{m}$ thick PIN diodes and 3mm^2 photoconducting diamond (PCD) filtered by aluminium, mylar and beryllium foils. The setup used for the experiments is shown in Fig 4. Both the PCDs and the PIN diodes were used on both machines. In the case of the NX1, the x-ray was detected through the extraction hole through the anode. This means that there is also an electron beam travelling along the same path. The electrons are excluded by the application of a magnetic field to deflect the electrons and also by the $10\mu\text{m}$ beryllium which scatters the electrons. The energy of the electrons have been determined in a previous experiment [11].

The initial pressure of neon was varied and the optimum pressure was found for the various electrode lengths and for charging voltages of 10kV and 14kV. Most of the datapoints were repeated 5-10 times for the NX1 and 20-200 times for the NX2. A fast acquisition system consisting of a Tektronix

TDS380 oscilloscope connected to a computer was used so that the x-ray for every shot up to a repetition rate of about 10 HZ could be obtained.



4. RESULTS

To obtain the SXR yield from the PIN diode pulse, the area under the oscilloscope trace is obtained and the total amount of SXR is calculated using a sensitivity factor into which has been folded the sensitivity versus wavelength characteristics of the PIN diode, the spectrum of the neon focus emission which had been separately obtained earlier using a crystal spectrograph [6] and the absorption of the beamline gas path and filters. The PIN diode measurements are cross-calibrated against a calibrated PCD detector. The PCD has a flat sensitivity over the range of SXR spectrum considered. Hence interpretation of the yield is more reliable. The measurements using the two detectors agree to within 20% on the NX2. All results are adjusted to the PCD calibration.

The results from the x-ray yield measurements are shown in Fig 5. Fig 5a shows that with the NX1, we obtained up to 5% conversion into soft x-ray from the capacitor bank energy and corresponding wall plug efficiency of 4% with the 4.5cm anode at 12kV. The x-ray yield varies within 50% of the maximum when the pressure is within 20% of the optimum. The typical variation of the x-ray yield when other factors like neon pressure, charging voltage are kept constant is about $\pm 35\%$ of the average x-ray yield.

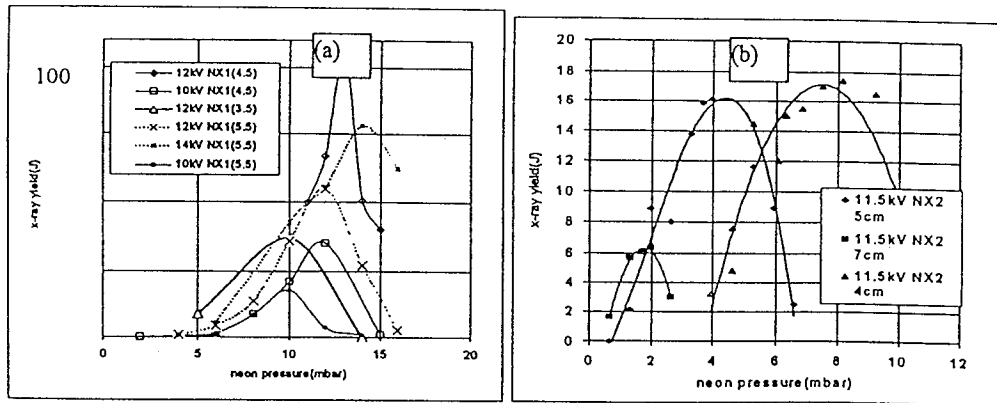


Figure 5. X-ray yield for different neon pressures for a) NX1 and b) NX2.

Figure 6 shows some representative oscilloscope current traces obtained using the NX1 with 4.5cm anode operated with a charging voltage of 10kV and the NX2 with the 5cm anode operated at 11.5kV with 4mbar neon. Some current dips to as low as 60% of the peak current when there are multiple focus within a short time of each other. More typical dips drop the current to 80% of the maximum which is what the 1st dip associated with the 1st focus event in figure 6a. It can be seen that the energy transfer into the plasma is more efficient for the NX2 as the dip shown in figure 6b dips to about 65% of the peak current with only one focus event.

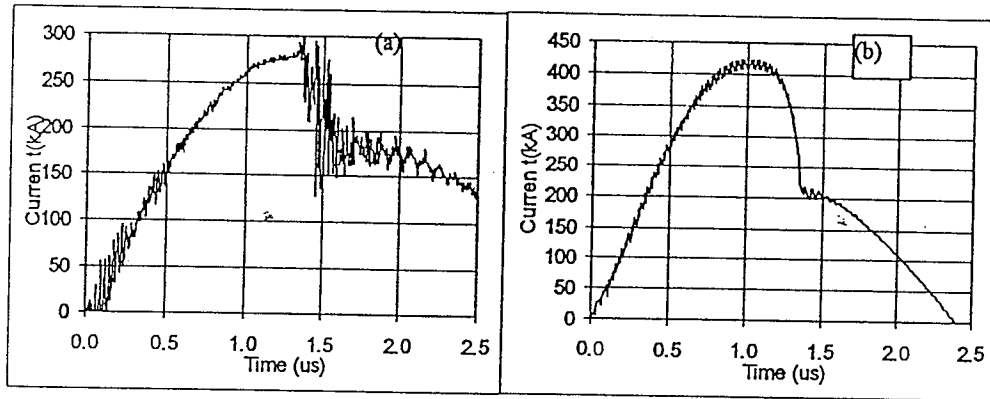


Figure 6 Some representative oscilloscope traces obtained from (a) the NX1 and (b) the NX2

Table 3 shows the parameters for maximum x-ray yield for some of the configurations we tried. It can be seen that the best SXR yield is at an average velocity of $4.5 \mu\text{scm}^{-1}$. With the shorter electrode, it is not possible to run the focus at a higher velocity as the focus would occur at a time too long before the natural current peak such that not enough of the capacitor bank energy has been converted to the magnetic field energy driving the plasma. However if the anode is made too long and the velocity pushed too high, the final focus temperature will become too high for efficient production of neon K shell lines.

Machine	Bank Voltage/ Energy (kV/kJ)	Length/ Equivalent (cm/cm)	Optimum Pressure (mbar)	Measured Current (kA)	t_{xx}^{**} (μs)	Average Axial Speed ($\text{cm}\mu\text{s}^{-1}$)	D (kAcm^{-1})	S ($\text{kA cm}^{-1} \text{ torr}^{-1/2}$)	SXR yield (J)
NX1	10/1.5	5.5/6	10	230	1.50	4.0	153	56	20
NX1	12/2.2	5.5/6	12	280	1.45	4.1	187	62	55
NX1	14/2.9	5.5/6	14	320	1.40	4.3	213	66	80
NX1	10/1.5	4.5/5	12	230	1.25	4.0	153	56	35
NX1	12/2.2	4.5/5	13	280	1.10	4.6	186	60	105
NX1	12/2.2	3.5/4	10	280	1.10	3.6	187	68	35
NX2	11.5/1.9	7	2	340	1.30	5.4	170	139	7
NX2	11.5/1.9	5	4	400	1.15	4.4	200	115	18
NX2	11.5/1.9	4	7	410	1.05	3.8	205	90	15

Table 3 Comparative performance of NX1 and NX2

*The equivalent length takes into account that the NX1 is curved so that the run down length is slightly longer.

** t_{xx} =time at end of axial phase, or start of compression, taken as 0.25/0.3 us before SXR pulse for the NX1/NX2.

Figure 7 shows SXR lithographic exposures to confirm the SXR flux of NX1 and NX2 /12/. The resists used have a sensitivity rated at $100\text{mJ}/\text{cm}^2$ and are placed 40cm from the focus. Magnets are placed to deflect the electron beams associated with the plasma focus /13/ to ensure that the exposure are by SXR. The mask is a $1\text{ }\mu\text{m}$ thick gold mesh with grid separation of $5\text{ }\mu\text{m}$. The NX1 beamline has a 3 times poorer transmission ratio than the NX2 beamline. These lithographs confirm that the NX1 produces more than 3 times the SXR yield per shot when compared to the NX2.

Figure 8 shows a flash electron lithograph exposed on PMMA with 10 shots of NX1. For electron lithographs the deflecting magnets were removed. The exposure was used to estimate the electron beam current as $50\text{ }\mu\text{A}$ over the 5 Hz burst . The electron energy was estimated as 30keV /11/.

5. CONCLUSION

We have demonstrated SXR lithographic exposures with just 300 shots from plasma focus sources and flash electron lithographic exposure with just 10 shots. We note that the NX1 and the NX2 have quite different yield performance. For each machine the observed speed at optimum yield for each anode length generally does correlate with the drive parameter S. However the value of S is significantly higher (up to 2 times) for equivalent speeds for the NX2 compared with the NX1. On the basis of machine scaling for neutrons /1/ we would have expected constant value of S for optimum operation. This difference may be the cause of the large difference in yield. Despite higher circuit performance the yield performance of the NX2 is significantly lower than the NX1. This may be due to the significantly lower value of S for the NX1 which could be related to a higher operational density (up to 3 times) of NX1 for equivalent speeds and D, when compared to the NX2. The higher optimum operational density at equivalent temperatures obviously favours a higher SXR yield for NX1. This yield superiority of NX1 could perhaps be ascribed to differences in electrode materials (oxygen-free copper for NX1 compared to stainless steel for the NX2), chamber configurations (carefully shaped channel and closed outer electrode for the NX1), perhaps even to the differences in backwall insulation materials and configuration.

In any case it appears that the NX1 chamber has the more promising features with maximum SXR yield over 100J and wall plug efficiency of 4%, compared to 18J and 1% for the NX2. By incorporating cooling in the NX1 chamber and increasing the charging capacity so that the NX1 chamber may be fired at 10Hz , 1kW of SXR power may be achieved which will expose a field at 30cm in less than 2sec on a $100\text{mJ}/\text{cm}^2$ resist, assuming a beamline transmission of 0.5. This should be sufficient for industrial throughput demands applied to microelectronics lithography aimed at $0.15\text{ }\mu\text{m}$ design rules.

Moreover, by using deuterium we expect a neutron yield of better than 10^9 per shot and 10^{10} neutrons per shot when operating the cooled NX1 in a prolonged burst at 10Hz . Such a powerful compact neutron source will have interesting applications.

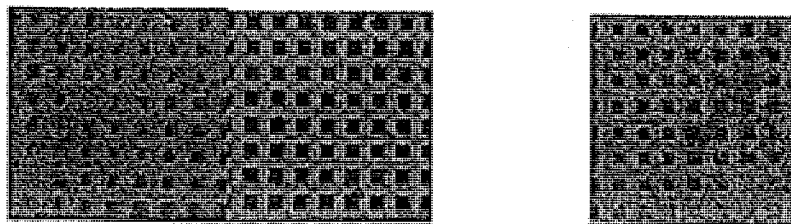


Figure 7 Test exposure (a) NX1 (200 shots & 400 shots) and (b) NX2 (300 shots)

Resist has a rated sensitivity of $100\text{mJ}/\text{cm}^2$

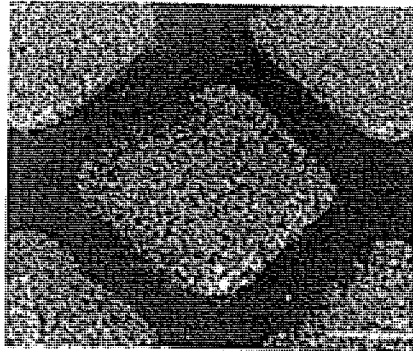


Figure 8 Flash electron lithograph on PMMA, 10 shots (NX1)

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PRESSURE MEASUREMENT AND CORRECT YIELD OF POWERFUL SOFT X-RAY SOURCE

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Abstract

The development of soft x-ray (SXR) lithography is crucial to the continuing progress in miniaturization of microelectronics. The NTU-NIE NX2 plasma focus is being developed as the most powerful soft x-ray source in its class for SXR lithography. One problem encountered during its development was wrong measurement of SXR yield due to unreliable pressure measurement using an electrical Convectorr gauge. This led to a wrong value of the beamline transmission ratio which then resulted in wrong estimates of SXR yield. The objective of the project is to calibrate the electrical gauge. An oil filled U-tube manometer was developed to provide the reference pressures for calibration of the Convectorr gauge used previously in the NX2 SXR measurements. The calibration shows that the Convectorr gauge over read by a factor of three between the pressure range of 0.4-0.8torr and by larger factors beyond 1 torr. This gave greatly exaggerated values to the SXR yields. Using the correctly calibrated pressure, SXR yield are now correctly and reliably obtained showing that the NX2 produces 300W of SXR during its burst of repetitive shots making it the most powerful device of its class. This is confirmed by trial SXR lithographic exposures.

Introduction:

Singapore will be the first "intelligent City State" in the world and progress is steadily being made towards this goal. The most critical technology towards this objective is information technology. This relies crucially on computer technology. It is necessary to pack more processing power into smaller packages. Miniaturization needs to be accelerated. Packing density of computer elements need to be increased. Currently the limiting factor is the size of features in microchips, at about 0.2 micrometer.

The limit is imposed by lithography, the process of transferring from the master pattern or mask to the resist. (See Fig 1)

This is due to the "light" which is used - ultraviolet. Its wavelength is not short enough for the small features that one would like to achieve. The next development making possible further miniaturization is to use shorter wavelength: soft x-ray (SXR).

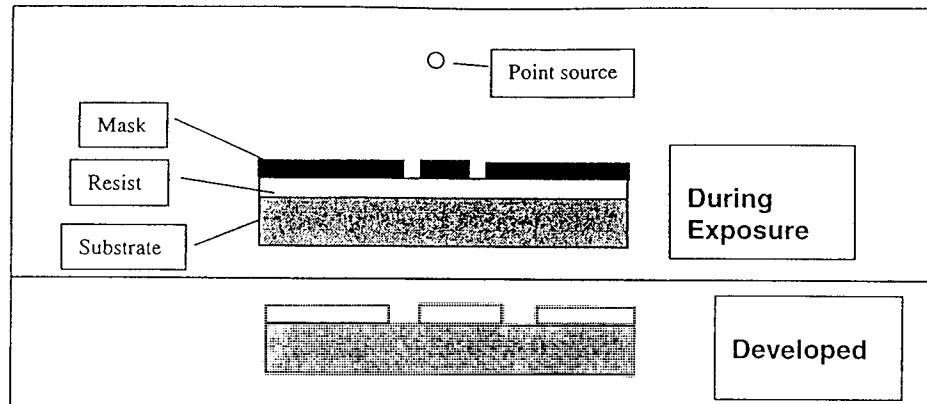


Figure 1. The lithography process

The synchrotron (electron storage ring) is suitable for producing the powerful soft x-ray required. The synchrotron facility costs tens of millions of dollars and several years to commission. Singapore has just made the decision to acquire one. In the meantime, important experiments are being constructed at NTU/NIE with a simpler but sufficiently powerful source. Unlike the synchrotron, the NIE device depends on highly compressed plasma with a high temperature at 3 million Kelvin, like conditions near the centre of the sun. The NIE device is a plasma focus designated as NX2.

In the NX2, a powerful electrical discharge is used to produce the hot plasma. (Plasma composes ionized gases. It is electrically conducting) Special electrodes are used to compress and focus the plasma. This enables high plasma density and temperature to be reached. These are needed to produce the correct type of soft x-rays (with wavelengths between 0.8-1.4 nm) in sufficiently powerful bursts. A schematic is shown in Fig 2, indicating the coaxial electrode structure in which the plasma is heated in two steps as follows:

- Region where the plasma is accelerated to high speeds and also the
- Region where it is compressed to high density and temperature.

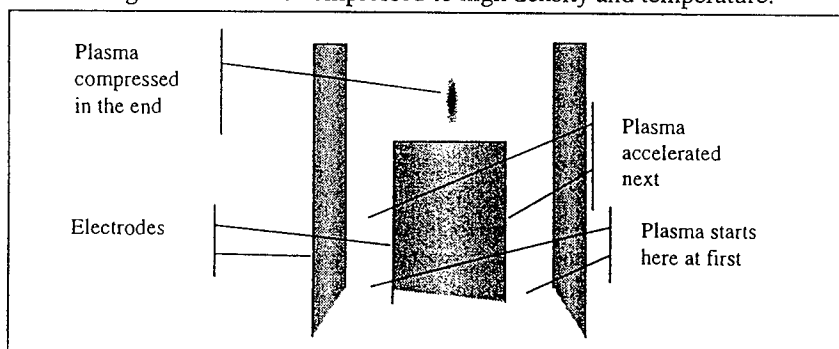
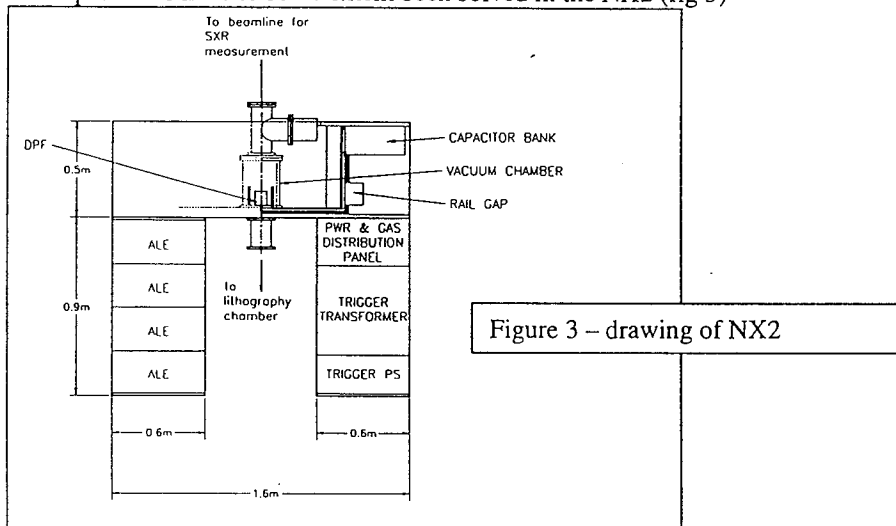


Figure 2: Plasma focus

There are several technical factors that must be achieved to produce sufficiently powerful bursts of soft x-rays with the correct wavelength:

- high currents (up to ½ million amp)
- controlled compression
- high repetition rate
- very high peak power of several gigawatts
- high average input of electrical powers of 30 kilowatt
- electrode materials and coating are important
- cooling of electrodes

These problems have to some extent been solved in the NX2 (fig 3)

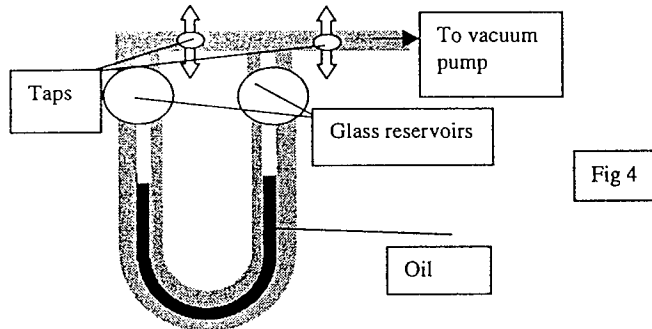


The NX2 produces powerful bursts of soft x-rays. However there are several problems in the accurate measurement of the soft x-ray yield. These problems had gradually been solved, one-by-one, but at the start of this project one problem still needed to be resolved. This is described below.

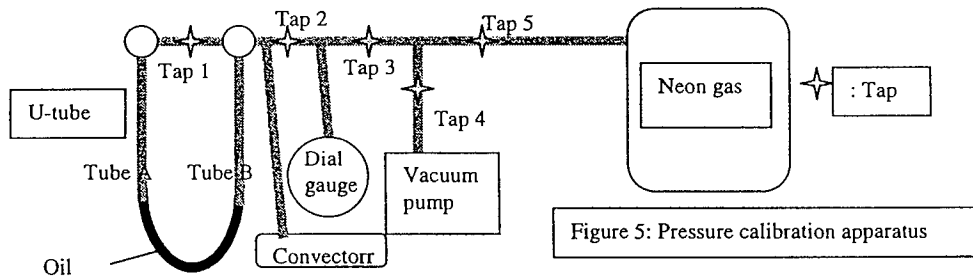
For the NX2, a “photo-conducting diamond” (PCD) is used to measure the soft x-rays. The measurement is normally made at the end of a beam line. Because SXR is easily absorbed by neon, the signal that the PCD gives out has to be interpreted taking into consideration filters that are used and the column of neon in the beam line. The correction for the neon column depends critically on the pressure. In the design of the NX2, this pressure is measured, for convenience, by electrical Convectorr gauges. However electrical pressure gauges are very unreliable under the conditions of our experiments because of the high currents and voltages of the discharge. It was suspected that the Convectorr gauge was not reading correctly. The wrong measurement of pressure would lead to wrong measurement of soft x-ray yield; thus the aim of the project is to calibrate the Convectorr gauge.

Experimental set-up

To calibrate the Convectorr gauge we developed an oil-filled U-tube manometer for comparing its pressure reading against that of the Convectorr. The required pressure range is from low pressure (taken as 0 torr) to 10 torr or 10 mm Hg. This is a range of pressure which is easily measured (by direct reading of the difference in heights (or head) of the two arms of the U-tube manometer) since 1 mm Hg equals about 15mm of oil, in terms of pressure exerted. Since we can easily measure a head of 1mm of oil we can then measure the pressure to better than 0.1 mm Hg or 0.1 torr. Our U-tube manometer is shown in Fig 4.



We connected the U-tube to a vacuum pump, to the Convectorr gauge and to neon gas in the arrangement as shown in Fig 5 below.



To obtain a calibration point, we open all the taps except tap 4 and 5. Next, tap 4 is slowly opened to let the vacuum pump pump the air out of the system. Now there is vacuum (taken as zero-pressure) in tube A & B. We then isolate tube A by closing tap 1. Tap 4 is closed now. Tap 5, a needle valve is gradually opened to let gas into the system, raising the pressure. The dial gauge, Convectorr and tube B will experience the pressure. Tube A however is at zero pressure and the pressure in tube B would push down the oil in it. This creates a difference in readings between tube A and tube B. This difference (H mm) measures the pressure exerted on tube B and the dial and the Convectorr gauges. The pressure is $P = H \cdot (\rho_{oil} / 13.6)$ torr. The density of the oil ρ_{oil} , used had been found, by using a density bottle, to be 0.86 g/ml.

U tube(torr)	Dial Gauge(torr)	Convectorr	U tube(torr)	Dial Gauge(torr)	Convectorr	U tube(torr)	Dial Gauge(torr)	Convectorr
0	0	0.22	0.82	0.95	3.3	1.47	1.71	6.8
0.24	0.19	0.4	0.88	0.95	4.2	2.12	2.28	210
0.41	0.38	1.1	1.00	1.15	6.8	5.53	6.08	420
0.47	0.57	1.5	1.06	1.14	6.7	11.41	12.54	710
0.65	0.76	1.9	1.12	1.30	12.7	15.76	17.29	820
0.71	0.95	2.6						

Table 1: Results for calibrating of pressure

In taking the measurement, it was noticed that the Convectorr readings had large fluctuations, even when the pressure was held steady. Typically 4 readings was taken to determine the average value of the Convectorr measurements.

Looking at the whole range of measurements (see fig 6 as well) it is noticed that the dial gauge generally agrees with the measurement by manometer. The Convectorr reads 2 to 3 times higher pressure from 0.4 torr to about 0.8 torr. Above 1 torr, the Convectorr measurements jumps to very high values. It is clear that this particular Convectorr gauge is completely unreliable for use in the NX2

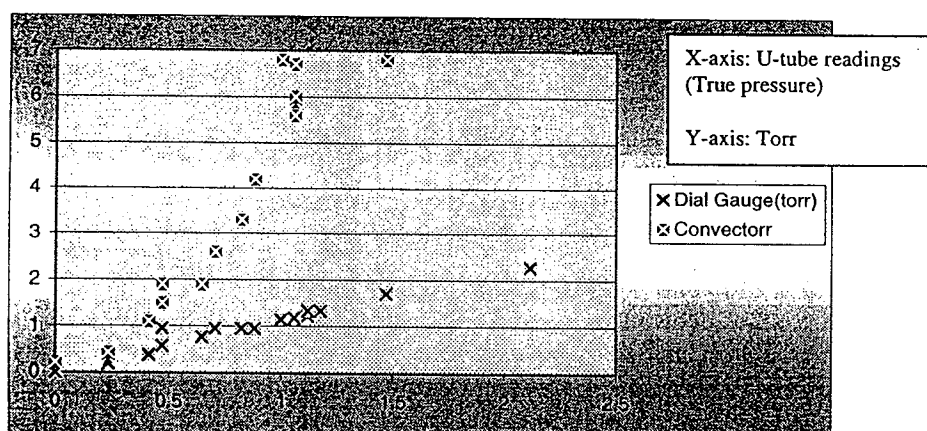


Fig 6: Convectorr measured pressure against absolute pressure measured by U-tube manometer

Discussion

Figure 7 is a graph of calculated beamline transmission vs beamline pressure. The beamline transmission would be 1 if there were no attenuation of the soft-x-rays at all. Because of attenuation of the filters, even when there is no neon pressure (perfect vacuum) at all there is still about 73% absorption by the filters, so that the transmission is 0.27%. At a neon pressure of 1 torr, the transmission is reduced to 0.13. Similarly at a neon pressure of 3 torr, the transmission is further reduced to 0.032.

We consider a typical example when the NX2 was operated at 1 torr true pressure, using the Convectorr the pressure (from fig 6) was measured (wrongly) as 5 torr. From the transmission curve (Fig 7) the transmission would be taken, (for 5 torr in beamline) as

0.01. The actual transmission factor (for true pressure of 1 torr) should be 0.13 for the correct pressure of 1 torr. Thus the transmissions factor was wrongly taken to be 13 times smaller than it actually was. This led to a huge error in the soft-x-ray yield; using the Convectorr registered pressure.

In that measurement the PCD output interpreted according to the Convectorr pressure would give 180 J whereas the actual yield was only 15 J.

Using the correctly measured pressure in the plasma focus NX2, the correct soft-x-ray yield was obtained. The highest yield of the NX2 was determined to be 18 J per shot and at 16 shots per second, almost 300W of soft-x-rays were produced during the burst lasting up to several minutes. At this level of yield a range of 300-500 shots is estimated to be required to expose a typical soft-x-ray resist in the experimental set-up of NX2. During our trials 400 shots produced a satisfactory test exposure as shown in Fig 8. This confirms that our soft-x-ray yield measurements are now reliable and accurate, now that the pressure gauges have been properly calibrated. Despite being substantially lowered by our calibration, the soft-x-ray power now correctly measured on the NX2 still ranks among the highest achieved by such machines to date.

Figure 7: Graph of Beamline transmission VS pressure

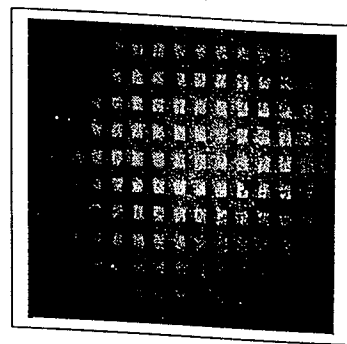
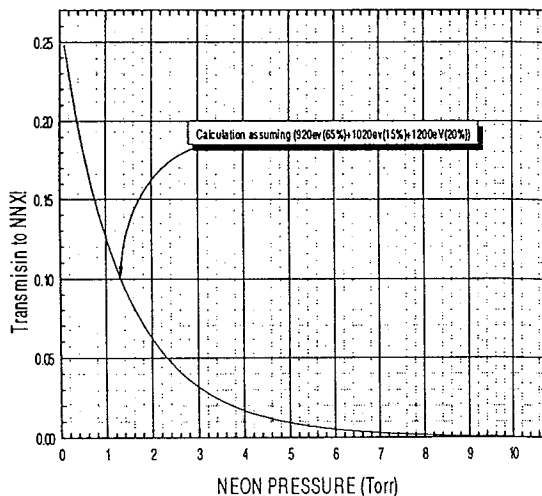


Fig 8: Test Lithography exposure, grid lines are 5 μ m apart

Conclusion

Using an oil filled U-tube manometer we calibrated the Convectorr pressure gauge used previously in the NX2 plasma focus soft-x-ray source. The calibration shows that that Convectorr gauge is not reliable or accurate, over reading by a factor of 3 up to 0.8 torr and by much more beyond 1 torr. This gave greatly exaggerated values to the soft-x-ray yields. Using the correctly calibrated pressure soft-x-ray yields are now correctly and reliably obtained in the NX2 soft-x-ray source. This is an important step in the development of the NX2 as a powerful soft-x-ray source for soft-x-ray lithography.

On the structure and composition of polycrystalline carbon nitride films synthesized by reactive rf magnetron sputtering

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Abstract

Polycrystalline β -C₃N₄ films have been deposited on single-crystal KCl(100) substrates using reactive rf magnetron sputtering. The films have been characterized by transmission electron microscopy (TEM), X-ray photoelectron spectroscopy (XPS) and atomic force microscopy. A large number of grains are found distributed in various regions of the film. The dimension of the largest grain is about 4 μ m. The film is composed mainly of C and N with a small amount of O. XPS data show N-bonded to sp³-hybridized C with some surface oxidation. The N/C ratio in the β -C₃N₄ region is deduced to be 1.23–1.27, close to an expected stoichiometric value of 1.33. The TED-measured interplanar spacings suggest that the crystalline grains are hexagonal with lattice parameters of $a = 6.30$ Å and $c = 2.46$ Å. © 1998 Elsevier Science B.V. All rights reserved.

1. Introduction

A type of carbon nitride, isomorphous to Si₃N₄, has been suggested by Liu and Cohen [1–3]. From ab initio calculations based on an empirical model for the hardness of the light covalent materials, a particular phase of carbon nitride, β -C₃N₄, has been predicted to have a bulk modulus of 4.83 Mbar, which is higher than that of diamond (4.43 Mbar), the hardest known material on earth. β -C₃N₄ may prove to be a remarkably novel material for wide applications ranging from microelectronics to aircraft propulsion. Exploring the synthesis and properties of such a hypothetical material is also significant to research in the fields of condensed matter physics,

material science and chemistry. Motivated by the above significance, efforts have been made experimentally to synthesize this hypothetical material using a variety of sophisticated techniques. These include laser ablation of graphite in an atomic nitrogen atmosphere [4], rf diode sputtering [5,6], rf plasma assisted hot filament chemical vapor deposition [7], on beam assisted deposition [8], as well as DC or rf magnetron sputtering [9]. Of all the above techniques, only a few techniques have been found to be promising for forming polycrystalline carbon-nitride films. Magnetron sputtering is a conventional and a powerful technique in film deposition, although only preparation of amorphous carbon-nitride films have been reported so far. This Letter will present the successful synthesis of polycrystalline β -C₃N₄ films on single-crystal KCl(100) substrates, by reactive rf magnetron sputtering.

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2. Experimental procedure

The deposition of carbon-nitride films has been carried out in an rf magnetron sputtering system where a 10-cm-diameter high-purity ($> 5\text{ N}$) graphite target is located on an rf powered electrode. The substrates are located 6 cm away from the target and rotated at a speed of 1 rpm in order to obtain deposition uniformity. The vacuum chamber is evacuated to a base pressure of 1.5×10^{-3} Pa, prior to deposition. Sputtering is conducted using 200 W rf power, in a nitrogen plasma at a filling gas pressure of 20 Pa. Since the deposition rate decreases with increasing substrate temperature and thermal desorption leads to the loss of N-containing species from the growing film surface, the substrates are intentionally unheated. Their temperatures typically rise to about 70°C during deposition. In order to reduce damage to the growing film resulting from bombardment by energetic particles, the substrates are left unbiased. KCl crystal is chosen as the substrate material, partly because the deposited film can be easily detached for TEM analysis.

3. Experimental results

3.1. Surface morphology

The deposited films adhere well to the single-crystal KCl(100) substrates and appear to be brown in colour to the naked eye. The morphology of the C–N film with a deposition time of 120 min is

studied using an atomic force microscope (Digital Instrument Nanoscope IIIa). An image of the surface is shown in Fig. 1 with both height and phase data. It is seen from this figure that a number of grains, with varying sizes, cover the whole substrate surface. The biggest grain is estimated to be $4\text{ }\mu\text{m}$ in diameter.

3.2. Film composition

Subsequent composition analyses have been performed in a VG ESCALAB MkII X-ray photoelectron spectroscope (XPS), fitted with an Mg K α source and a hemispherical energy analyzer. Wide survey scans of the film surface have been obtained at a 50 eV analyzer pass energy and show only the presence of C, N and O (see inset of N 1s spectrum in Fig. 2a). Narrow scans of the C 1s and O 1s peaks (at a 20 eV pass energy) have been obtained at two photoelectron emission angles (α) of 75° and 20° to the sample surface, in order to distinguish surface species from the bulk species. The spectra thus obtained are fitted with gaussian peak components mixed with 20% lorentzian peak shapes using a least squares routine, after Shirley background subtraction. Full-width-half-maximum (FWHM) values of 2.0 and 2.4 eV are used for $\alpha = 75^\circ$ and 20° respectively, for all peak components. The reason for the larger FWHM value at $\alpha = 20^\circ$ is caused by the slight differential charging over the sample surface associated with bigger analysis areas.

Fig. 2a shows the C 1s and N 1s spectra obtained

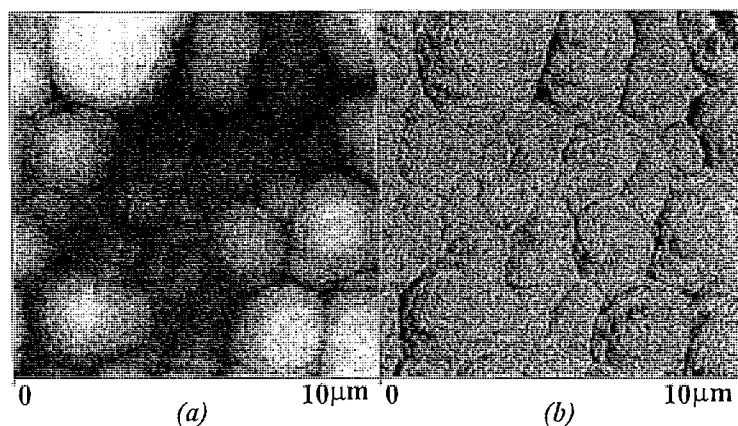
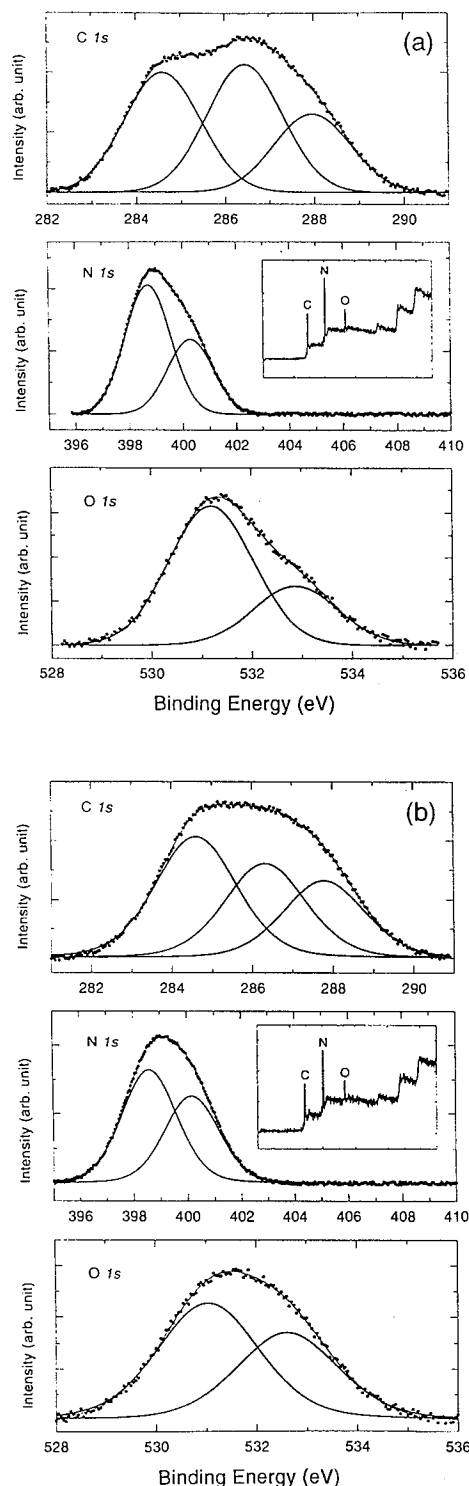


Fig. 1. Atomic force micrograph of the crystalline C–N film deposited on a single-crystal KCl(100) substrate with a deposition time of 120 min using (a) height data (z -range: $2\text{ }\mu\text{m}$) and (b) phase data (z -range: 50°). The dimension of the biggest grain in the film is measured to be about $4\text{ }\mu\text{m}$.



for $\alpha = 75^\circ$. The C 1s spectrum clearly shows the presence of adventitious carbon species on the surface as the component at the lowest binding energy (BE). This component is enhanced at $\alpha = 20^\circ$ (Fig. 2b) as would be expected for a surface species and is used as the reference peak (284.6 eV) for charge shift corrections. It is possible that the component may also be derived from graphite-like carbon as observed by Matsui et al. [10]. The peak fitting routine yields two other components located at BE = 286.4 and 287.9 eV, which are assigned to C–N and N–C–O like species. Reports elsewhere have designated peaks at similar positions to sp^2 - and sp^3 -hybridized C species bonded to N, for example, Marton et al. [11] (286.1 ± 0.2 and 287.7 ± 0.2 eV) and Tabbal et al. [12] (285.8 and 287.0 eV), based on early XPS data on pyridine (C_5H_5N) and urotropine (hexamethylene-tetramine; $C_6H_{12}N_4$). However, using data by Beamson and Briggs [13] from N-containing polymers such as poly(ethyleneimine) (PEI) and poly(2-ethyl-2-oxazoline) (PEOx), it appears that the chemical shift for each single N-bonded C species is 0.56 eV. Applying the idea of Pauling charge to the C–N bond, we may expect the chemical shift for β - C_3N_4 to be 2.0–2.2 eV so the C–N peak assignment is justified. It may be noted that peak assignments contain some inherent ambiguity and that the present C 1s data show the C–N component to be of much higher intensity than what has been reported previously [11,12]. The peak positions and FWHM in this Letter are guided by the clear separation of the adventitious C from the C–N component, whereas using additional peaks in the fitting (to distinguish sp^2 - and sp^3 -hybridized C species) clearly leads to spurious and inconsistent results for the two photoelectron emission angles. Hence, we find no basis to deconvolute the C–N component into two subsidiary peaks and believe that this component indicates β - C_3N_4 . The component at 287.9 eV arises from C sites where one or more N atoms have been replaced by O atoms due to surface oxidation of the pristine β - C_3N_4 film, giving rise to N–CO–N or N–C=O species. The data from acrylamide polymers and nylon in Briggs and Beamson [13], indicate chemical shifts of between 3.0 and 3.6 eV for such C species,

Fig. 2. X-ray photoelectron spectra for C 1s, N 1s and O 1s obtained at α of 75° (a) and 20° (b).

which agree with the 3.3 eV shift observed in our case. That the oxidation is more surface than bulk related can be seen from the increased intensity of this component for $\alpha = 20^\circ$, as compared to the C–N peak. The oxidation also results in a slight reduction in the N content of the film.

Proper peak assignments have to include both the N 1s and O 1s spectra. Two components at 398.7 and 400.3 eV are obtained in the peak fit for N 1s spectra in Fig. 2a,b. The first can be identified with the N–C species in the form of β - C_3N_4 . Again, we rely on the data from PEI [13], where the N 1s peak is located at 398.7 eV. However, as noted in Marton et al. [11], the trigonal geometry at the N site in β - C_3N_4 should lead to a reduced electron density contribution from the lone pair and thus increase the

BE value, although it is not known whether the additional shift could be as much as 1 eV, as suggested by those authors. The second peak at 400.3 eV is identified with the N–CO species. Following the same line of reasoning, this value is best compared with that of poly(ether imide) (KAP) [13] where the N atom is also located on a trigonal site. KAP gives a value of 400.2 eV. As is in the C 1s spectra, the O-related peak is enhanced in the more surface-sensitive scan at $\alpha = 20^\circ$ (Fig. 2b). Again, the peak assignments differ from those of Marton et al. [11] who have also obtained two peaks in the N 1s spectra at 398.5 and 400.0 eV, but have assigned the higher BE peak to N atoms bonded to sp^2 -hybridized C species.

Peaks corresponding to N_2 physisorbed on

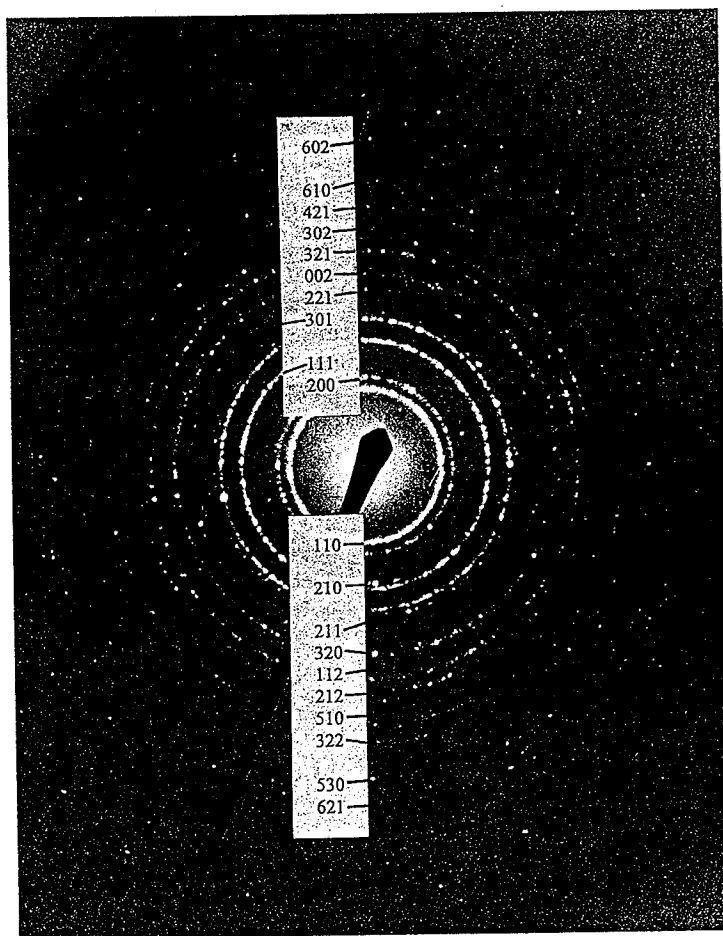


Fig. 3. An electron-diffraction pattern obtained for a sample with a deposition time of 30 min. The d -spacings calculated from the diffraction rings and the relative intensities are given in Table 1.

graphite (BE = 404 eV) [14] and atomic N (BE = 409.9 eV) [15] are not observed in the N 1s spectra, which implies that all N atoms in the film are indeed bonded to C atoms. From the peak areas of the C 1s and N 1s spectra, the N/C ratio calculated from the β -C₃N₄ components yield values of 1.23 and 1.27 for $\alpha = 75^\circ$ and 20° , respectively, which indicates the high quality of the film, both at the surface and in the bulk.

The O 1s spectra can be used to further substantiate the above data interpretation. The spectra in Fig. 2a,b show two components at 531.2 and 532.9 eV, which typify π - and σ -bonded O atoms to C in the form of N–C=O and O–NC–O. Comparing the spectra for $\alpha = 75^\circ$ and 20° , it appears that the σ -bonded species are more prevalent on the surface than in the bulk. It should be noted that either form can be expected to yield similar BE values for the C 1s and N 1s spectra, so the presence of O on the surface is consistent with surface oxidation of the β -C₃N₄ film. Using the O-related components from the C 1s and N 1s spectra and the whole O 1s en-

velop, the calculated C/N/O ratios are 1:1.11:0.69 and 1:1.18:0.62 for $\alpha = 75^\circ$ and 20° , respectively, indicating a uniform layer of oxidised film.

3.3. Film crystallinity

The structural study of the sample has been carried out using a JEOL-2010 transmission electron microscope operated at 200 KeV. The specimen is prepared by separating the deposited film from the KCl substrate in de-ionized water. The film is then mounted on a copper grid. A standard Au sample is used to determine the camera constant. Fig. 3 shows an electron diffraction pattern of the sample with a deposition time of 30 min. This figure reveals that the film is of polycrystalline structure with a high degree of crystallization. The interplanar spacings d are directly measured from Fig. 3 using the pre-determined camera constant and are tabulated in Table 1.

The measured d -spacings, together with those theoretically predicted by Liu and Cohen [1] and

Table 1

Comparison of the TED data with the calculated β -C₃N₄ using lattice parameters of $a = 6.30 \text{ \AA}$, $c = 2.46 \text{ \AA}$ and the results of Refs. [1] and [5]

This work			Ref. [1]		Ref. [5]	(hkl)
TED		Calculated $a = 6.30 \text{ \AA}$, $c = 2.46 \text{ \AA}$	Calculated $a = 6.43 \text{ \AA}$, $c = 2.46 \text{ \AA}$		Calculated $a = 6.3 \text{ \AA}$, $c = 2.38 \text{ \AA}$	
$d (\text{\AA})$	l	$d (\text{\AA})$	$d (\text{\AA})$	l	$d (\text{\AA})$	
3.15	s	3.150	3.213	m	3.150	110
2.72	s	2.728	2.783	s	2.728	200
2.04	m	2.062	2.103	s	2.062	210
1.94	s	1.939	1.953	m	1.899	111
1.65	s					
1.58	w	1.580	1.598	w	1.559	211
1.47	w	1.462	1.543	w	1.445	301
1.35	w	1.326	1.345	w	1.313	221
1.26	w	1.252	1.277	w	1.252	320
1.23	m	1.230	1.229	w	1.190	002
1.16	w	1.146				112
1.12	m	1.116	1.133	m	1.108	321
1.05	w	1.056				212
1.02	w	1.019				302
0.97	w	0.980				510
0.93	vw	0.951				421
0.87	vw	0.877				322
0.83	vw	0.832				610
0.77	vw	0.779				530
0.73	vw	0.731				602
0.72	vw	0.723				621

s, m, w and vw represent strong, medium, weak and very weak.

Table 2

Comparison of the lattice parameters suggested by this work with the theoretical predictions and experimental suggestions of other works

Parameter	This work	Ref. [5]	Ref. [1]	Ref. [16]	Ref. [17]	Ref. [18]
a (Å)	6.30	6.30	6.43	6.37	6.41	6.402
c (Å)	2.46	2.38	2.46	2.40	2.40	2.404
V (Å ³)	84.55	81.80	88.10	84.67	85.53	85.33
B (Mbar)			4.27	4.50	4.37	4.51
c/a	0.390	0.378	0.383	0.377	0.374	0.376

V is the equilibrium volume and B is the bulk modulus.

those experimentally observed by Yu et al. [5] are listed in Table 1. The intensities of the diffraction rings of our work match the theoretical β -C₃N₄ reasonably well. The measured d -spacings, however, are generally lower than those of the theoretical calculations. Adopting a procedure similar to that of Yu et al. [5], and assuming a hexagonal structure, a new set of lattice parameters is deduced to be $a = 6.30$ Å and $c = 2.46$ Å. From these values, the d -spacings are re-calculated and added to Table 1. It is clearly seen that the measured d -values agree with the recalculated values well, except for $d = 1.65$ Å which is also observed by Yu et al. [5]. Here, the identification of the Miller indices has been guided by the calculated structure factors using the present lattice parameters and additional information contained in Teter and Hemley [18].

The lattice parameters obtained from the current work lie between the theoretical prediction of Liu and Cohen [1] and the experimental finding of Yu, et al. [5]. Recently, Reyes-Serrato et al. [16] obtained the values of $a = 6.37$ Å and $c = 2.40$ Å, using the ab initio Hartree–Fock method. Two additional sets of a and c have also been suggested by Liu and Wentzcovitch [17] and Teter and Hemley [18]. These lattice parameters are summarized and compared in Table 2. Although our value of c/a is slightly larger than the others, the volume of our unit cell is not significantly different.

4. Conclusion

Polycrystalline β -C₃N₄ films have been deposited on single-crystal KCl(100) substrates using rf magnetron sputtering technique. A large number of grains

with size up to 4 μ m are observed to cover the entire substrate. XPS data show that an N/C ratio close to the stoichiometric value for β -C₃N₄ has been obtained. From the TED-measured interplanar spacings d , a new set of lattice parameters is deduced. The intensity of the TED matches with the theoretical prediction of Liu and Cohen [1] well.

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A Powerful Soft X-ray Source for X-ray Lithography Based on Plasma Focusing

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Abstract

A source of soft X-ray emission (9–14 Å) based on the miniature 15 kJ plasma focus was developed and tested. The X-ray emission was channelled along the chamber axis through an opening in the inner electrode (anode). A regime with a mean output of more than 100 J per discharge was found. At a discharge current of 280 kA and repetition rate of 3.5 Hz achieved by the device, its lifetime was estimated to be 10^7 commutations (about a year of continuous operation). A demonstration experiment on irradiation of an X-ray resist is discussed.

1. Introduction

Current progress in a number of areas of science and technology related to the study and manufacture of nanostructures (such as investigations of "wet" biological fabrics and nanoelectronics technology) is based on mastering the production of sources of radiation with wavelengths of the order of or shorter than 0.1 μm and the accompanying techniques for forming structures using this radiation. It is obvious that the most important sources are those with wavelengths shorter than the scale indicated. For such sources to be effectively used in nanophysics, they must satisfy a whole series of specific requirements; the most important of these are that their spectra be as monochromatic as possible and that the beams of radiation diverge as little as possible. It is clear that X-ray lasers would provide an ideal solution to this problem. Work on such lasers, however, is still in a rudimentary stage, and it is too early to count on rapid progress in this area to provide a technologically and commercially viable installation. Fortunately, there are other powerful sources of soft X-ray radiation with parameters that are fully satisfactory for the requirements of some areas of science and technology. Unsolved problems concerning these sources are the reproducibility of the soft X-ray pulses, and the high rate of operation and the lifetime of installations.

Investigations are being carried out along two main directions, using proximity and projection X-ray techniques. In the first case, the optimum wavelength is very short (usually of the order of 10 Å), in order to avoid diffraction effects without simultaneously decreasing the gap between the object and detector (resist) to technologically unacceptable values (usually several micrometers). In the second case,

longer wavelength radiation is used (of the order of 100 Å), so that it is possible to use X-ray optics based on multi-layer reflecting mirrors and phase-zone plates. After fifteen years of work in this field, only three sources appear to be promising for the applications indicated above: sources based on synchrotron radiation from relativistic electrons, sources based on laser produced plasma, and pinch-plasma sources. The first type of source requires relatively expensive accelerators, in particular, steppers (due to the necessity that they be positioned vertically); the second has a low efficiency and a number of technological deficiencies. In connection with this, recent work [1, 2] in this field has given more and more attention to point sources of soft quasi-monochromatic X-ray emission based on the z-pinch. Because of their constructional properties, "plasma focus" installations are the best for such sources [1–4]. In light of the factors indicated above, we concentrated our attention on creating a soft X-ray source based on a plasma focus pinch device.

We thus developed and tested a plasma-focus soft X-ray source (9–14 Å). The main energy storage devices in our setup were four KMK-30-8 high-voltage impulsive capacitors [9] with total energy storage capacity to 15 kJ. The commutators were four EVOLYUTA-1 [5, 6] thyatrons with cold cathodes, each designed for commutating up to 150 kA. One of the main problems that had to be solved during the development of the facility was providing a long lifetime. Our solution was based on selecting the most current elements and systems and lowering their operational parameters in comparison to the maximum allowable values. At the discharge current of 280 kA and repetition rate of 3.5 Hz achieved by our device, we estimate its lifetime to be 10^7 commutations (about a year of continuous operation). The soft X-ray source itself was a miniature plasma-focus chamber filled with neon at a pressure of 10–25 mbar. The X-ray emission was channelled along the chamber axis through an opening in the inner electrode (anode). The radiation was recorded using PIN diodes. Roughly 20 000 discharges were produced on the four-capacitor device. We searched for an optimal operational regime and adjusted the shape and dimensions of the plasma-focus chamber electrodes to optimize the device for the absolute X-ray radiation output. We found a regime

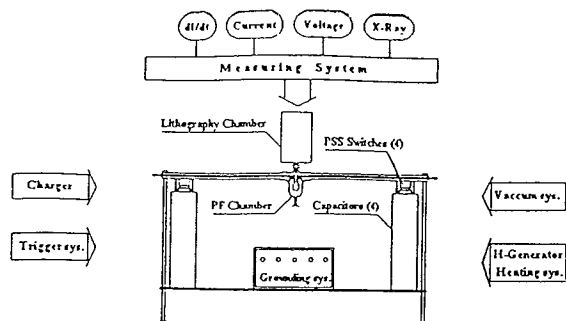


Fig. 1. The schematic diagram of the basic device

with a mean output of more than 100 J per discharge. We conducted a demonstration experiment on irradiation of an X-ray resist with characteristic dimensions for its element of about 5 μm .

2. General description of the device's construction

Our device consists of the following constructional elements and systems:

- energy storage provided by four capacitors;
- a discharge device;
- four pseudo-spark gaps, commutating the capacitor discharge to the discharge chamber;
- four heating systems for the commutator hydrogen generators;
- a four-channel system for ignition of the switches based on a spark gap;
- a pulse generator that sets off the ignition system for the pseudo-spark gaps;
- high-voltage buses and a collector;
- a "plasma-focus" discharge chamber;

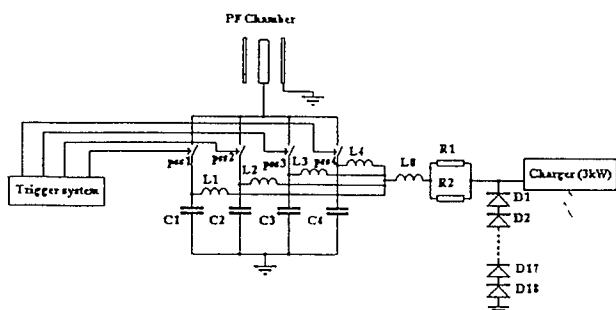


Fig. 2. The main electric circuit for the basic device.

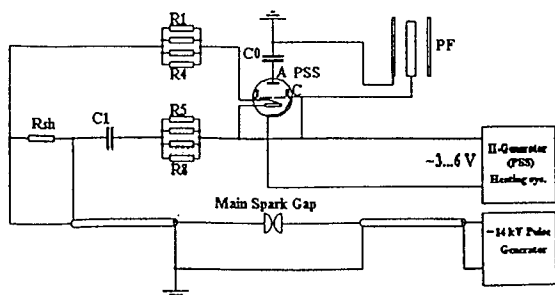


Fig. 3. The main circuit of the ignition system.

- a vacuum pumping system;
- a system for filling the discharge chamber with working gas, with control of the final pressure;
- an output channel for the X-ray radiation, permitting investigations of the parameters of the radiation and irradiation of X-ray photo-resists;
- a discharge system and safety system;
- a set of diagnostic methods and recording devices.

Figure 1 shows a schematic diagram of the device. The four high-voltage capacitors are located at the four corners of a rectangle with sides $1050 \times 990 \text{ mm}^2$; a commutator is installed directly on each capacitor. The device uses a discharge circuit with a grounded plus. The plasma focus chamber is placed in the current collector, which is made of brass with an application of kaprolon nylon as an insulator, so that the vacuum system connects to it from below (Fig. 1). The output channel for the X-ray radiation is directed upward, where a chamber for irradiation of an X-ray resist with X-ray dosimeters is mounted, with its own vacuum pumping system. Collet clamps are used to hold the plasma focus chamber in the current collector. Figure 2 shows the electric circuit for the device. The main circuit for the ignition system, which will be described in more detail, is presented in Fig. 3.

3. The high-voltage capacitors

The high-voltage impulsive capacitors used for energy storage were developed at the St. Petersburg State Technical University especially for our device. They have been given the KMK-30-8 (low-inductance castor capacitors, voltage 30 kV, capacitance 8 μF , with design inductance 10 nH). The special construction of the capacitor leads ensures not only small inductance of the capacitor itself, but also provides for a low-inductance connection for the commutator. This was possible because the construction elements for the mating – the capacitor and commutator – were made mutually compatible by the engineers during the planning of the device. The system of capacitor leads and prefabricated buses has enhanced thermal and dynamical stability, which makes it possible to achieve a nominal current value of up to 350 kA (on one capacitor) during a discharge to a low-inductance load. The use of polymer capacitor plates and capacitor papers with enhanced electrical strength allowed us to substantially decrease the thickness of the dielectric section and weaken the edge of the foil. The capacitor weight is 70 kg and its dimensions are $240 \times 270 \times 680 \text{ mm}^3$.

Due to the use of an optimal structure for the combined insulation, the design capacitor lifetime for nominal voltages is 10^6 discharges. The capacitor is intended to operate with aperiodic discharges at a repetition rate of up to 1 Hz. If the operational voltage is lowered, it is possible to increase the pulse repetition rate, and the capacitor lifetime increases according to the power law dependence $(U/U_0)^6$. For example, at voltages that are half the nominal voltage, i.e., about 15 kV, the expected increase in the lifetime is two orders of magnitude. In other words, the capacitor lifetime at a voltage $U = U_{\text{nom}}/2$ should be of the order of 10^8 discharges, which should correspond to a time interval of 3 years for continuous operation with a repetition rate of 3 Hz.

We note, however, that the conditions for aperiodic discharge are important when estimating the capacitor lifetime. In the device described, the discharge has the form of decaying oscillations which are not aperiodic. In this case, the capacitor lifetime is determined by some effective voltage, made up of the charging voltages and the amplitude of the second half-wave of the discharge voltage (the maximum polarity reversal voltage). The operational charging voltage in our experiment was 12 kV; as can be seen from the voltage oscillogram (Fig. 8), the polarity reversal voltage was 70% of the charging voltage, or 8 kV. Thus, we should estimate the lifetime of the capacitor for these conditions using an effective voltage $U_{\text{eff}} = 20$ kV. The lifetime of our high-voltage KMK-30-8 capacitor in this case is slightly higher than 10^7 discharges, i.e., about a year of continuous operation.

4. The commutator

To commutate the impulsive energy to a load in the device, we used a thyatron with a cold cathode, also called a pseudo-spark gap or low pressure spark gap. We used an EVOLYUTA-1 [5-7] low pressure spark gap with maximum anode voltage 25 kV, maximum anode current amplitude 150 kA, maximum discharge frequency 50 Hz, and minimum operating age (lifetime) in terms of the total charge commutated of more than 5×10^5 C.

Figure 4 shows the external appearance and construction of the EVOLYUTA-1 pseudo-spark gap. The low pressure spark gap is filled with gas at a pressure of 0.01–0.8 Torr. For currents to approximately several kiloamperes and pulse durations to 1 μ s, initiation and development of the discharge, as well as the achievement of the conducting phase, occur in a gas-filled medium; for larger currents and pulse durations – as in vacuum conditions – they occur in vapours of material from the hard metallic cathode. The ballast volume is open to the inter-electrode space via four openings with diameter 3–4 mm, located in a circle with a 40 mm circumference.

Studies of the low pressure spark gap showed that the rapid decrease of the electrical strength of the spark gap caused by the appearance of dielectric films of ceramic material on the sides of the cathode surface had a very large influence on its longevity. We were able to fully eliminate this effect using a special, so-called re-entrance arrangement of the main electrodes, a screening system, and special dielectric covering for the inner surface of the ceramic insulator to protect it from the action of the arc discharge.

The main role in increasing the lifetime indicators of the low pressure spark gap is played by the special construction

of the cathode. Erosion of the cathode was decreased using a "sandwich" structure, with layers of materials with different values for their heat sublimation. The uppermost layer, facing the anode, has the minimum value, and layers of materials with increasingly larger heats of sublimation are arranged deeper.

This cathode operates as follows. In the initial period, as is usual, the discharge causes a local destruction of some part of the working surface around the circumference of the cathode opening. The low-melting material vaporizes from this area, with subsequent exposure of the underlying layer of high-melting material, leading to a worsening of the conditions for vaporization. As a result, a deficit of charge carriers arises, and the discharge voltage is decreased. Since it is energetically favourable for the discharge to burn in the low-melting material, a situation is created in which the discharge channel is shifted to the neighbouring section of the working surface, where the layer of low-melting material has not been depleted. With time, nearly the entire surface layer of low-melting material is depleted in this way. After this, the depletion of the deeper, second layer begins. In principle, if there are several layers of different materials, this process is repeated for each, leading to the destruction of increasingly deeper layers.

Thus, during the operation of the spark gap, this "sandwich" structure automatically regulates the more even, complete, and sequential depletion of the cathode, thereby increasing its longevity. Making the working surface of the cathode from low-melting material creates conditions that lower the energy required to maintain the burning of the arc discharge and ensure that the current pulse has a smooth shape, without breaks or sharp oscillations.

In the ignition node, we used a cylindrical igniter of polycrystalline boron carbide-nitride mounted on a ceramic plate. One of the ignition electrodes was a pin at one end of the cylinder; the second electrode, which is in the shape of a copper wire spiral, bends around the middle part of the lateral surface of the cylinder. Due to its polycrystalline structure, the igniter has a rough surface with many protuberances, which form a large number of contact points with the winds of the copper wire, each with its transition resistance. When the ignition voltage is delivered, a spark forms at one of the points of contact, where the conditions for energy release are optimal; if the ignition energy is sufficient, this spark causes the development of a discharge spanning the gaseous space above the surface of the igniter between the electrodes. The field formed between the cathode and igniter causes electrons from the resulting discharge plasma to be injected through the cathode openings into the space between the cathode and anode of the low pressure spark gap, igniting the main discharge.

In this process, sparks are created at various points of the igniter. The igniter material and the copper wires gradually vaporize. The service time for this type of construction exceeds 5×10^6 pulses for ignition parameters $U_{\text{tr}} = 2$ kV, $I_{\text{tr}} = 100$ A, and $C_{\text{tr}} = 0.2$ μ F. During the working regime of the ignition system, about 0.4 J of energy is released in the igniter. In order for the operation of several spark gaps to be highly synchronous (see below), we used nanosecond ignition pulses with energy two orders of magnitude lower than recommended. No deviations from the usual working regime of the low pressure spark gap were noted. This mode

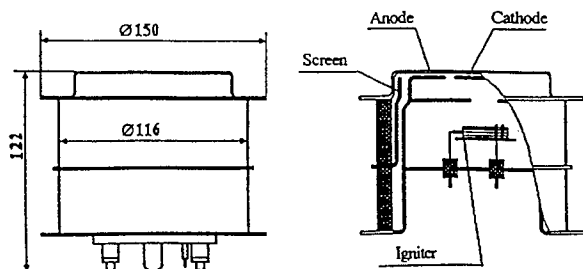


Fig. 4. The external appearance and construction of the EVOLYUTA-1 pseudo-spark gap.

of operation should increase the expected lifetime of the ignition system of the low pressure spark gap. The resistance of the igniter R_i was usually from 10 Ohm to several kOhm.

A variable voltage from 3–6 V was applied to the hydrogen generator (not shown in Figure 4); the specific value of this voltage was carefully chosen for each low pressure spark gap in a series of "practice" starts, and must be controlled during its subsequent use, since it determines the operational pressure of the gas in the interelectrode space, and consequently the electric strength of the discharge. Experience showed, however, that after starting from different voltages for each of the four low pressure spark gaps, after about 100 starts, all four pseudo-spark gaps began to operate very regularly at a single voltage, equal to 5 V. One of the leads of the hydrogen generator is connected to the cathode of the low pressure spark gap. This required the use of isolation transformers (designed for 100 kV) in the power chain for the hydrogen generator for each of the four low pressure spark gaps. The initial winding of the transformer was fed from its thyristor circuit, ensuring smooth regulation of the hydrogen generator voltage.

It should be noted that the construction for the low pressure spark gap we have described makes it possible to use it in a periodic operating regime, i.e., when the first and second half-periods of the discharge current are equal in amplitude. As we already noted the discharge has the character of a decaying oscillation; in our device, this does not affect the longevity of the low pressure spark gap in any way. To estimate the expected lifetime of the low pressure spark gap in the experiment described, we can begin with the fact that roughly 0.15 C of electric charge is transferred through it in a single discharge. Considering the passport value for the maximum total charge transfer of 5×10^5 C, we estimate that the lifetime of the spark gap will be 3×10^6 discharges.

5. System for starting and synchronization of the EVOLYUTA-1 pseudo-spark gap

To achieve high reproducibility (stability) of the parameters for the X-ray radiation obtained in a plasma focus installation, the time scatter for the operation of the high-precision EVOLYUTA-1 spark gaps used for the commutating must be minimal (not more than several nanoseconds). This requirement is also made by safety considerations – when the scatter in the starts of the discharges for each of the capacitors is so small, it is not possible to have a situation where the discharge of the capacitor that discharged first goes not to the plasma focus, but instead to another "late" capacitor.

It was not possible to satisfy this condition using the starting circuit for the low pressure spark gaps proposed by their developers, since it provided a starting pulse front of 0.5 μ s. We therefore developed a series of other circuits. The best results were obtained when we used a generator in which a square-wave voltage impulse is formed using a coaxial cable and high-pressure (1–5 atm) spark gap. The main starting circuit is shown in Fig. 3. One four-channel gas spark gap and, correspondingly, four charge and discharge cables, each of length 6 meters, were used (one channel is depicted in Fig. 1. Thus, the system made it pos-

sible to obtain high voltage (4–5 kV) impulses with duration $t = 2l/V_f$ where V_f is the velocity of propagation of the electromagnetic wave in the cable and l is the cable length. The duration of the leading edge of the impulse is determined by the inductance of the spark gap and the discharge space in it. In our case, the leading edge was about 6 ns and the impulse duration was 60 ns.

When developing this circuit, we tested both three-electrode and two-electrode gas spark gaps. In the first case, the third electrode, located between the two main electrodes, acted to initiate (ignite) the discharge, while in the second case, the circuit worked in a "self-breakdown" regime. In order to ensure stable, uninterrupted operation of the system in a Hertz regime, we used the two-electrode spark gap. The decrease in the instability of the time of breakdown of the gas gap was due to the fact that the spark gap was tuned to the self-breakdown long before the maximum discharge voltage was achieved (in our case at 6 kV as opposed to the maximum discharge voltage of 15 kV).

Operation of the spark gap in a Hertz repetition regime was provided by the impulse charge circuit of the charge cables (Fig. 3). In order to have synchronization with the diagnostic spark gap apparatus, another channel was added, i.e., another charge and discharge cable were used. The ignition impulse was applied to the controlling electrode of the pseudo-spark gap through a KVI-3 S3 isolation capacitor. A shunting resistance R_{sh} installed in one of the channels was used to remove the charge from the cables.

6. The plasma focus chamber

The basis of our experiments was a miniature plasma focus chamber, initially developed as a neutron source using deuterium as the working gas. This chamber provided up to 10^8 fast neutrons per discharge for 3 kJ of energy stored in the storage device. During a low-inductance discharge, a short-lived (10–100 ns) hot (T_e and T_i to 1 keV), dense (to 10^{19} particles per cm^3) plasma formed on the axis of the plasma focus chamber; during the time it exists, this plasma is a source of neutrons and X-ray radiation over a wide spectrum (this formation is called the "plasma focus"). The chamber electrodes are prepared of especially pure unoxidized copper. Special technology is used during the assembly of the chamber, such as welding of the metal by an electron beam; spray application of a metallic layer onto the ceramic surface, so as to make it suitable for subsequent vacuum welding with metallic components; and so forth. Very important distinguishing properties of the chamber are the absence of any rubber seals and the matching of the joining materials in their coefficients of thermal expansion.

In order to outfit the chamber for X-ray lithography, it was necessary to change the construction of its inner electrode so that we could output the X-ray radiation through it, with subsequent channelling to an irradiation target with an angular aperture of 5 degrees. In order to increase the intensity of the radiation extracted from the plasma focus chamber at the required soft X-ray wavelengths (9–14 Å) required for X-ray lithography, we used neon as the working gas (Ne IX and Ne X lines). Exchanging the deuterium gas usually used in the chamber with neon required some changes in the chamber construction to ensure that the electrical and dynamical parameters of the discharge

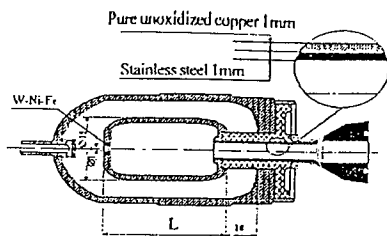


Fig. 5. The late version of the plasma focus chamber.

were consistent. In particular, we varied the length of the inner electrode L (Fig. 5) in the range from 35 mm to 54 mm (the optimal length proved to be about 45 mm).

For each inner electrode length, we selected the initial pressure for the working gas filling the chamber. Our selection criteria were that the time of formation of the plasma focus should coincide with the beginning of the decay of the discharge current curve, and also that the "singularities" in the current oscillogram be deep. The transition to a full-scale experiment with four capacitors required substantial increase in the mechanical strength of the X-ray output channel, since the magnetic field corresponding to the increased current for this case proved to be so large that its pressure crushed the channel after 30–50 "firings". We were able to eliminate this deficiency by filling the inner electrode with a two-part output channel: coaxial tubes of copper and stainless steel welded together in the outer part of the chamber. In its final form, the inner electrode of the plasma focus chamber has an insert made of a high-melting W-Ni-Fe alloy with an opening of diameter 1 mm, which, in addition to increasing the longevity of the chamber, will make it possible in future experiments to use differential vacuum pumping for the volume of the plasma focus chamber itself and the X-ray lithography chamber. This is very important, in view of the large absorption coefficient of gaseous neon in the working wavelength range for X-ray lithography. One of the late versions of the plasma focus chamber is schematically depicted in Fig. 5. As can be seen from this figure, the plasma focus chamber is neither a Filippov- nor a Mather-type chamber [3, 4], but rather, the electrode configuration places it somewhere between them. A chamber of this construction makes it possible to irradiate a $(27 \times 27) \text{ mm}^2$ square area 430 mm from the plasma focus with soft X-ray radiation.

7. Experiment with a single capacitor

This experiment preceded the full-scale tests using the device described above, and was done to verify the performance of the elements used. We used a single high-voltage capacitor as the energy storage device; this capacitor had the same parameters as described above, but was an earlier version made by the same producer, and therefore differed in its larger dimensions and mass. The ignition of the low pressure spark gap was carried out using the circuit developed by its manufacturer (the recommended ignition parameters are presented above).

One significant way in which the preliminary experiment differed from the main one (apart from scale) was the use of a charging circuit with a negative inner plasma focus electrode and, accordingly, a positive outer electrode (the

housing of the chamber). It is known that when a plasma focus chamber is used as a generator of neutrons or hard X-ray radiation, it is important that its inner electrode be the anode. Many years of study of the plasma focus phenomenon have shown that precisely in this case there are extinction phenomena when the current is pinched, which lead to the efficient acceleration of charged particles in the plasma, and consequently to the generation of hard radiation. In order to obtain soft X-ray radiation from the plasma focus in the form of Bremsstrahlung and line radiation of the hot neon plasma, it was not necessary to achieve the conditions under which current extinction phenomena and acceleration of charged particle fluxes would be observed. In this sense, the question of the electrode polarity lost its relevance. Nonetheless, we decided to use the traditional plasma focus electrode polarity for the full-scale device, and to output the radiation through a channel in the inner – positive – electrode. This decision to output the radiation through the anode was dictated by the fact that during the formation of the plasma focus during the discharge, there is a powerful cumulative plasma jet (and flux of accelerated ions, when there is particle acceleration) directed toward the cathode. If the radiation is output through the cathode, which is easier in terms of construction, the problem arises of protecting the output diaphragms, beryllium filters, etc. from the destructive action of the plasma and ion jets. In addition, it is very desirable to differentially pump the working gas (neon) due to its large absorption coefficient for the working radiation (wavelength 9–14 Å). This pumping should begin as near the pinch as possible, which is difficult to realize if the radiation is output through the cathode. These problems do not arise if the output is through the anode. We should add, that, as noted earlier, the output channel in the full-scale device is located at the top of the chamber. This also eliminates the necessity to clean the output filter of macroparticles incident from the plasma focus zone, as is done, for example, by Sato *et al.* [8], for the case when the radiation is output below.

For the preliminary experiment with a single capacitor, however, the inner electrode of the plasma focus chamber was chosen to be the cathode. This was done to simplify the assembly of the device, which was primarily intended only to test the electrical systems. In fact, as will be seen, this choice confirmed the fact that plasma focus is more effective when the inner electrode is positive.

Figure 6 depicts the circuit for the preliminary experiment, in which about 5000 discharges were produced. In these experiments, the capacitor was charged to a voltage of 13–15 kV; the discharge current reached values of 110–

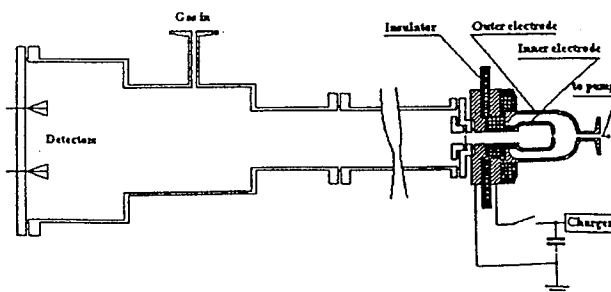


Fig. 6. The circuit of the preliminary experiment.

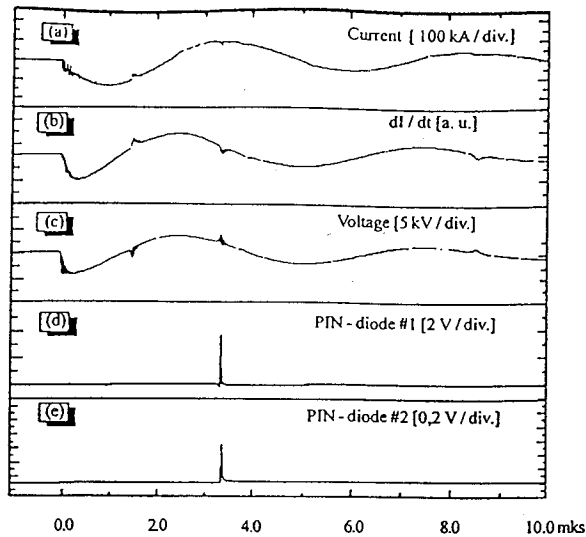


Fig. 7. Oscilloscope traces of current (a), dI/dt (b), voltage (c) and PIN-diode signals (d,e).

120 kA. The initial pressure of the working gas (neon) was varied over a wide range from 0.1–25 mbar; short (60 ns) impulses of X-ray radiation were recorded using PIN diodes in the pressure interval from 0.5–2.0 mbar (Fig. 7). It is interesting to note that, as can clearly be seen in the oscillogram in Fig. 7, the X-ray radiation is generated during the second half of the discharge current, i.e., at the time when the inner plasma focus chamber electrode takes on the function of the anode. This time corresponds to the so-called “singularities” in the curves for the current, voltage, and current derivative. In a number of cases, similar, “singularities” were also observed in the first half of the discharge (as, for example, in Fig. 7), but the observed X-ray impulse always corresponded to the “singularities” in the second half. Without embarking on a detailed discussion of this phenomenon, we emphasize that its main origin is the non-traditional polarity when the plasma focus chamber is commutated on in the charging chain. It is clear that this is also the reason why the intensity of the X-ray emission in this experiment was not very high (in the best discharges, it was not much greater than 0.5 J into the full solid angle).

The device worked in both a single and repetition regime. The range of repetition rates extended from 0.1–10 Hz. We conducted series of 100 or 200 discharges. The main result of this experiment was that it displayed the effectiveness of the selected circuit elements in the repetition regime. The highest temperature in this case is reached inside the plasma focus chamber itself. When we used only simple external water cooling of the chamber housing, its overheating was the main factor limiting the duration of a series. Because of the danger of excessive overheating of the inner plasma focus chamber electrode, the duration of the test series at a repetition rate of order 10 Hz did not exceed 50 discharges. It became clear from these experiments that in order to efficiently cool the chamber, it is most important to intensively remove heat from the inner electrode. Based on the results of the repetition regime experiments with a single capacitor, we decided to develop a new construction for the plasma focus chamber, allowing direct-flow cooling of its inner electrode.

8. The main experiment

The battery of four capacitors for the main experiment was charged to a voltage of 12 kV. The precise value of the battery's capacitance was 31.2 μ F; thus, the energy stored before each discharge was 2.25 kJ. More than 20 000 discharges were produced on the device. After some adjustment, the ignition system provided synchronous operation of the four commutators, with a time scatter not exceeding 2 ns. The maximum of the discharge current in the first half was 280 kA. As we have already noted, the polarity when the charging circuit was turned on was such that the inner plasma focus chamber electrode was the anode. On oscillograms of the discharge current and voltage, we observe a well-defined “singularity” roughly at the place of maximum current virtually from the very first runs (Fig. 8). We varied the initial pressure of the working gas (neon) in the chamber in the range from 5–25 mbar. This enabled us to achieve the best agreement in the electrical and dynamical characteristics of the discharge for each version of the plasma focus chamber having a particular anode length. When the initial pressure was properly chosen, the “singularity” fell precisely at the maximum of the current oscillogram. The intensity of the X-ray radiation at this point was maximum.

The device operated in a single-start regime, and also in short series with various repetition rates. We used a charging device with limited power (3 kW) to charge the capacitor battery; in repetition regime experiments with the full capacitor battery, this enabled us to raise the discharge repetition rate only to 3.5 Hz. Compared to the single-capacitor experiment, the main experiment used a plasma focus chamber and current collector with a more massive input electrode, which should have provided more reliable electrical contact for the input and more intensive heat removal from the electrode. This did not provide a complete solution to the problem of overheating of the chamber during its operation in the repetition regime, however. This problem will apparently only be solved with the development of a plasma focus chamber with direct-flowing cooling.

The plasma focus soft X-ray radiation was recorded using two BRX 65 PIN diodes 62 cm from the plasma focus. The lithography chamber with the PIN diodes was separated from the plasma focus chamber by a beryllium filter with thickness 20 μ m. Its volume was vacuum pumped by diffusion drift, so that the path from the filter to the detector was

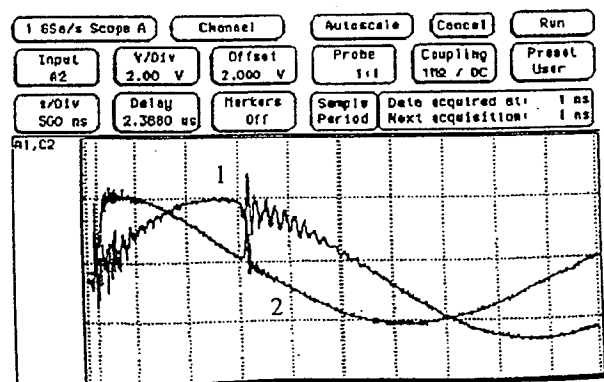


Fig. 8. Oscilloscope traces of the discharge current (1) and voltage (2).

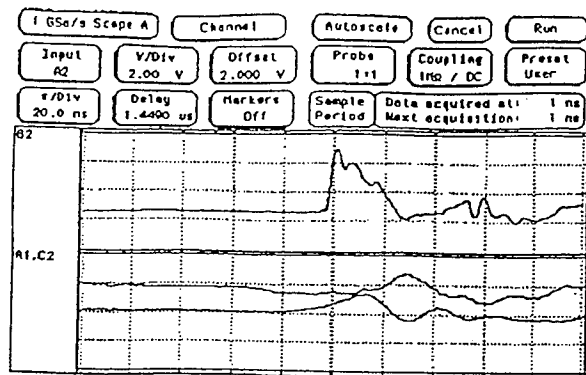


Fig. 9. The signals from the plasma focus X-ray bursts.

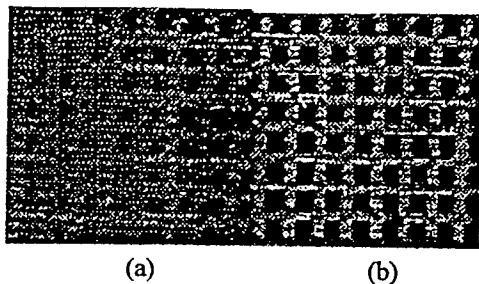


Fig. 10. The test exposure of the PMMA positive X-ray resists (a)-200 shots and (b)-400 shots.

transparent for the radiation of the required wavelength range (9–14 Å). The neon column inside the plasma focus chamber and the beryllium filter significantly weakened the radiation flux, however (this is a serious deficiency of this experiment, which will be corrected when differential pumping is used). Nevertheless, the detectors reliably detected the signals from the plasma focus X-ray bursts (See Fig. 9). Applying a two-channel method (with two different filters) made it possible to confidently determine whether the radiation detected was in the desired wavelength range. Dose calculations based on the experimental recordings using the transmission curves for neon and the materials used for the filters made it possible to determine the intensity of the recorded radiation. For the most advantageous version of the plasma focus chamber (with anode length 43 mm), this intensity was on average about 100 J per burst into the full solid angle. In order to be certain of the results

obtained, we used PIN diodes, X-ray calorimeters, vacuum diodes, and RAR 2495 photofilms to measure the absolute soft X-ray output (the RAR 2495 photofilms were calibrated using impulsive lasers and laser plasma as a soft X-ray source, isotopic sources and a two-exposure method, and a synchrotron radiation beam from an accelerator of the Lebedev Physical Institute).

9. Conclusion

We conducted demonstration experiments on the irradiation of PMMA positive X-ray resists with sensitivity of the order of 1 J/cm^2 (see Fig. 10). These experiments will be described in detail in a future paper. Here, we present only their main result: test objects with characteristic dimensions $100 \times 5 \mu\text{m}$ were successfully recorded with high contrast in the resists, which were located about 40 cm from the source, after about 100 bursts. In order to decrease the number of plasma focus bursts required for the resist exposures, and also to transfer the technique to spatial elements with dimensions of the order of $0.1 \mu\text{m}$, it is necessary to use specialized X-ray resists with enhanced sensitivity at wavelengths 9–14 Å and to take special measures to suppress the smearing of the image by vibration of the device during the multiple irradiation of the resist.

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Soft X-Ray Yield Measurement in a Small Plasma Focus Operated in Neon

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Abstract—The United Nations University/International Center for Theoretical Physics Plasma Focus Facility (UNU/ICTP PFF), a small plasma focus, has proven very useful as a training device for research initiation and as a test bed for applications. In this work, its performance in terms of a soft X-ray (SXR) source is examined. The total SXR yield when operated in neon is measured using low-cost detectors, including a calorimeter and a five-channel filtered PIN system. For a charging voltage of 14 kV with 2.9 kJ stored energy, the optimum operating pressure in neon is found to be in the range of 2.7–3.3 torr, resulting in a total SXR yield of 6J/shot into 4π steradians measured by the calorimeter in agreement with the PIN detectors. Spectral data shows that 64% of the total SXR yield is contributed by the Ly- α and He- α lines and 36% by the rest, mainly the radiative recombination. The low total SXR yield (0.2% of stored energy) is consistent with numerical computations of focus dynamics, which reveals that 3% of stored energy is converted into plasma energy. This low conversion rate into plasma energy is due to the large inductance of 110 nH of this simple single-capacitor device. Thus, for development as a SXR source, reduction of inductance is necessary.

Index Terms—Crystal spectrograph, PIN photodiode, plasma, plasma focus, pulsed X-ray calorimeter, soft X-ray.

I. INTRODUCTION

PROXIMITY X-ray lithography is being developed at many laboratories as the solution to the microelectronics industry requirements for reliable submicron design rule lithography. Consequently the development of bright soft X-ray (SXR) sources has become an important technological goal. The two main approaches being pursued for such sources are the multibeam synchrotron orbital radiation (SOR) source and single-beam point sources of various types. Point sources are generally less complex and much cheaper than the SOR source, however issues of SXR flux and exposure field uniformity are critical for point sources if they are to match the performance of the SOR source. The point source concepts that have been investigated are plasma sources such as laser-plasma, Z-pinch device, and dense plasma focus device [1]. Among these sources, it is known that the plasma focus is very compact, cost effective, and easy to maintain.

Investigations with plasma focus sources designed specifically for SXR proximity lithography appear promising [2]–[4]. X-ray output of up to several hundred watts, averaged over the duration of a burst of several hundred shots in the wavelength

range from 8–14 Å, has been achieved. This present work seeks to find out if the simple single-capacitor plasma focus, designated as the United Nations University/International Center for Theoretical Physics Plasma Focus Facility (UNU/ICTP PFF) which has proven very useful for research initiation [5] in several laboratories and as a test bed for diverse applications [6], may also be used as a base for the development of a high repetition rate plasma focus to be used as a high intensity SXR source. In this connection, one of the objectives is to carry out quantitative SXR measurements with low-cost but reliable instrumentation so that these measurements may also be readily adopted by other laboratories operating the UNU/ICTP PFF [5]. For this purpose we have selected a calorimeter and a five-channel filtered PIN detector system (using easily available and low-cost diodes) from cost considerations. For comparison it is noted that in many studies, photodiodes have been employed to measure both the time resolved and total SXR flux [2]–[4]. In some studies thermoresistive detectors have been employed to measure SXR yield.

In the present work, to obtain the absolute SXR yield we make the assumption that the X-ray emission is isotropic in nature. Operating the plasma focus with a constant charging voltage and varying the pressure of the neon working gas, the relationship between the absolute SXR yield and gas pressure is obtained.

II. EXPERIMENTAL METHODS

A. Calorimeter

Fig. 1 shows schematically the diagram of the calorimeter used for measuring the total X-ray yield. The detailed description of this detector is referred to [7]. One of the principal advantages of using a calorimetric detector is its flat response to radiations of different wavelengths, provided, of course, that the radiation is fully absorbed by the exposed surface of the detector. This detection system is suitable for measurements on pulsed sources (of duration less than 400 ns) of any radiation wavelength greater than 0.05 Å.

A suitable means of calibrating this detection system is by depositing a pulse of energy of known magnitude in the absorber material through a built-in resistor (see 2 in Fig. 1). An electrical pulse of 190 ns duration and of varying magnitude was applied to the calibration resistor ($R = 17.3 \Omega$) and the meter reading (in arbitrary units) as a function of the deposited energy was obtained, as shown in Fig. 2.

The reading displayed on the meter is the peak value obtained by the peak holder circuit (7). Fig. 3 shows a typical

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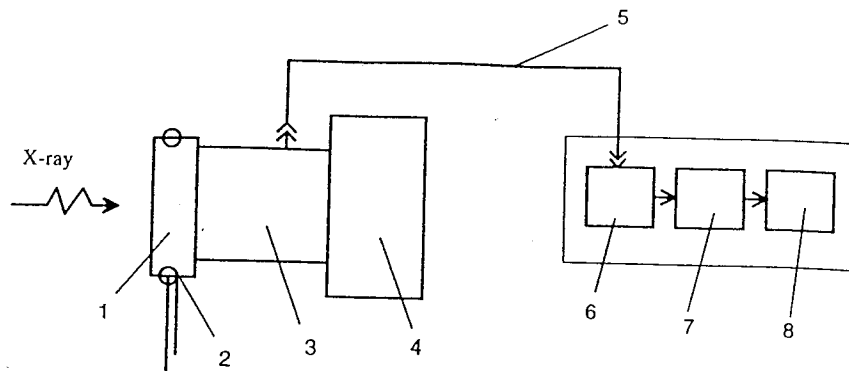


Fig. 1. Schematic diagram of calorimeter for X-ray yield measurement. 1) Absorber. 2) Calibration resistor 3) Thermal couples. 4) Base plate with constant temperature. 5) Shielded signal cable. 6) Amplifier. 7) Peak signal holder. 8) Digital meter.

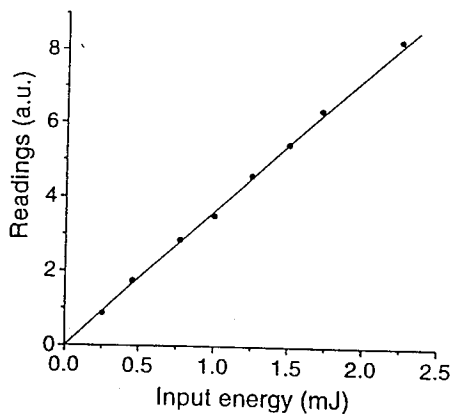


Fig. 2. Calibration of the calorimeter.

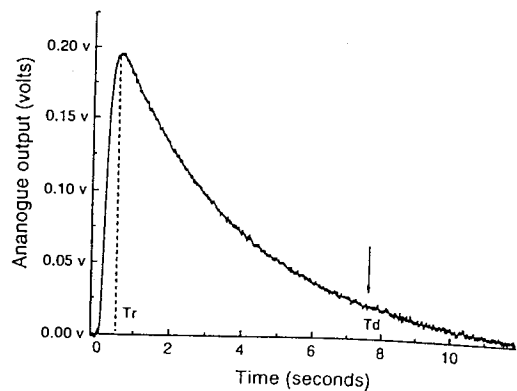


Fig. 3. Analog signal from calorimeter without "peak-holder."

voltage signal from the thermocouple chain when the peak holding circuit is eliminated for an input electrical energy of 1.5 mJ. It can be seen that it takes $t_r \sim 0.5$ s for the signal to peak and $t_d \sim 8$ s to drop to 10% of its peak value. Measurements revealed that both t_r and t_d change only slightly when the input energy varied from 0.02–2.5 mJ. In our case, the pulsed energy incident on the detector is of the order of 0.2 mJ and the repetition rate is ~ 2 shot/min, clearly within the operational limits of this detector.

B. Five-Channel SXR Detector

For a simple method of measurement giving results immediately for every shot, an array of five windowless BPX65 photodiodes was used in this work, both to obtain spectral information (in combination with filters) and for time-resolved X-ray measurements. Filters suitable for the wavelength range of 1–15 Å were selected and are specified in Fig. 4, along with the overall computed sensitivity of the filter photodiode combination as a function of wavelength [8].

C. Experimental Set-Up

The experiments were carried out on the NIE-SSC-PFF plasma focus, a variant of the UNU/ICTP PFF [5] as illustrated

schematically in Fig. 5. The device is of the Mather type with 16.5 cm long copper electrodes with an inner and outer diameter of 1.9 and 6.4 cm, respectively. The inner anode is hollow and the outer cathode comprises six cylindrical rods (of 9.5 cm in diameter) arranged hexagonally. The energy storage bank is a single 30 μ F capacitor. The system design is optimized [5] for operation at 15 kV (3.3 kJ bank energy) in deuterium at 4 torr. In the present work, pure neon is used as the working gas, and the charging voltage is set to 14 kV, corresponding to an input energy of 2.9 kJ. These conditions resulted in a maximum discharge current of 160 kA when operated at an optimum filling pressure of 3 torr.

The calorimeter and the five-channel PIN detector were mounted inside the vacuum chamber as shown in Fig. 5, being at distances of 230 and 276 mm from the focus plasma, respectively. The field of view of each detector is centered in the equatorial plane of the PF gun and 5 mm above the top surface of the anode. A 20 μ m beryllium foil was placed in front of the calorimeter to shield it from visible and infrared radiation. Between the focusing region and the detectors, two apertures of 6 mm diameter were used to prevent the shock wave from damaging the filters.

Other diagnostics employed simultaneously were a voltage probe comprising a resistive divider and two Rogowski coils to measure the discharge current and its first derivative.

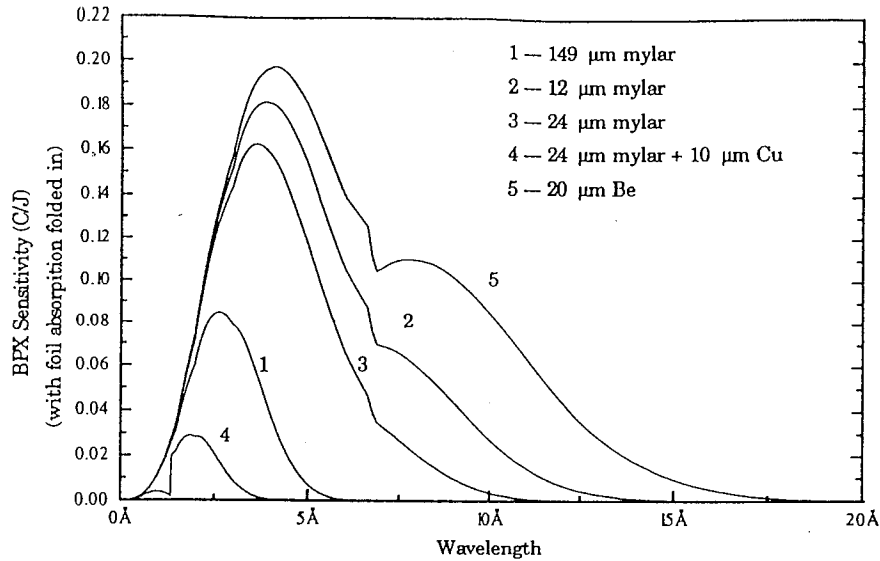


Fig. 4. BPX65 sensitivity.

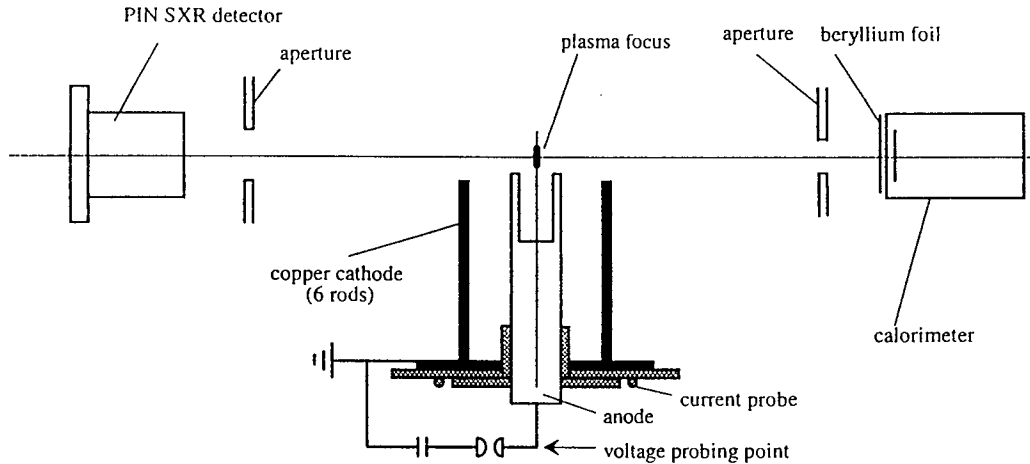


Fig. 5. Total X-ray yield measurement set-up using a calorimeter and PIN detector.

III. DATA AND ANALYSIS

A. Estimation of X-Ray Yield by PIN Detector

Keeping the charging voltage at 14 kV and varying the filling pressure from 1.5–5.7 torr, experiments were carried out to determine the effect on the X-ray yield. Fig. 6 shows a typical set of oscillograms.

From Fig. 6 it can be seen that Channels 2 and 5 show large signals, Channel 3 has a small signal, while Channels 1 and 4 have no signal. Referring to the sensitivity plot (Fig. 4), this means that the X-ray spectrum is mainly in the wavelength region longer than 7 Å. This result is in agreement with our spectrogram [11], [12] (a typical example is shown in Fig. 7) obtained by a flat crystal spectrograph. These results are also in agreement with those obtained by other authors using crystal spectrograph [3], [4], which show that the wavelength range

is within 8–14 Å for similar focus devices operated in neon. In general, it is found that for small neon plasma focus, the helium alpha line (He- α) at 13.447 Å and the hydrogen-like alpha line (Ly- α) at 12.132 Å are the most intense features of the neon spectra, whereas the other line radiations and the free-to-bound continua are weaker, as shown in Fig. 7 in our plasma focus. From the spectral data as shown in Fig. 7, we found that at the optimum condition, about 44% of the total energy is at 13.447 Å, 20% at 12.132 Å, and 36% in the rest region.

The signal from one channel of this five-channel PIN detector, combined with the relative spectrum data of our neon plasma focus, is used to obtain the total X-ray output. The absolute spectrum $X(\lambda)$ is related to the relative spectrum $E(\lambda)$ by

$$X(\lambda) = k \cdot E(\lambda) \quad (1)$$

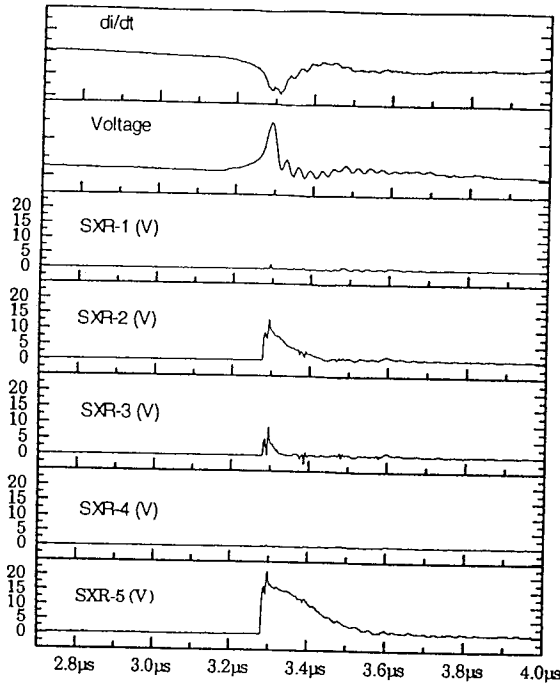


Fig. 6. Typical discharge in neon (2.5 torr).

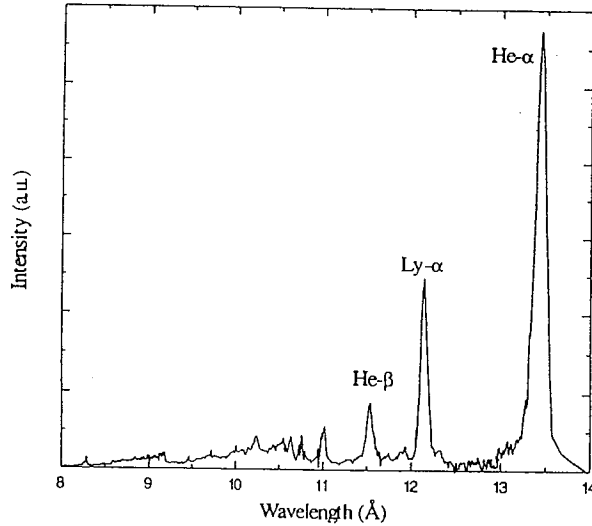


Fig. 7. X-ray emission spectrum of neon plasma.

where k is a constant for each discharge. The area under the PIN signal Q_s is

$$Q_s = \int_p X(\lambda) f(\lambda) f_n(\lambda) d\lambda = k_p k \int E(\lambda) f(\lambda) f_n(\lambda) d\lambda \quad (2)$$

where $f(\lambda)$ is the sensitivity of the PIN detector with filter absorption folded in, $f_n(\lambda)$ the transmission coefficient for the X-ray through the neutral neon gas, and $k_p = (s/4\pi r^2)R$, with $r = 276$ mm being the distance between the PIN diode and

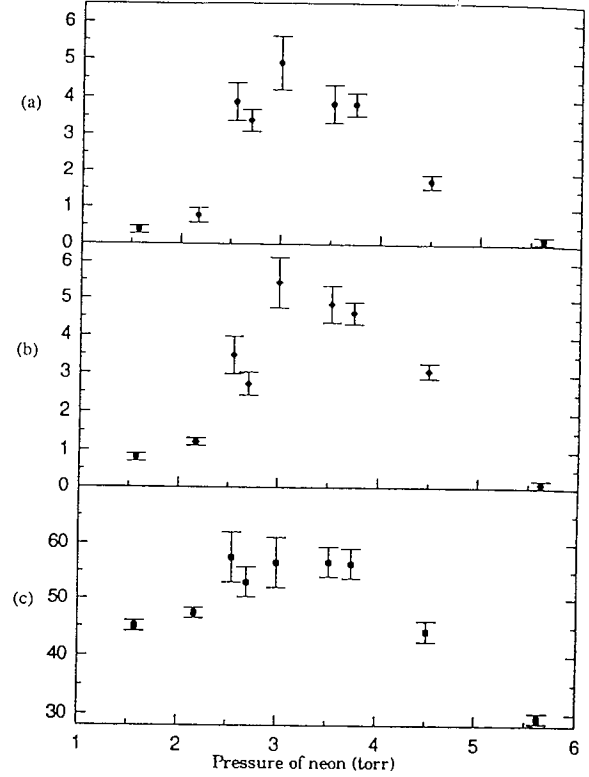


Fig. 8. (a) X-ray yield (joules) measured by Channel 5 of the five-channel detector incorporating spectral information obtained from spectrograph. (b) X-ray yield measured by calorimeter (joules). (c) Input energy (joules).

focus region, $s = 1$ mm², the detection area of the sensor, and $R = 50$ ohm the resistance of the terminator. $f(\lambda)$ is shown in Fig. 4. $k_p = 5.1 \times 10^{-5}$ (ohm) is the factor after taking into account all the geometrical and electrical parameters.

From (2) we solve for k

$$k = \frac{Q_s}{k_p \int E(\lambda) f(\lambda) f_n(\lambda) d\lambda} \quad (3)$$

The total energy of X-ray output W is then obtained

$$\begin{aligned} W &= \int X(\lambda) d\lambda = k \int E(\lambda) d\lambda \\ &= \frac{\int E(\lambda) d\lambda}{k_p \int E(\lambda) f(\lambda) f_n(\lambda) d\lambda} \times Q_s. \end{aligned} \quad (4)$$

The results are shown in Fig. 8(a). Channel 5, which includes the SXR spectral band for neon plasma focus, is used for this work. The spectrum is taken for each filling pressure. We fire 10–15 shots for each filling pressure and take the average value for the data point. The same procedure is followed in the next two sections.

B. Determination of Absolute X-Ray Yield Using the Calorimeter

To determine the absolute SXR yield from the calorimeter signal, it is necessary to correct for the absorption of the 20 μm Be foil placed in front of this detector by making use of the spectral data. Following a similar deduction as in the above section, the total yield W is related to the reading (Q) from the meter by

$$W = \frac{\int E(\lambda) d\lambda}{k_c \int E(\lambda) f_b(\lambda) f_n(\lambda) d\lambda} \times Q \quad (5)$$

where k_c is the calibration factor after taking into account the geometrical parameters, and $f_b(\lambda)$ and $f_n(\lambda)$ are the transmission coefficients for the X-ray through 20 micron Be foil and the neutral neon gas, respectively. The results are shown in Fig. 8(b). In this calculation of total yield, we have assumed an isotropic source, whereas in fact, the emission is stronger in the axial direction. We have considered the angular distribution of emission that shows that our estimation, based on isotropic emission and measuring in the radial direction, gives a slight underestimate.

C. Energy Going into Plasma Focus

For comparison, Fig. 8 also shows the input energy for every discharge. Taking the product of the voltage (V) signal and current (I), we obtain the value of $V \times I$ as a function of time, i.e., the power-time curve. The current used here is the current flowing through the pinch, which is obtained by multiplying the total current by a “current shedding” factor. For this focus device, current shedding factors (0.78–0.93) for different pressures (1–6 torr) were obtained in earlier experiments. Fig. 9 shows a typical $V \times I$ curve. The area of the focusing peak corresponds to the energy that goes into the focus plasma. It is noted that $\Delta(V \times I)$ is underestimated because of the slow response of the voltage probe. The measurements are consistent with electrical input energy into focus of less than 5% of stored energy. Sometimes several peaks were observed. In this paper, the evaluation of the X-ray intensity and the energy input into the focus plasma were carried out merely for the first peak of SXR signal.

IV. DISCUSSION AND CONCLUSION

A calorimeter correlated with a five-channel filtered PIN detector system has been successfully used to reliably measure the total X-ray yield generated from a small plasma focus device, the UNU/ICTP PFF. The calorimeter is calibrated absolutely using its built-in calibration resistor. In this work, the final uncertainty in the absolute SXR flux results mainly from the approximation nature of the derived spectrum and the way we divide the spectral range into two peaks and a flat portion.

For a charging voltage of 14 kV with 2.9 kJ stored energy, the optimum operational pressure in neon for this machine is found to be close to 3 torr. The total SXR yield is 6 J/shot. This yield is only 0.2% of the stored electrical energy of about

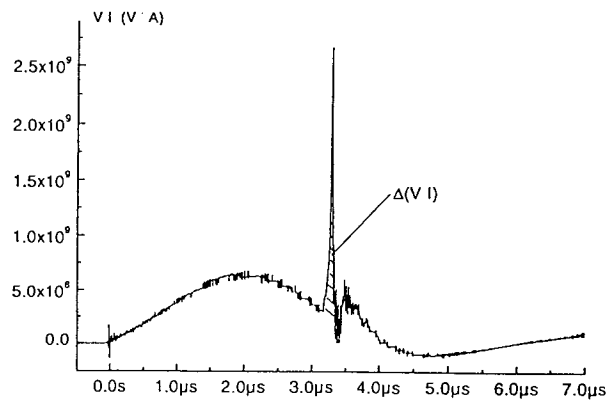


Fig. 9. Typical $V \times I \sim t$ curve.

3 kJ. The outputs of the five-channel PIN detector show that the X-ray emission is within the wavelength range of $> 8 \text{ \AA}$, with 64% of the total yield in $> 12 \text{ \AA}$, corresponding to the two most intense alpha lines from Ne IX and Ne X and their satellite lines. Results obtained by both detectors were consistent. One conclusion is that our low-cost instrumentation reliably measures the SXR yield and may be incorporated into the facilities of the UNU/ICTP PFF for training and research purposes.

A second conclusion is that the SXR yield efficiency of the UNU/ICTP PFF of 0.2% is low. Computation using a dynamic model [9], with the focus dynamics divided into an axial phase followed by a radial implosion phase, shows that this low yield is to be expected because of the high external (stray) inductance L_o of 110 nH of our device. This stray inductance is very large compared to the focus tube inductance that rises from a low value to some 20 nH at the end of the axial phase and then to some 40 nH during the radial phase. The computation shows that 3% of stored energy goes into the energy of the focussed plasma. This low proportion of energy transferred to the focused plasma agrees with the voltage-current measurements that also indicate a low proportion (less than 5%) of stored energy converted into electromagnetic energy transferred to the focus pinch region.

To gain further insight, computations were also carried out with the same system but with L_o reduced to 10 nH. As expected, there is a dramatic change to the distribution of energies in various parts of the system, with more than 10% of stored energy going into the focus plasma. Moreover, reducing L_o from 110 to 10 nH almost doubles the current into the focus tube while also almost halving the current rise time. This allows, indeed requires [10], a corresponding increase in anode radius a and a decrease in anode length L from considerations of optimum value of I/a (current per cm of anode radius) and time matching. The corresponding change, by a factor of almost four, of the aspect ratio a/L toward a “fatter” anode leads to a further rise of conversion efficiency into plasma energy to greater than 25%. Since the scaling of the modeling is such that the temperature and density of the focused plasma remain approximately the same [10] for the various configurations considered when each configuration is

optimized, it is reasonable to assume that the SXR yield will depend on the focus plasma energy content. Thus reduction of L_o as above will lead to a large increase of the SXR yield. Technically to achieve such a low inductance in the capacitor bank requires a system that splits the required capacitance into many small parallel capacitors with many switches also operated in parallel. Such a system would unfortunately be no longer low cost, but would be necessary, however, for the high performance needed for application as a high intensity SXR source.

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Simulations of laser-produced plasma dynamics in an ambient gas

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The expansion of a laser-produced plasma is studied using two computational methods and compared to experiments. The simulations and experiments were performed using a 1- μm , 600-mJ, 6-ns laser pulse. It was found that there was good agreement between the 1D Lagrangian code, the snow plow model, and the experiments for our conditions.

1. Introduction

It is possible to produce a high-density plasma by irradiating a solid target with a laser. Depending on the intensity of the laser and the target material and geometry, it is possible to obtain a wide range of X-ray sources, for example, X-ray lasers, high harmonic generation (Norreys *et al.* 1996), black-body radiation (Hammel *et al.* 1993), line radiation (Bernstein & Comisar 1970; Davis *et al.* 1988; Xenakis *et al.* 1992; Turcu *et al.* 1993), and bremsstrahlung. The line radiation from a laser plasma can be used for a wide range of applications, such as X-ray microscopy and lithography. For such applications, it is of importance not only to produce the plasma, but also to ensure that the energy in the plasma is contained so that the optics required for these applications are not damaged. The presence of a high ambient gas pressure can act as a buffer to reduce the effect of the laser-produced plasma on the optics by absorbing the energy. However, a high gas pressure results in the laser breaking down the gas before it reaches the target. There also may be a reduction in the amount of soft X rays that can be extracted. In this paper, we study the dynamics of the shock wave produced after the laser irradiation by numerical simulation and experiment.

2. Method

The Hyades program was used to simulate the experiments on a computer. Hyades is a Lagrangian hydrodynamics and energy transport code in one dimension that can be in a slab, cylindrical, or spherical geometry and three temperatures (electron and ion temperatures are described by Maxwell–Boltzmann statistics, and the radiation is assumed to be Planckian). Energy transport is modeled using diffusion. Ionization can be calculated using Saha, Thomas–Fermi, or fully stripped models. Tables based on real materials are used to obtain thermodynamic and equation-of-state quantities. Lagrangian formalism (in which the spatial mesh moves with the material) is used to describe the hydrodynamic motion because plasma parameters like density have a very large variation. A full description of the 1D Lagrangian code can be obtained from Cascade Applied Sciences (1993). The results from the Hyades code also have been compared to another code, the 1D Lagrangian code Medusa, which was documented by Rodgers *et al.* (1989). The results from both codes are very similar.

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The Hyades code was used to simulate different types of conditions: (1) slab target fully ionized; (2) slab targets; (3) slab target with ambient argon at about 0.1 bar; and (4) spherical target with ambient argon about 0.1 bar. For conditions 2–4, the target is started off at a low temperature and the Saha model is used for the ionization.

It is also possible to obtain the shock front velocities by using the simpler models that were used by Ahlborn and Ariga (1976), who extended earlier work to fit data obtained from experiments where the blast waves at early times were dominated by heat transfer rather than by shock heating. Also, Ahlborn (1972) described the dynamics of decaying laser sparks in gases. Several works on blast waves have been published since 1946 (Sedov 1946; Taylor 1950). These early publications showed that there was a relationship between the radius of the blast wave, the initial density, and the energy coupled into the blast wave using dimensional analysis and the concept of self-similar flow. Sakurai (1953, 1954) solved the equations of motion of the blast wave by using the principle of similarity by numerical methods for the case of plane and cylindrical waves.

We also present in this paper a simple method of estimating the blast wave expansion. Without going into details about the mechanisms, if we use a snow plow model and assume that all of the mass is swept up by the shock and give the shock mass a fraction of the laser energy, it is possible to estimate the speed v by using

$$\frac{1}{2}mv^2 = E_{abs}, \quad (1)$$

where $m = m_g + m_s$ is the sum mass of the gas swept up (m_g) and the mass of ablated solid (m_s),

$$m_g = \rho_0 \frac{4}{3}\pi r^3, \quad (2)$$

E_{abs} is the amount of energy transferred to the motion of the plasma, r is the radius of the blast wave (as indicated in figure 2), and ρ_0 is the mass density of the surrounding gas. Note that this analysis can be extended to a plane or cylindrical geometry by changing the form of equation (2).

The speed used should be the root mean square of the whole expansion. If we use the shock front for comparison, we must keep in mind that the front will travel faster than the rest of the mass.

Two important parameters, the absorption and the amount of material ablated, can be estimated from the experiments and the snow plow model. The velocity at a late time is insensitive to the amount of mass ablated when the mass of gas swept up is much greater than the mass of the solid ablated. The velocity can be obtained from the experiments by measuring the radius at a late time for two slightly different times. The swept-up mass m_g is obtained from equation (2) and substituted for the mass in equation (1), from which the laser energy absorbed E_{abs} is thus obtained. Similarly, the velocity at an early time, for example, just after the laser pulse, is dependent on the mass of the material ablated. Measuring the early shock velocity allows us to estimate the mass of the material ablated.

The calculations were performed by using a spreadsheet in which all of the laser energy was dumped into a specified thickness of the solid, calculating with small increments in time Δt the speed v by using equation (1), followed by the radius using $r = r + v \times \Delta t$, followed by the swept-up mass using equation (2), and repeating the whole process. A flow chart of the process is shown in figure 1.

The experiment was performed using a 1- μm , 600-mJ, 6-ns Nd-laser focused to 10^{11} Wcm^{-2} . The expansion of the plasma was monitored using a 1-ns nitrogen-laser-pumped green dye laser pulse as a schlieren probe beam. Details about the experiment can be found in Kumar (1996). Figure 2 shows the setup for the experiment. About 400 mJ is incident on the target at an intensity of about 10^{11} Wcm^{-2} . The results were taken over a large number of shots while varying the time delay between the probe and the main beam.

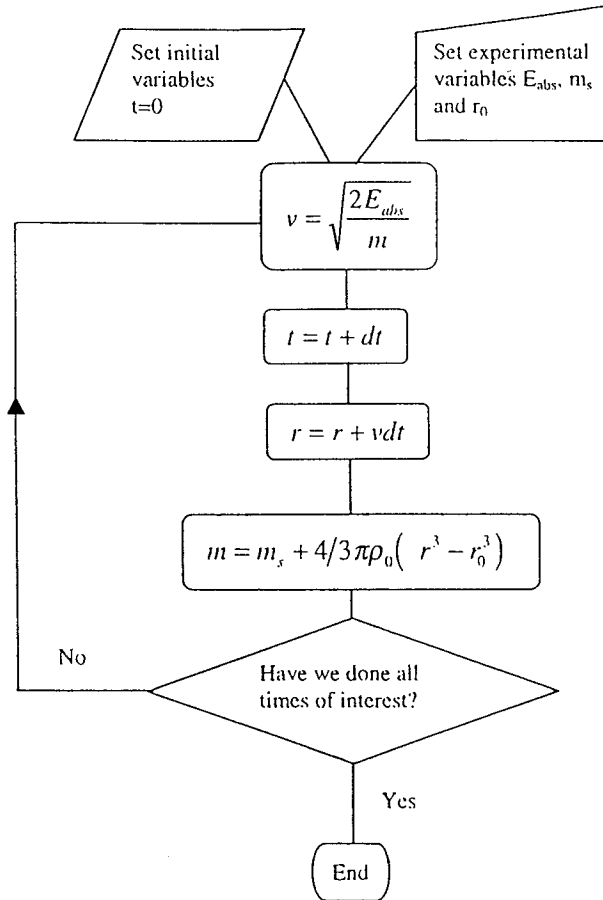


FIGURE 1. Flow chart showing method for solving the equations for the snow plow model.

3. Results

3.1. Hyades result for a fully ionized slab target in a vacuum

From the graphs of electron density versus distance (figure 3), it can be seen that there is a fast electron front moving at $0.5 \times 10^6 \text{ ms}^{-1}$ after the laser pulse. The calculated electron temperature has a peak of about 120 eV just after the laser pulse, falling to 50 eV at a late time of 150 ns. The fast ions moving with the electrons to maintain quasi-neutrality thus would have kinetic energies of 1 keV/nucleon at early times.

3.2. Hyades result for a slab target not fully ionized

If the target is not always fully ionized, results similar to the above are obtained (figure 4) for densities below the laser critical density. The solid is started off with a low temperature that is high enough to still allow some ionization. The expansion is still at the same speeds, but the density falls faster in time as the plasma cools.

3.3. Hyades result for a slab target in 0.1-bar argon

Figure 5 shows the results when an ambient gas (argon) is introduced into the system. A steepening shock front is observed. The electron density is high at the shock front due to its

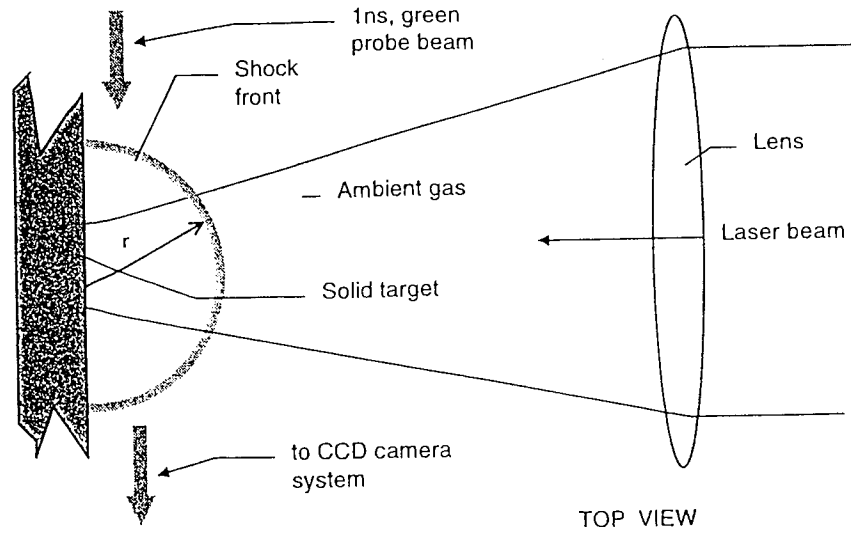


FIGURE 2. Experimental setup.

higher temperature and also a compression of the gas. The shock front moves at a speed of about $70 \times 10^5 \text{ ms}^{-1}$ initially (just after the peak of the laser pulse), which corresponds to an ion kinetic energy of around 100 eV. The speed falls to about one-third of that after about 60 ns. The peak electron temperature is still 120 eV but falls to 50 eV at 150 ns. A peak in density from the material ablated from the solid also can be seen moving at 10^5 ms^{-1} .

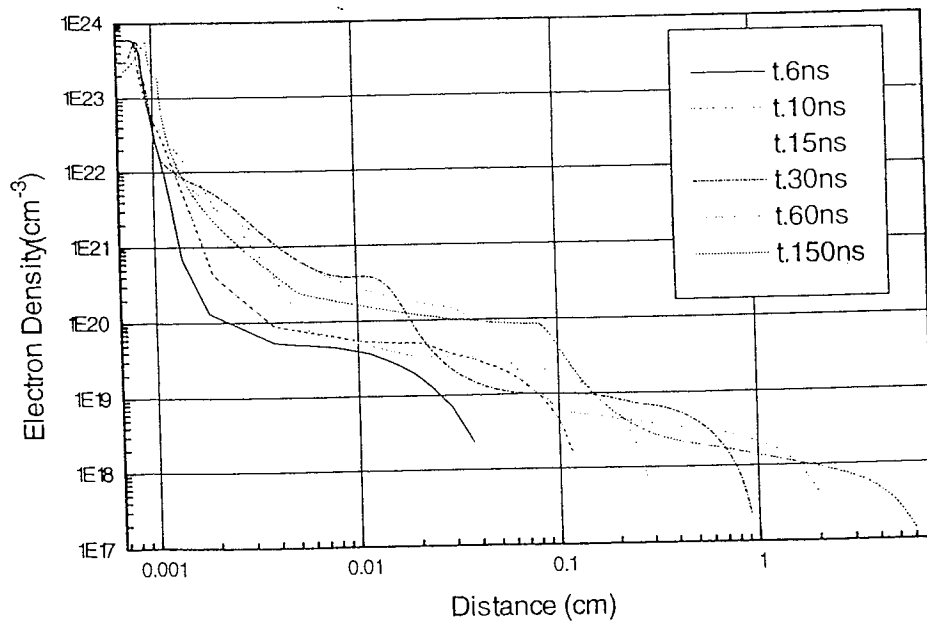


FIGURE 3. Graph of electron density against distance (log scale) at various times obtained by using Hyades. Fully ionized slab target.

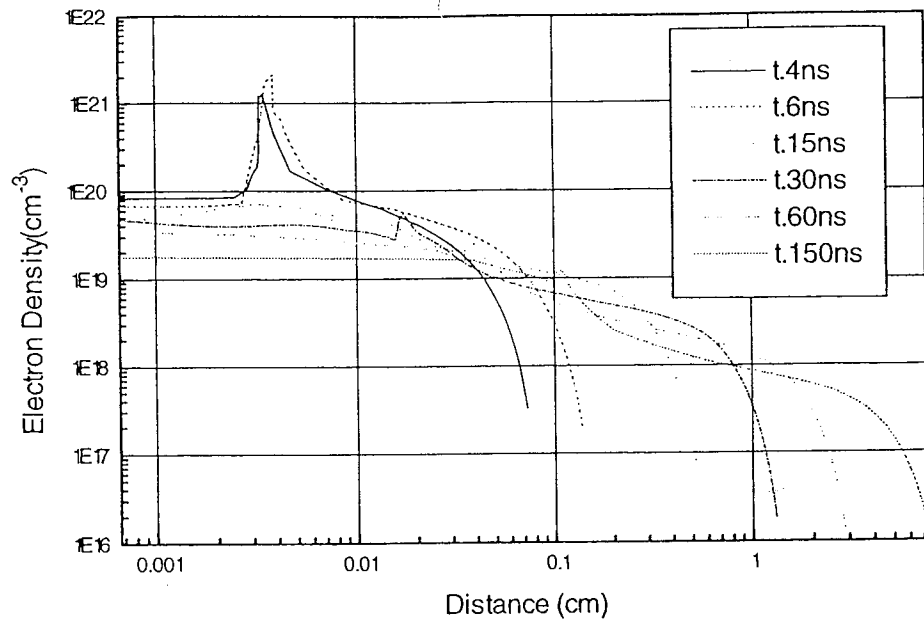


FIGURE 4. Graph of electron density against distance (log scale) at various times obtained by using Hyades. Slab target; ionization calculated using Saha.

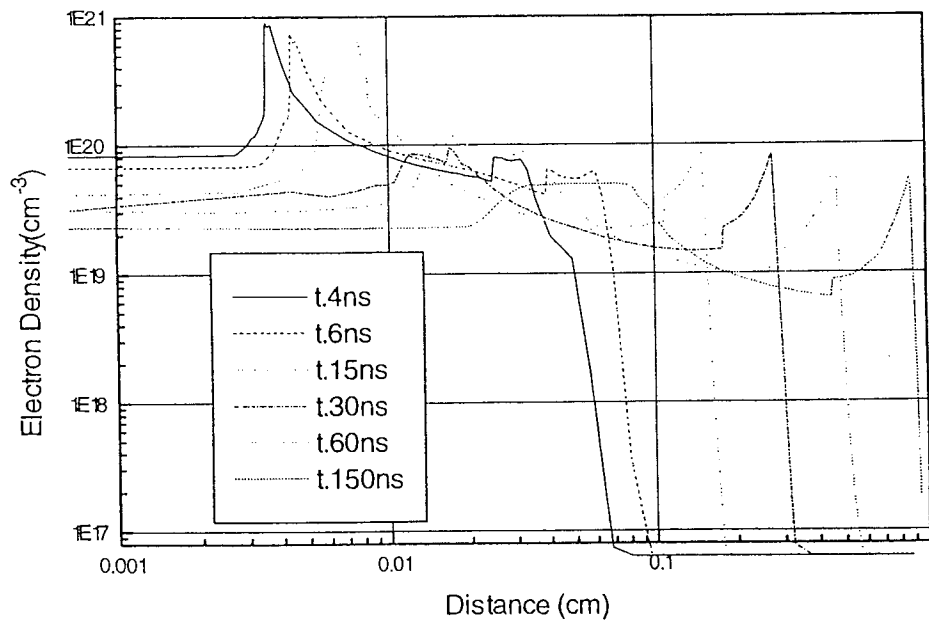


FIGURE 5. Graph of electron density against distance (log scale) at various times obtained by using Hyades. Slab target expanding into a gas; ionization calculated using Saha.

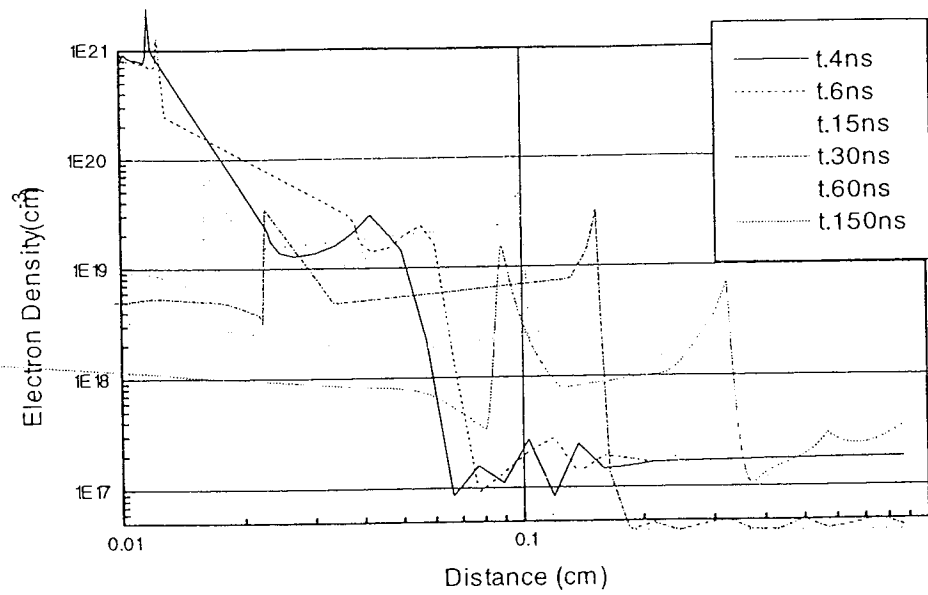


FIGURE 6. Graph of electron density against distance (log scale) at various times obtained by using Hyades. Spherical target expanding into a gas; ionization calculated using Saha.

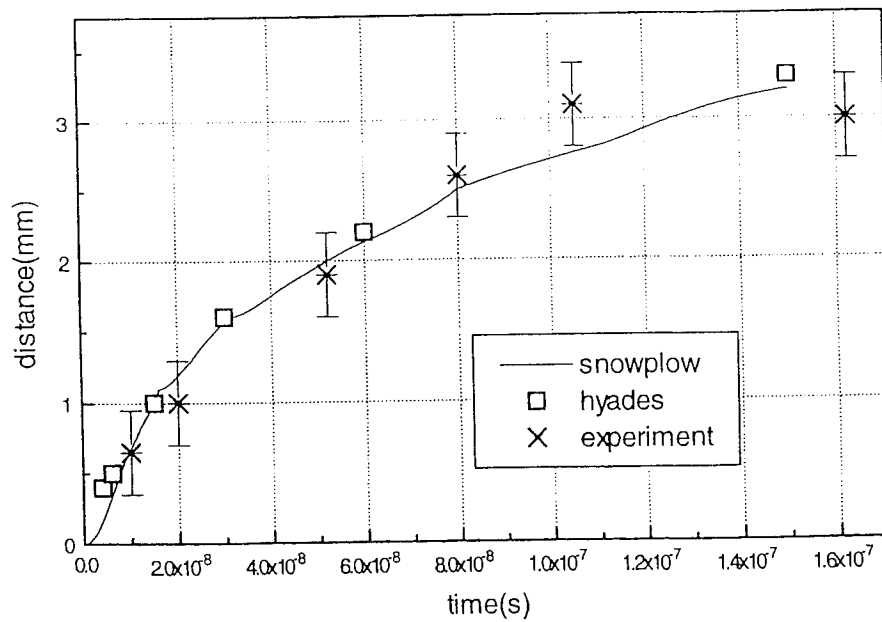


FIGURE 7. Typical result from the snow plow model with points obtained from Hyades (figure 4) and experimental results plotted for comparison. For the snow plow model, 450 mJ was dumped into 1 μm of the solid material, silicon.

3.4. Hyades result for a spherical target in 0.1-bar argon

When a spherical geometry is used in Hyades, an approximation is used by starting the target as a sphere that is $100\text{ }\mu\text{m}$ in radius. This target is about twice the size of the laser spot. The initial laser intensity on the target is $1 \times 10^{11}\text{ cm}^{-2}$. The total amount of energy incident on this target is about 2 J. The results are shown in figure 6. The shock front again is observed from the computation, but this time the shock speed decrease with time is more pronounced. The speed is about 10^4 ms^{-1} between 60 and 150 ns after the laser pulse. This is expected from an energy consideration, because a larger mass is swept up in such a geometry compared to a slab geometry.

3.5. Results from the snow plow model compared to Hyades and experiments

Figure 7 is a typical result from the snow plow model for 450 mJ of absorbed energy for a typical solid with a density of 3 kg^{-3} in a gas with a mass density of 0.17 kg^{-3} . This computation should give results similar to the fourth type of Hyades computation and to experimental results if we correctly guess the amount of energy absorbed and the initial mass. In this case, we have taken E_{abs} as 450 mJ and the mass ablated as coming from a $1\text{-}\mu\text{m}$ layer from the target.

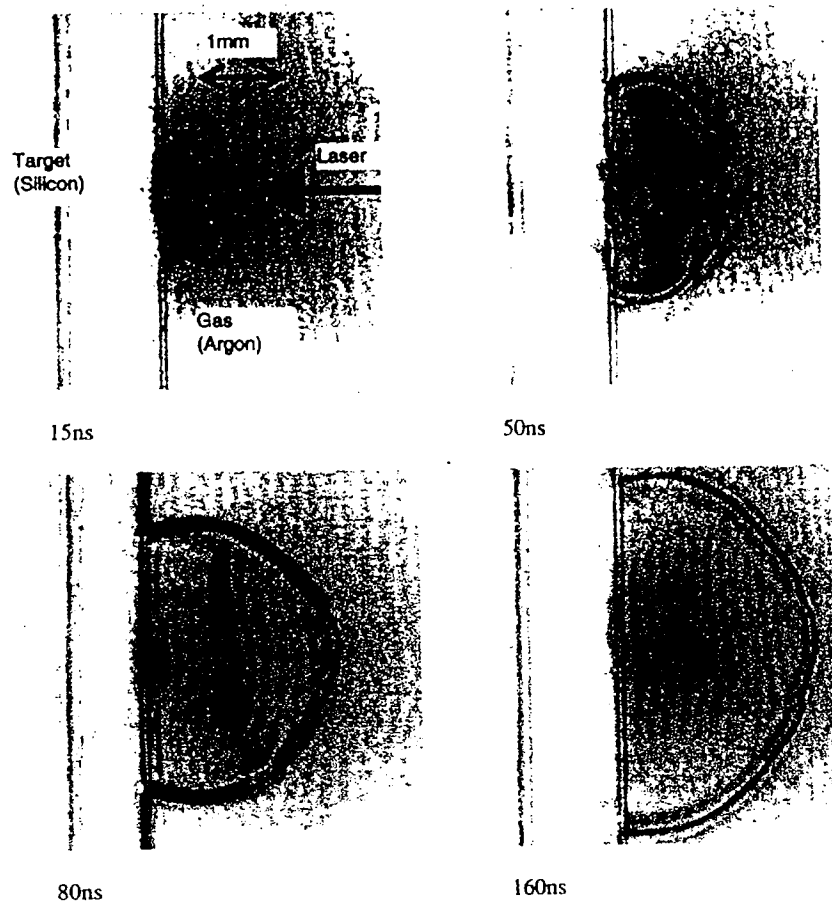


FIGURE 8. Some typical schlieren photographs of the expansion taken at 15, 50, 80, and 160 ns, with solid silicon target in 100-mbar argon.

Schlieren photographs from the experiment are shown in figure 8. The radius of the expansion was obtained from the edge visible in the schlieren photographs.

Further experiments were performed using lead targets and nitrogen as a filling gas. The laser spot size was varied to produce different intensities by defocusing and by using different lenses. The experimental results are presented in figure 9. It can be seen that the results are the same as those obtained with a silicon target in argon. This is because 100 Torr of air has almost the same mass loading on the shock as 100 mbar of argon. There is also very little variation in the expansion when the laser intensity is varied over two orders of magnitude.

4. Discussion and conclusion

Since both of the computations are 1D, it is not possible to reproduce the detailed structure that was observed in the experiments. However, it is possible to reproduce the position of the shock front and the velocities from the code. The dynamics of the shock front were shown to be almost independent of the laser intensity over the range of 10^{10} – 10^{12} Wcm^{-2} .

The 1D Lagrangian codes are able to give estimates of the absorption fraction without experimental input. The codes show that almost 100% of the laser energy is absorbed by inverse bremsstrahlung, which agrees with previous experiments done near these intensities (Tabak *et al.* 1994). Also, profiles of temperature and densities can be obtained which can be compared to experimental results.

The less complex snow plow model allows us to see immediately that the speed of expansion is controlled only by the amount of energy transferred to the plasma. With an estimate of the energy absorbed and the amount of material it is absorbed into, it is possible to estimate the temperature of the plasma and the amount of soft X rays emitted, as described by Bernstein and Comisar (1970). The snow plow model also matches the actual energy used in the experiments more accurately.

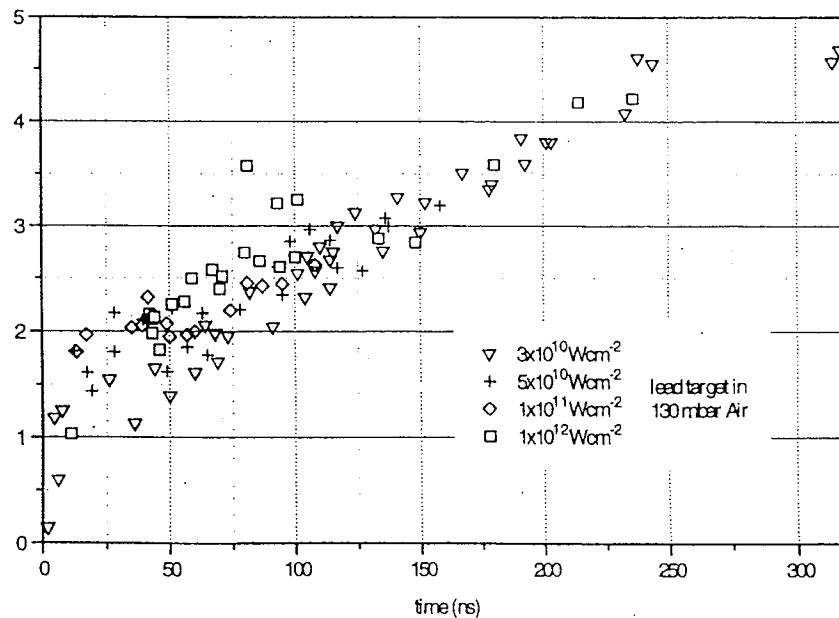


FIGURE 9. Typical results from the experiments but with lead target and 100-Torr air atmosphere. Different laser intensities were used by varying the spot size.

When the wave reaches a distance r , the final energy of each molecule of gas also can be obtained from equations (2) and (3):

$$\frac{E_{abs} A m_n}{\frac{4}{3} \pi r^3 \rho_o} = 5.7 \times 10^{-4} \left(\frac{E_{abs}}{1 \text{ J}} \right) \left(\frac{r}{1 \text{ cm}} \right)^{-3} \left(\frac{P}{1 \text{ bar}} \right)^{-1} \text{ eV}, \quad (3)$$

where P is the pressure of the ambient (ideal) gas, A is the relative molecular mass of the ambient gas, and m_n is the mass of a nucleon. The blast wave can be considered to have stopped when the energy per molecule in the wave becomes comparable to the internal energy per molecule at room temperature.

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High Rep Rate High Performance Plasma Focus as a Powerful Radiation Source

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Abstract—Basic operational characteristics of the plasma focus are considered from design perspectives to develop powerful radiation sources. Using these ideas we have developed two compact plasma focus (CPF) devices operating in neon with high performance and high repetition rate capacity for use as an intense soft X-ray (SXR) source for microelectronics lithography. The NX1 is a four-module system with a peak current of 320 kA when the capacitor bank ($7.8 \mu\text{F} \times 4$) is charged to 14 kV. It produces 100 J of SXR per shot (4% wall plug efficiency) giving at 3 Hz, 300 W of average SXR power into 4π . The NX2 is also a four-module system. Each module uses a rail gap switching 12 capacitors each with a capacity of $0.6 \mu\text{F}$. The NX2 operates with peak currents of 400 kA at 11.5 kV into water-cooled electrodes at repetition rates up to 16 Hz to produce 300 W SXR in burst durations of several minutes. SXR lithographs are taken from both machines to demonstrate that sufficient SXR flux is generated for an exposure with only 300 shots. In addition, flash electron lithographs are also obtained requiring only ten shots per exposure. Such high performance compact machines may be improved to yield over 1 kW of SXR, enabling sufficient exposure throughput to be of interest to the wafer industry. In deuterium the neutron yield could be over 10^{10} neutrons per second over prolonged bursts of minutes.

Index Terms—Lithography, plasma focus, X ray.

I. INTRODUCTION

FOR MATHER'S type plasma focus operation it is observed experimentally [1], [2] that the quantity designated as the drive parameter [2] $S = (I/a)/\rho^{1/2}$ (where I is the driving current, a the anode radius and ρ the operational gas density), a measure of speed, both axial and radial, has an optimum value for each gas of operation. Thus for deuterium the average axial speed for optimum neutron yield appears to be just below $6 \text{ cm}/\mu\text{s}$ corresponding to a peak axial speed of $9\text{--}10 \text{ cm}/\mu\text{s}$ and a peak radial speed of some $25 \text{ cm}/\mu\text{s}$ as the plasma focus radial shock goes on axis. That the optimum speed should be so low for optimum neutron yield is surprising since one would expect from D-D fusion cross section consideration that the fusion yield should be enhanced by an increase in speed which should boost the

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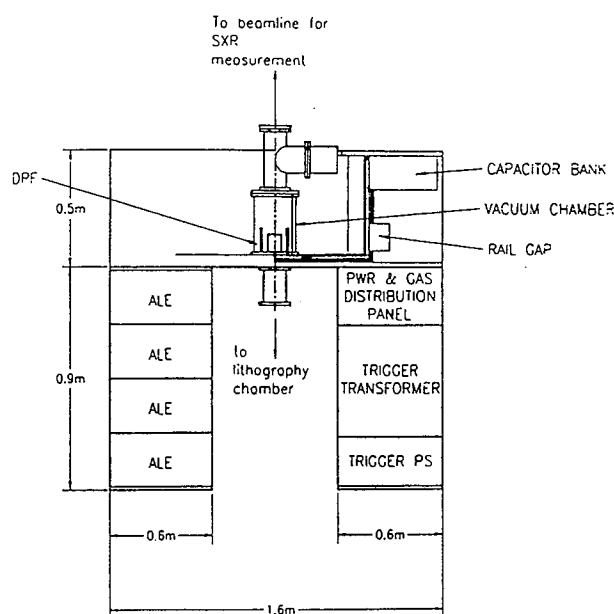


Fig. 1. General overview of the NX2 apparatus.

focus ions above the 1 keV observed for focus operation at the above mentioned optimum speeds. The speed limitation may be caused by a force-field flow-field decoupling effect [1]. An effort to achieve yield enhancement by breaking through the speed limit has been made [3].

At this point it may be useful to remark that the drive parameter S is a measure of the drive magnetic pressure per unit density or the drive magnetic energy per unit mass. Thus any model based on either the snowplow or slug model will have the driven speeds primarily dependent on this factor S . It may be necessary to apply correction factors to account, for example, for mass loss or current loss factors or even variations of such factors as the electromagnetic drive proceeds in stages. This applies to all electromagnetically driven plasma systems including the Z-pinch for which the implosion speed, treated either by a slug or snowplow model also scales as S (see, for example, the discussion of implosion time scaling in reference [4]).

Operating in noble gases for the generation of soft X-ray (SXR) an optimum speed may be more readily understood. For example, in neon the compressed plasma in the focus should have a temperature of some 400 eV if the radiation

TABLE I
SUMMARY OF ELECTRICAL CHARACTERISTICS

	Charging Voltage (kV)	Energy (kJ)	Repetition rate (Hz)	Current (kA)	Short circuit rise time or quarter period (μ s)
NX1	12	2.2	3 ¹	280	1.5
NX2	11.5	1.9	16	400	1.0
UNU/ICTP-PFF	14	2.9	Single shot	170	2.2

is required to be predominantly in the 0.8–1.4 nm for the purpose of microelectronics lithography. We have used a model computing plasma dynamics in the axial, radial, and radial reflected shock phases, incorporating a quasi-equilibrium radiative phase [5]–[7] to examine for example the optimum axial speed required to set the stage for optimum radiation in the 0.8–1.4 nm range. This model is used to correlate with experimental results which indicate an optimum average axial speed of 4.5 cm/ μ s.

It is important to note that the optimum speed for each of deuterium and neon operation remains nearly constant for the range of machines surveyed. This is particularly remarkable for deuterium operation where a value of S nearly constant at 90 kA/(cm-torr)^{1/2}, corresponding to a peak axial speed of just less than 10 cm/ μ s, is tabulated [1] over a wide range of machines from training machines of 3 kJ [2] to machines of 300 kJ. This means that for each gas the plasma temperatures in each of the dynamic phases, and by inference also in the compressed radiative phase, are identical for all machines, big and small, when optimized.

We next note that the quantity S is dependent on $D = (I/a)$ linearly whilst it depends only on the half power of ρ . Note also that over a two decade range of stored energy the optimized operational pressure has a range of only two [1]. Thus in a relative sense the density ρ and hence the quantity D may in the first approximation be considered also as constant when comparing different machines, all optimized. This clearly agrees with the design tendency to increase the anode radius proportionally with the available drive current. But there is also a fundamental significance.

For each gas, since we are dealing with the same compressed temperature and essentially the same density, radiation yield will depend on the product of compressed plasma volume and lifetime. Again since we are dealing with the same dynamical speeds and compressed temperatures any reasonable modeling [5], [8], [15] will show that each dimension of the pinched plasma is proportional to the anode radius, as is the lifetime of the compressed plasma. Thus radiation yield is proportional to a^4 . And since D is essentially constant for each gas, radiation yield, at least for neutrons and SXR, is proportional to I^4 . Such a scaling is energetically possible since whenever energy is taken from the circuit by the plasma such an energy extraction will reflect in a lowering of the current. Such a self-regulating mechanism will self-consistently limit the extraction of energy from the circuit.

Thus for a given stored energy, yield performance is related to current. Circuit inductance needs to be minimized. Our modeling also indicates the importance of minimizing the ratio of generator impedance to total impedance for efficient

transfer of energy to the plasma pinch. Practically, this is again accomplished by minimizing all the inductances from the capacitor bank through the switches right up to the collector flanges of the plasma focus head. Thus improving circuit performance should improve yield performance.

For applications, whilst the peak rates of yield may have significance for some time-resolved experiments, for other applications such as SXR lithography for microelectronics application there is a need for high average yield rates sustained over at least a duration of minutes, even for demonstration purposes. Thus ability to operate at high repetition rates in a prolonged burst is necessary.

The length of the anode is also of crucial importance [2], [8]. Computation and experience agree that a strong focus with optimum energy coupled into the focus pinch so as to emit intense radiation, is achieved when the radial compression starts (end of axial phase) at a time t_{ax} where t_{ax} is equal to t_r , t_r being a hypothetical risetime of the capacitor bank with a value between the short-circuited risetime and the risetime of the circuit loaded hypothetically with the full axial load. As a rule of thumb the short-circuited risetime may be used for a first estimate of the optimum anode length.

Thus for the deuterium focus with an optimum average axial speed of say 5.5 cm/ μ s the anode length should be 5.5 cm per μ s short-circuited bank risetime. For the neon focus taking the optimum average axial speed to be 4.5 cm/ μ s would give us an indicative optimum anode length of 4.5 cm for every μ s of short-circuited bank risetime.

What about the value of $D = (I/a)$? From a survey of experiments it is found that the current per unit anode radius has a design range of 150–220 kA/cm, for optimum neutron yield. We have used this range also as an indicative design range for our SXR facilities.

Based on the above considerations we have developed two high repetition rate compact plasma focus facilities, the NX1 and the NX2¹ to be powerful SXR sources for microelectronics lithography [9]–[11].

We note that the requirements for a point SXR lithography source may be expressed as follows: point source dimension less than 1 mm (focussed plasma viewed end-on) with emission in the wavelength range 0.8–1.4 nm and average SXR power of 1 kW at source over 4π delivered over a prolonged burst. This last requirement indicates what is needed from industrial wafer throughout considerations. For a resist with 100 mJ/cm² sensitivity exposed at a distance which cannot be less than 30 cm [10] from the point source, 1

¹The NX2 was manufactured and supplied by Alameda Applied Sciences Corporation, 2235 Polvorosa Avenue, San Leandro, CA 94577.

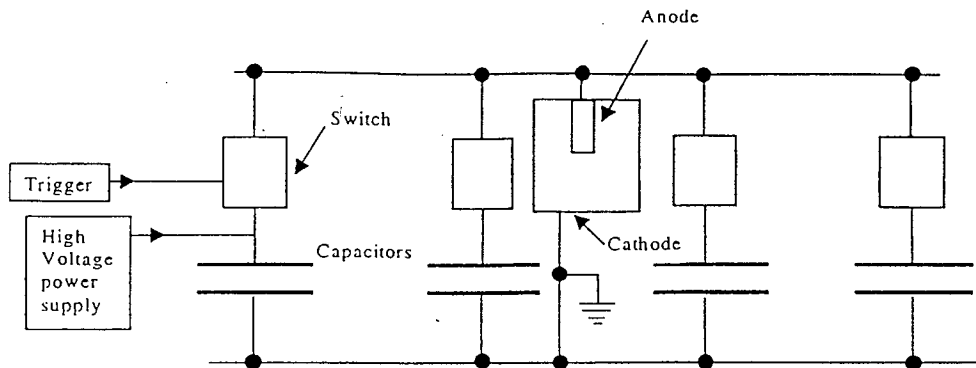


Fig. 2. Schematic of electrical system.

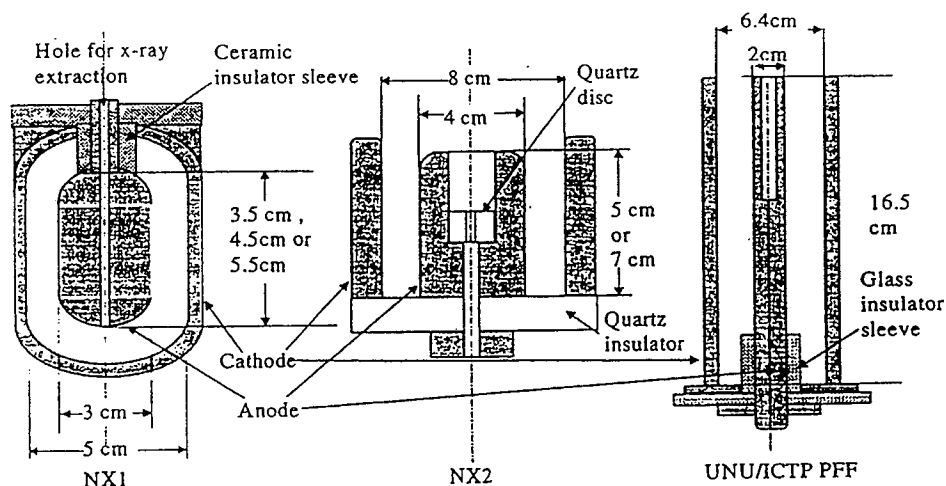


Fig. 3. Schematic of focus electrodes and chamber.

kW will deliver the required 100 mJ/cm^2 in 2 s assuming beamline transmission ratio of 0.5. A 2 s exposure time per field may be sufficient for industrial wafer throughput purposes. For demonstration purposes even a 100 W source is useful.

Other practical design features include compact footprint with ample space for a stepper to be integrated eventually into the facility.

II. APPARATUS

The plasma focus soft X-ray sources used in these experiments are low energy $\sim 2 \text{ kJ}$ plasma focus operated in neon. A general view of the NX2 is shown in Fig. 1. The design enables measurement of SXR yield at the same time as lithographic exposure is made. The footprint of the machine is $1.6 \text{ m} \times 1.6 \text{ m}$. There is a clear space for the integrated development of a stepper. The system is completely shielded against electromagnetic radiation.

Both the NX1 and NX2 plasma focuses are driven by $30 \mu\text{F}$ capacitor bank charged by ALE Systems model 802 high volt-

age capacitor chargers. The capacitor banks are connected to the focus via four switches (pseudo spark switches for the NX1 and rail gap switches for the NX2). Table I summarizes the characteristics of the electrical systems of the NX1, NX2. The characteristics of a benchmark system the United Nations University/International Center of Theoretical Physics Plasma Focus Facility (UNU/ICTP PFF) [2] are also included in Table I. A schematic of the NX1 and NX2 electrical system is shown in Fig. 2. The UNU/ICTP PFF is a simpler system consisting of one capacitor coupled to the focus with one spark gap.

Three chambers have been used in the NX1 (see Fig. 3) with oxygen-free copper anode lengths 3.5, 4.5, and 5.5 cm, respectively. Three anode lengths were tried with the NX2. The electrode dimensions are summarized in Table II. The NX2 stainless steel electrodes are cooled by water circulated through the electrodes using two Bay Voltex RRS-1650-AC chillers with a total cooling capacity of 9.6 kW.

III. EXPERIMENT

The diagnostics were 1 mm^2 area $10 \mu\text{m}$ thick *p-i-n* diodes and 3 mm^2 photoconducting diamond (PCD) filtered by

TABLE II
SUMMARY OF FOCUS ELECTRODES

	Anode diameter(cm)	Cathode diameter(cm)	Cathode type	Anode length(cm)	Electrode material	Insulator material
NX1	3	5	Hollow cylinder	3.5, 4.5, 5.5	Copper	Ceramic
NX2	4	8	16 rods	5, 7	Stainless steel	Quartz
UNU/CTP PFF	1.9	6.4	6 rods	16.5	Copper	Pyrex glass

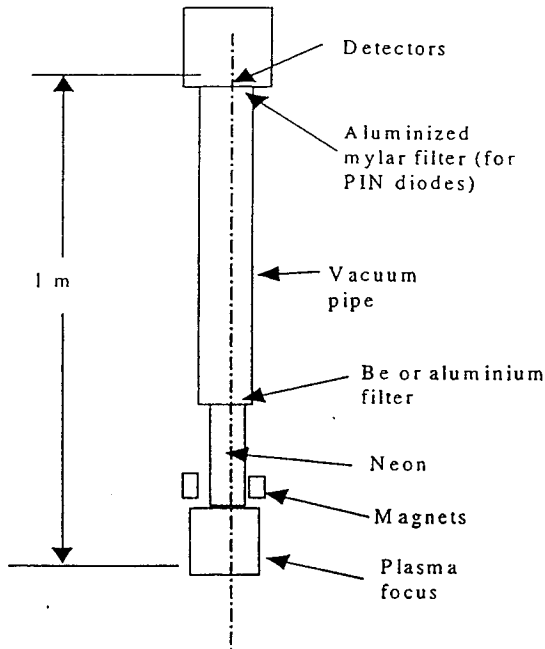


Fig. 4. Experimental set up for soft X-ray measurement.

aluminum, mylar, and beryllium foils. The setup used for the experiments is shown in Fig. 4. Both the PCD's and the *p-i-n* diodes were used on both machines. In the case of the NX1, the X-ray was detected through the extraction hole through the anode. This means that there is also an electron beam traveling along the same path. The electrons are excluded by the application of a magnetic field to deflect the electrons and also by the 10 μm beryllium which scatters the electrons. The energy of the electrons has been determined in a previous experiment [12] to be primarily less than 30 keV.

The initial pressure of neon was varied and the optimum pressure was found for the various electrode lengths and for charging voltages of 10 kV and 14 kV. Most of the datapoints were repeated five to ten times for the NX1 and 20–200 times for the NX2. A fast acquisition system consisting of a tektronix TDS380 oscilloscope connected to a computer was used so that the X-ray for every shot up to a repetition rate of about 10 HZ could be obtained.

IV. RESULTS

To obtain the SXR yield from the *p-i-n* diode pulse, the area under the oscilloscope trace is obtained and the total amount

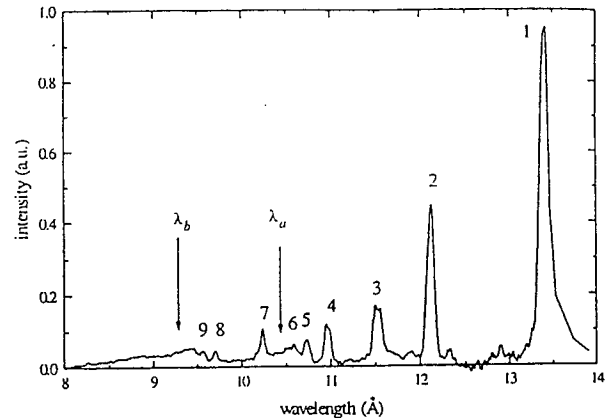


Fig. 5. Typical neon plasma focus spectrum.

of SXR is calculated using a sensitivity factor into which has been folded the sensitivity versus wavelength characteristics of the *p-i-n* diode, the spectrum of the neon focus emission (shown in Fig. 5) which had been separately obtained earlier using a crystal spectrograph [7], and the absorption of the beamline gas path and filters. The *p-i-n* diode measurements are cross calibrated against a calibrated PCD detector. The PCD has a flat sensitivity over the range of SXR spectrum considered. Hence interpretation of the yield is more reliable. The measurements using the two detectors agree to within 20% on the NX2. All results are adjusted to the PCD calibration.

The results from the X-ray yield measurements are shown in Fig. 6. Fig. 6(a) shows that with the NX1, we obtained up to 5% conversion into soft X-ray from the capacitor bank energy and corresponding wall plug efficiency of 4% with the 4.5 cm anode at 12 kV. The X-ray yield varies within 50% of the maximum when the pressure is within 20% of the optimum. The typical variation of the X-ray yield, when other factors like neon pressure, charging voltage are kept constant, is about $\pm 35\%$ of the average X-ray yield.

Fig. 7 shows some representative oscilloscope current traces obtained using the NX1 with 4.5 cm anode operated with a charging voltage of 10 kV and the NX2 with the 5 cm anode operated at 11.5 kV with 4 mbar neon. Some currents dip to as low as 60% of the peak current when there is multiple focus within a short time of each other. More typical dips drop the current to 80% of the maximum, which is what the first dip associated with the first focus event in Fig. 6(a) shows. It can be seen that the energy transfer into the plasma is more efficient for the NX2 as the dip shown in Fig. 6(b) dips to about 65% of the peak current with only one focus event. In

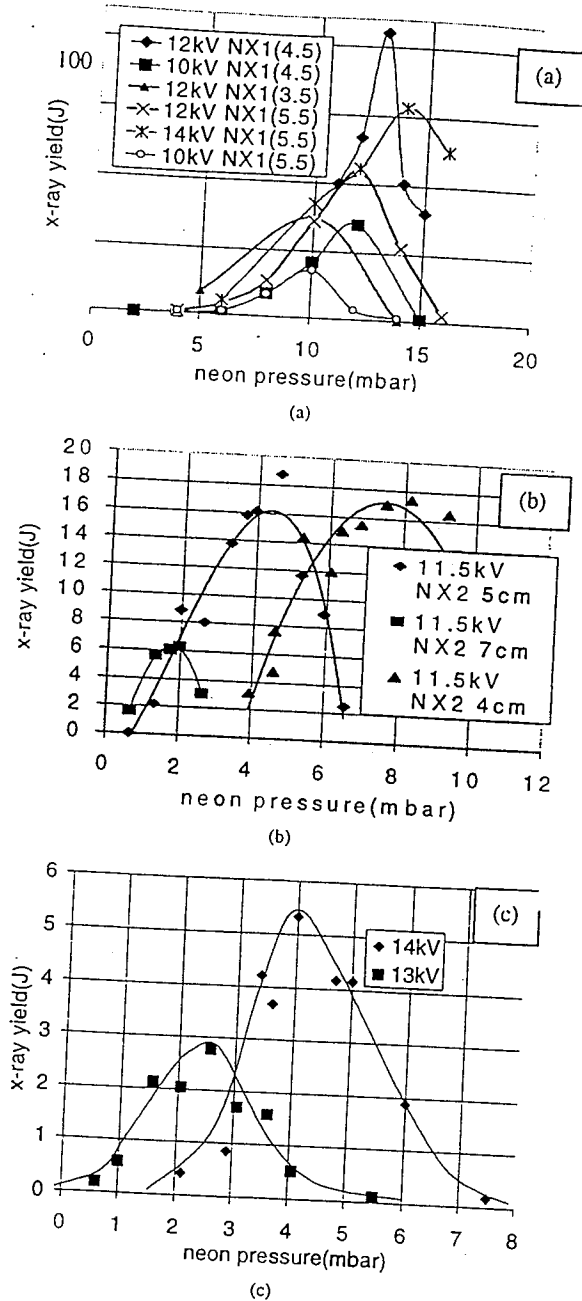


Fig. 6. X-ray yield for different neon pressures for (a) NX1, (b) NX2, and (c) UNU/ICTP PFF.

comparison, the UNU/ICTP PFF has a current dip of about 10% of the current maximum.

Table III shows the parameters for maximum X-ray yield for some of the configurations we tried. It can be seen that the best SXR yield is at an average velocity of $4.5 \mu\text{scm}^{-1}$. With the shorter electrode, it is not possible to run the focus at a higher velocity as the focus would occur at a time too long before the natural current peak such that not enough of the capacitor bank energy has been converted to the magnetic

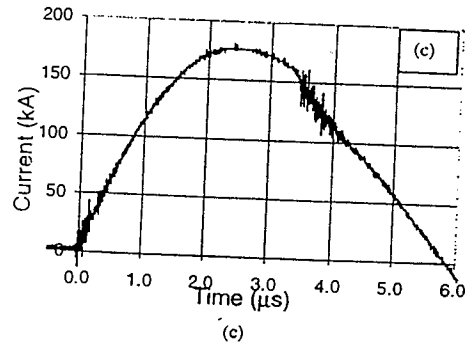
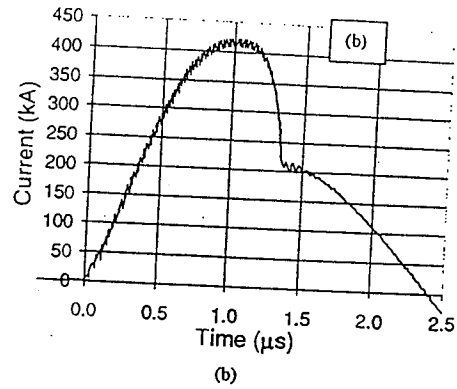
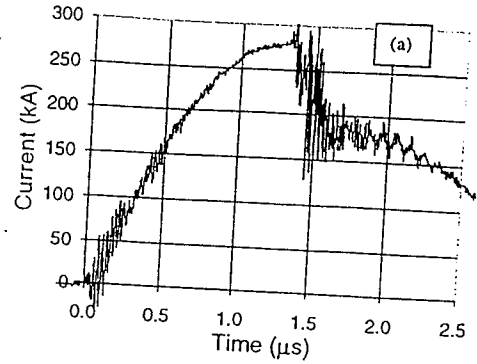


Fig. 7. Some representative oscilloscope traces obtained from (a) the NX1, (b) the NX2, and (c) UNU/ICTP PFF.

field energy driving the plasma. However if the anode is made too long and the velocity pushed too high, the final focus temperature will become too high for efficient production of neon *K* shell lines.

Fig. 8 shows SXR lithographic exposures to confirm the SXR flux of NX1 and NX2 [13]. The resist used has a sensitivity rated at 100 mJ/cm^2 and is placed 40 cm from the focus. Magnets are placed to deflect the electron beams associated with the plasma focus [14] to ensure that the exposures are by SXR. The mask is a $1 \mu\text{m}$ thick gold mesh with grid separation of $5 \mu\text{m}$. The NX1 beamline has a three times poorer transmission ratio than the NX2 beamline. These lithographs confirm that the NX1 produces mor-

TABLE III
COMPARATIVE PERFORMANCE OF NX1, NX2, AND UNU/CTP PFF

Machine	Bank Voltage/Energy (kV/kJ)	Length/Equivalent (cm/cm)	Optimum Pressure (mbar)	Measured Current (kA)	t_{ex} (μ s)	Average Axial Speed (cm μ s $^{-1}$)	D (kAcm $^{-1}$)	S (kA cm $^{-1}$ torr $^{-1/2}$)	SXR yield (J)
NX1	10/1.5	5.5/6	10	230	1.50	4.0	153	56	20
NX1	12/2.2	5.5/6	12	280	1.45	4.1	187	62	55
NX1	14/2.9	5.5/6	14	320	1.40	4.3	213	66	80
NX1	10/1.5	4.5/5	12	230	1.25	4.0	153	56	35
NX1	12/2.2	4.5/5	13	280	1.10	4.6	186	60	105
NX1	12/2.2	3.5/4	10	280	1.10	3.6	187	68	35
NX2	11.5/1.9	7	2	340	1.30	5.4	170	139	7
NX2	11.5/1.9	5	4	400	1.15	4.4	200	115	18
NX2	11.5/1.9	4	7	410	1.05	3.8	205	90	15
UNU/CTP-PFF	14/2.9	16.5	4.2	175	3.5	4.5	184	103	5.3
UNU/CTP-PFF	13/2.5	16.5	2.8	165	3.5	4.5	174	119	3.5

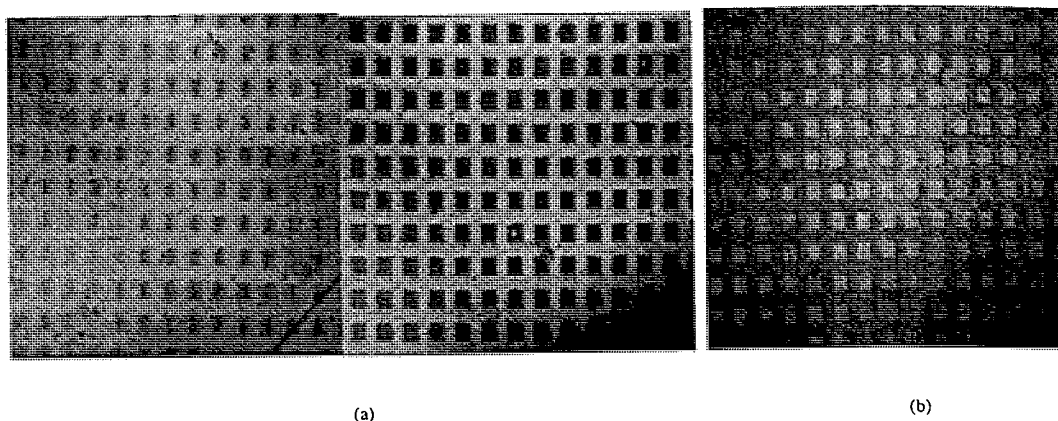


Fig. 8. Test exposure (a) NX1 (200 shots and 400 shots) and (b) NX2 (300 shots). Resist has arated sensitivity of 100 mJ/cm ^{2} .

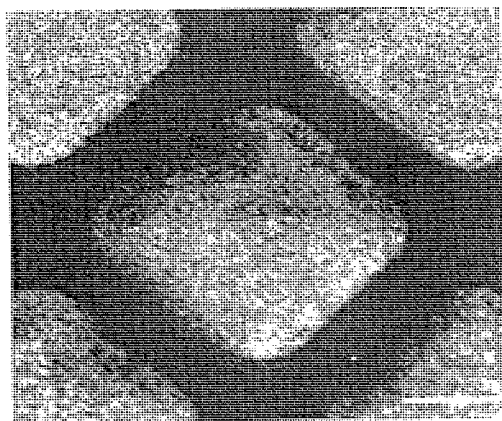


Fig. 9. Flash electron lithograph on PMMA, 10 shots (NX1).

three times the SXR yield per shot when compared to the NX2.

Fig. 9 shows a flash electron lithograph exposed on polymethylmethacrylate (PMMA) with ten shots of NX1. For electron lithographs the deflecting magnets were removed. The

exposure was used to estimate the electron beam current as 50 μ A over the 5 Hz burst. The electron energy was estimated as 30 keV [13].

V. CONCLUSION

We note that the NX1 and the NX2 have quite different yield performances. For each machine the observed speed at optimum yield for each anode length generally does correlate with the drive parameter S . However the value of S is significantly higher (up to two times) for equivalent speeds for the NX2 compared with the NX1. On the basis of machine scaling for neutrons [1] we would have expected constant value of S for optimum operation. This difference may be the cause of the large difference in yield. Despite higher circuit performance the yield performance of the NX2 is significantly lower than the NX1. This may be due to the significantly lower value of S for the NX1 which could be related to a higher operational density (up to three times) of NX1 for equivalent speeds and D , when compared to the NX2. The higher optimum operational density at equivalent temperatures obviously favors a higher SXR yield for NX1. This yield superiority of NX1 could perhaps be ascribed to differences in electrode materials (oxygen-free copper for NX1 compared to

stainless steel for the NX2), chamber configurations (carefully shaped channel and closed outer electrode for the NX1), perhaps even to the differences in backwall insulation materials and configuration. In terms of S values at optimum, the behavior of the UNU/ICTP PFF appears to be closer to the NX2 than the NX1.

In any case it appears that the NX1 chamber has the more promising features with maximum SXR yield over 100 J and wall plug efficiency of 4%, compared to 18 J and 1% for the NX2. By incorporating cooling in the NX1 chamber and increasing the charging capacity so that the NX1 chamber may be fired at 10 Hz, 1 kW of SXR power may be achieved which will expose a field at 30 cm in less than 2 s on a 100 mJ/cm² resist, assuming a beamline transmission of 0.5. This should be sufficient for industrial throughput demands applied to microelectronics lithography aimed at 0.15 μ m design rules.

Moreover, by using deuterium we expect a neutron yield of better than 10^9 per shot and 10^{10} neutrons per second when operating the cooled NX1 in a prolonged burst at 10 Hz. Such a powerful compact neutron source will have interesting applications.

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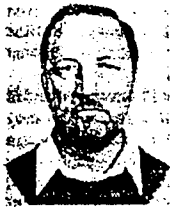
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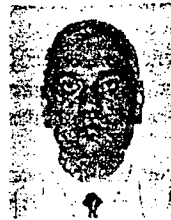
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A CRYSTAL SPECTROGRAPH AND ITS APPLICATION IN PLASMA FOCUS

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Abstract

A new compact crystal spectrograph (size $4 \times 4 \times 7 \text{ cm}^3$) for soft x-ray measurement in a plasma focus facility was designed and studied. The spectrograph has an adjustment system with 5 degrees of freedom making it easy to align and use. The spectrograph provides spatially resolved spectrum in one dimension over 0.1-5 nm wavelength range. A TIAP crystal with different form (flat or curve) was used to obtain spatially resolved spectra of Ne and Ar ions from DPF plasma focus. Such a spectrograph is also suitable to be used coupled to soft x-ray streak camera or x-ray CCD detectors.

Introduction

Many pulsed laboratory plasmas are intense sources of x-rays^{1,2}. Recent results with dense plasma focus (DPF) generators show promise for soft x-ray contact lithography^{3,4}. On the other hand, radiation processes are so significant during the evolution of these plasmas that many of their properties can be diagnosed by studying the radiation emitted from them^{5,6}.

The X-ray crystal spectrograph with spatial resolution is one of the most powerful diagnostic tools for dense plasma focus experiment⁷. A variety of available crystals with forms such as flat or curved, and with suitable lattice constant, diffraction coefficients and mechanical properties offer the possibility to make an optimum choice of the dispersive element and spectroscopic scheme in accordance with the aims of the diagnostics. Among the parameters relevant for optimization, spectral range, luminosity, dispersion, spatial and spectral resolutions are very important.

The emissions of x-ray from a DPF are characterized by high intensity, column-form source and wide spectral emission range. In addition strong shock wave from compressions must be taken into account. These properties of the plasma source demand that the crystal spectrograph must have a flexible adjustment system and must be designed to be effective in an environment with shock waves.

There are various schemes for measuring the soft x-ray using diffraction from a flat single or double crystal, a curved crystal, or a layered synthetic microstructure^{7,8,9}.

In this paper, we describe a new crystal spectrograph for the soft x-ray in our plasma focus facility as shown in Fig. 1.

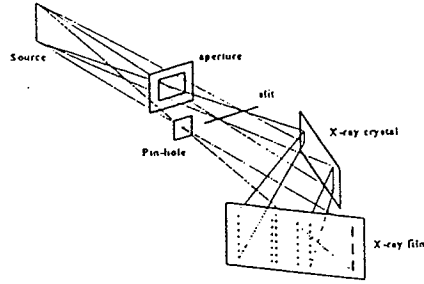


Fig. 1 Schematic diagram of the spectrograph and a soft x-ray source

Our spectrograph has an adjustment system of five degrees of freedom, and can be installed using two pieces of crystal. This design makes it possible to measure a wider spectrum region of x-ray emission. The spectrograph has not only the advantage of easy adjustment, higher efficient and higher spectral resolution, but also the capability of providing spatially resolved spectrum in one dimension over 0.1-5 nm wavelength range. A TIAP crystal was used, and the spatially resolved spectra of Ne, Ar ions from DPF were obtained. Furthermore an extension to measuring range may be made by easily changing to another crystal.

Basic Structure and Parameters

The properties of the x-ray crystal spectrograph follow the general theory of Bragg x-ray diffraction equation

$$m\lambda = 2d \sin \theta, \quad (1)$$

here m is the m -order diffraction, $2d$ is the crystal lattice constant, λ is the x-ray wavelength, and θ is the x-ray diffraction angle. It is very easy to install different forms of the crystals (flat and curve) in our spectrograph for various purposes. Using a curved crystal enables us to measure a wider range of x-ray spectrum. However it is very difficult to obtain an analytical solution for the relation between the position and the x-ray wavelength. Generally a flat crystal is used to measure x-ray spectral line and make x-ray diagnostics.

The relation between a wavelength λ_x and its position x on the film was done for several papers, some mathematics formulae for x-ray crystal spectrograph have been established by Kopper at Livermore Laboratory and by Hirano in Gunma University. According to our spectrograph geometry shown in the Fig. 2, we can derive a simple analytical expression for the relationship as follows:

$$MA = \overline{F} \operatorname{ctg} \left(\alpha + \arcsin \frac{\lambda}{2d} \right) \quad (2)$$

where MA is the distance between the line position A and projection M on the film, F is the distance between image S' and film M , and α are the angle of crystal plane with respect to the film.

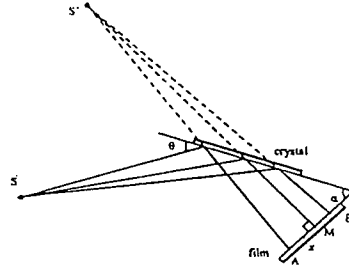


Fig. 2 Crystal spectrograph's geometry and X-ray diffraction trace.

In practice, it is difficult to measure the geometry of the spectrograph accurately. Therefore the observed wavelengths are measured with reference to two or more reference lines for which the wavelengths are known. Assuming that the known wavelength λ_A and λ_B at the A and B positions, according to the geometry of the Fig. 2, the unknown wavelength λ_x of the spectral line on the film then is given by

$$\lambda_x = 2d \sin \left[\arccos \left(\operatorname{ctg} \left(\alpha + \arcsin \frac{\lambda_A}{2d} \right) - \frac{L_{Ax}}{F} \right) - \alpha \right], \quad (3)$$

$$F = L_{AB} \left[\operatorname{ctg} \left(\alpha + \arcsin \frac{\lambda_A}{2d} \right) - \operatorname{ctg} \left(\alpha + \arcsin \frac{\lambda_B}{2d} \right) \right]^{-1} \quad (4)$$

where L_{AB} is the separation between line λ_A and line λ_B on the film plate, L_{Ax} is the distance from line λ_A to the line λ_x studied. From the above equations, one may see that the errors in the determination of wavelength arise mainly from the errors of the reference lines'

wavelengths, the separations and α . In the present work, spectral lines were measured two or more times and then the results were averaged. The wavelengths were calculated using several known lines on the film. F and α were taken as non-variable parameters, and the iteration was performed by least square fit. Finally the corresponding wavelengths at arbitrary positions are evaluated. Compared with the polynomial fitting of the dispersion curve, this method has the advantage of more convenience, wider wavelength coverage and higher accuracy.

A line may be identified after wavelengths determination by comparison of the measured wavelengths with previous observation of various ions' spectra. On the other hand, the identification of the lines in the present work was mainly made on the basis of empirical isoelectronic extrapolation or interpolation.

Resolution and Dispersion

In the equation (3), the accuracy of λ is dominated by the uncertainties of L , α , β and δ . Therefore, the incremental change in the wavelength is described as

$$\Delta\lambda = \left(\frac{\partial\lambda}{\partial L}\right)_{\alpha,\beta,\delta} \Delta L + \left(\frac{\partial\lambda}{\partial\alpha}\right)_{L,\beta,\delta} \Delta\alpha + \left(\frac{\partial\lambda}{\partial\beta}\right)_{L,\alpha,\delta} \Delta\beta + \left(\frac{\partial\lambda}{\partial\delta}\right)_{L,\alpha,\beta} \Delta\delta, \quad (5)$$

where ΔL , $\Delta\alpha$, $\Delta\beta$ and $\Delta\delta$ are maximum possible errors in the measurement of the location of the distance between reference wavelength and wavelength studied, in setting the angle of the crystal, in fluctuation of the soft x-ray source and in quality of the crystal, respectively. In general, we scan the film with large amplification and this method is used to greatly decrease the relative error of measurement on the parameter $\Delta L / L$. The dispersion $(\partial\lambda / \partial L)$ and $(\partial\lambda / \partial\alpha)$ is obtained from equation (3), and the results of the parameters of $(\partial\lambda / \partial L)(\Delta L / \lambda)$ and $(\partial\lambda / \partial\alpha)(\Delta\alpha / \lambda)$ are estimated to be 0.03%. The parameter $(\partial\lambda / \partial\delta)(\Delta\delta / \lambda)$ only depends on the quality of the crystal, and it is about 0.02% for TIAP crystal ($2d = 2.578$ nm). In our DPF system the x-ray source is fairly large, producing a large value for the parameter $(\partial\lambda / \partial\beta)\Delta\beta$ and results in serious source broadening on spectral lines. A pinhole was used to reduce the source broadening.

The spatial resolution only depends on the width of the slit in front of the spectrograph. In our spectrograph, the distance from the x-ray source to the slit is 80 mm, and the distance from the slit to the recording film is 72 mm. This configuration indicates that the magnification of the image of the x-ray source is 0.9 times and the spatial resolution is 50 μm . A better spatial resolution of the spectra can be obtained if we narrow the width of the slit. However a narrow slit will result in loss of intensity.

Photographic Film for the Soft X-ray Detection

We have examined several types of films for use as a soft x-ray detector. The no-screen film (Kodak No-screen film, S-5F No-screen film, etc.) were very sensitive, and they were suitable for very soft x-ray range (5-30 nm) recording¹⁰. For DPF x-ray radiation spectral films such as Kodak direct expose film, S-5F film, etc., can be used in the experiments. We mostly used Kodak TMG/RA-1 as our x-ray recording film which we found slightly more sensitive than Kodak TMS/RA-1.

The position of the detector in our spectrograph is very flexible. In our system it could be coupled to x-ray CCD camera for studying time resolved x-ray emission spectra. In that arrangement we will have spectral, temporal and spatial resolution.

Experimental Condition

Experiments were performed on the NIE-SSC-PFF¹¹. A compact dense plasma focus (CPF) was connected to a capacitor that was discharged into a gas-filled (vacuum) chamber housing a cylindrical electrode geometry. The capacitor had capacitance of 30 μ F and an internal-inductance of 110 nH and was charged to 11-15 kV, with a neon or argon gas filling pressure between 2.0 and 4.5 Torr. The input energy varies from 1.8 to 3.3 kJ under these operating conditions. The detailed CPF device was described in previous paper¹².

The machine parameters that were varied in this work were the filled gas pressure, capacitor charging voltage, and the inner electrode configuration. The x-ray spectral output was measured with a flat-crystal spectrograph using Kodak TMG/RA-1 direct exposure film and TiAP diffraction crystal with known integral reflection coefficient. The spectrograms were densitometered and computer processed to obtain spectral intensities. Total radiation path length (x-ray source to film) was about 152 cm.

Experimental Data and Results

Examples of the spectra (symbol 1-6) and x-ray pinhole image (side on, symbol α) obtained from a Ne gas-filled CPF are shown in Fig. 3(a). Fig. 3(b) presents its micro-densitometer tracing, and Fig. 3(c) gives a lineout trace of x-ray pinhole image.

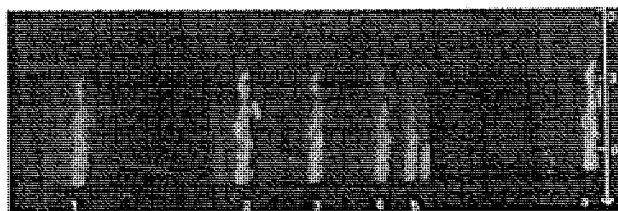


Fig. 3(a) Examples of the spectrum obtained from a neon gas-filled CPF

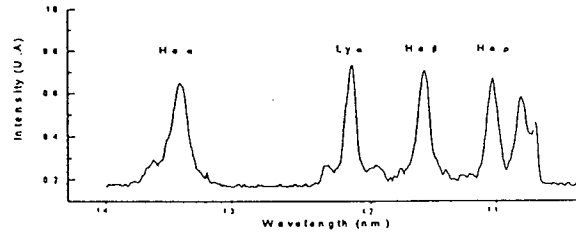


Fig. 3(b) The microdensitometer tracing of x-ray emission spectrum of a highly ionized neon plasma

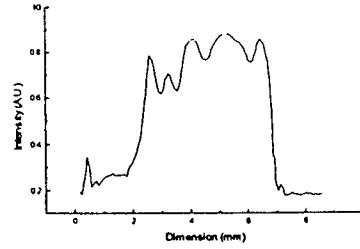


Fig. 3(c) The lineout trace of x-ray pinhole image

Following a method described in part 2, we have identified and classified those lines in Table 1 which were electron transitions from H-like, He-like and Li-like neon ions.

no	ions	transition
1	Ne IX	$1s^2-1s2p$
2	Ne X	$1s-2p$
3	Ne IX	$1s^2-1s3p$
4	Ne IX	$1s^2-1s4p$
5	Ne IX	$1s^2-1s5p$
6	Ne IX	$1s^2-1s6p$
7	Ne X	$1s-3p$
8	Ne X	$1s-4p$
9	Ne X	$1s-5p$

Table 1 Classification of x-ray emission spectral lines of a highly ionized neon plasma.

In general, the intensity of satellite spectrum is quite weak and the spectral peak intensities from electron transition $1s-np$ states of H-like ions are slightly stronger than that of He-like ion lines. However, we also found X-ray intensities of He-like ion are stronger than that of H-like ion emissions. This observation may be related to instabilities.

The resonance lines, combinations, satellites and continuum can be used to diagnose plasma electron temperature and density. For simplicity, a steady state ratio between consecutive ions in a corona model plasma may be written as¹³

$$\frac{n_{i+1}}{n_i} = 1.27 \times 10^8 \times \frac{\zeta T_e^{3/4}}{x_i^{11/4}} \exp\left[-\frac{x_i}{T_e}\right] \quad (6)$$

where x_i is the i th ion ionization potential in eV, T_e is the electron temperature in eV, ζ is the number of electrons of out shell. Using this equation, the fraction of ionization of states at different temperature is calculated. By comparing the experimental to theoretical results with H-like ion and He-like ion emission intensities, the plasma temperature in our CPF is estimated as 250 eV in the hot-spots.

Using several combination spectral lines and a resonance line of $1s^2$ - $1s2p$ electron transition, the plasma electron density can be estimated¹⁴. However, the large size of the x-ray source in our CPF has caused source broadening and resulted in overlap of combination lines and resonance of $1s^2$ - $1s2p$.

The image of the CPF x-ray source shows a complex structure as seen in Fig. 4(a). Spatial distribution of the soft x-ray intensities and the spectrally analyzed image are compared in Fig. 4(b) and interpreted as follows.



Fig. 4(a) The image of the CPF x-ray source with spectral resolution shows a complex structure

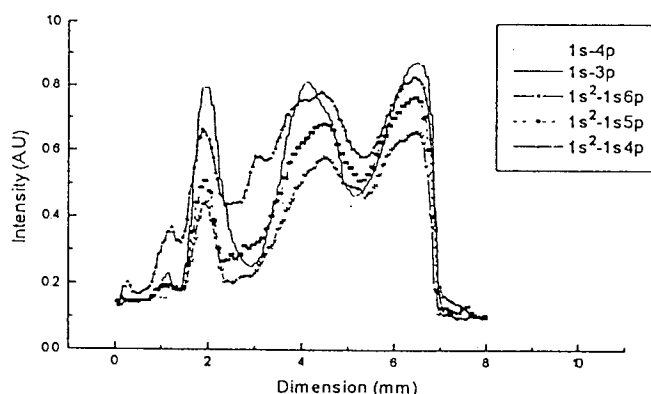


Fig. 4(h) The spatial distribution of the soft x-ray spectral intensities

There is a column of the plasma with several localized bright spots. These spots are circular and sharp-edged indicating that they are actually the source of x-rays. The size of each of these spots is estimated to be typically 100 μm in diameter. The side-on image of plasma emission is the appearance of a thin column with a 5.0-8.0 mm length. The diameter of the column estimated from the emission image is 400-700 μm .

Using a large-lattice ($2d = 6.55 \text{ nm}$) OHM crystal, instead of TIAP in our spectrometer enables us to obtain even longer wavelength in range of 2.0 to 6.0 nm. However the spectral intensities are very weak. One of the main difficulties faced in our study was that the softer x-rays were heavily absorbed by the beam-attenuating coatings. Theoretical estimation indicates that the absorption coefficient for 3 nm soft x-ray is 19 times larger than that for 0.8 nm x-rays for an attenuating coating made of a 100 nm thick Formvar film plus a 400 nm thick aluminum film⁹. We can not choose a thinner window because of the very strong shock wave in the CPF.

For comparison a similar study of the plasma x-ray emission feature from Ar-gas filled CPF was also made. We still observed a few clear spectral lines. However, the area of X-ray emitted from Ar plasma was obviously limited, and the spectral intensity is very weak.

Conclusion

A compact crystal spectrograph for the soft x-ray region in our plasma focus facility was designed and examined. The design of the spectrograph makes it easily align and use, with good spatial resolution over one dimension and a spectral range of 0.1-5 nm.

Strong soft x-ray spectral emissions from CPF are observed. High space resolution was achieved. A detailed study of the CPF parameters and structure were carried out.

The results show a complex x-ray spatial and spectral distribution. It consists of a column of plasma with several localized bright spots. The size of each of these spots was estimated to be typically 100 μm in diameter and their temperature was estimated to be 250 eV.

Acknowledgments

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POWERFUL SOFT X-RAY SOURCES AND HIGH RESOLUTION LITHOGRAPHY

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We have developed two powerful soft x-ray (SXR) sources, the NX1 and NX2. At 300W SXR yield (into 4π) these are among the most powerful point SXR sources in the world. Using the NX2, we have demonstrated SXR lithography down to below $0.2\mu\text{m}$. This paper discusses basic operational characteristics of the plasma focus from design perspectives in order to develop powerful radiation sources. Using these ideas we have developed the NX2. The NX2 operates with peak currents of 400kA at 11.5kV into water-cooled electrodes at repetition rates up to 16 Hz to produce 300W SXR in burst durations of several minutes. Using neon we have SXR in the wavelength range of 0.8-1.4nm, comparable with the output wavelengths from synchrotron light sources. Harder radiation may be obtained by using other gases e.g. argon. Such high performance compact machines may be improved to yield over 1 kW of SXR, enabling sufficient exposure throughput to be of interest to wafer industry.

INTRODUCTION

We have developed two high power soft x-ray (SXR) sources, the NX1 and the NX2 based on the principle of plasma compression. Producing 300W SXR power (into 4π), these are among the most powerful point SXR sources in the world.

We have demonstrated SXR lithography by reproducing features smaller than $0.2\mu\text{m}$ in size using the NX2.

Operating in neon the SXR has a wavelength range comparable to that from a synchrotron light source. For our plasma source, we may reduce the wavelength to 0.5nm by using other gases e.g. argon. This would extend the range of applications.

DESIGN CONSIDERATIONS

For Mather's type plasma focus operation it is observed experimentally^{1,2} that the quantity designated as the drive parameter² $S = (I/a)\rho^{1/2}$ (where I is the driving current, a the anode radius and ρ the operational gas density), a measure of speed, both axial and radial, has an optimum value for each gas of operation. The drive parameter S is a measure of the drive magnetic pressure per unit density or the drive magnetic energy per unit mass. Thus any model based on either the snow-plow or slug model will have the driven speeds primarily dependent on this factor S . It may be necessary to apply correction factors to account, for example, for mass loss or current loss factors or even variations of such factors as the electromagnetic drive proceeds in stages. This applies to all electromagnetically driven plasma systems including the Z-pinch for which the implosion speed, treated either by a slug or snowplow model also scales as S (see, for example, the discussion of implosion time scaling in reference³).

Operating in noble gases for the generation of soft x-ray (SXR) an optimum speed may be readily understood. For example in neon the compressed plasma in the focus should have a temperature of some 400 eV if the radiation is required to be predominantly in the 0.8-1.4 nm for the purpose of microelectronics lithography. We have used a model, computing plasma dynamics in the axial, radial, and radial reflected shock phases, incorporating a quasi-equilibrium radiative phase⁴⁻⁶ to examine for example the optimum axial speed required to set the stage for optimum radiation in the 0.8-1.4 nm range. This model is used to correlate with experimental results, which indicate an optimum average axial speed of 4.5 cm/ μ sec.

It is important to note that the optimum speed for each of deuterium and neon operation remains nearly constant for the range of machines surveyed. This is particularly remarkable for deuterium operation where a value of S nearly constant at 90 kA/(cm-torr)^{1/2}, corresponding to a peak axial speed of just less than 10 cm/ μ sec, is tabulated¹ over a wide range of machines from training machines of 3 kJ² to machines of 300kJ. This means that for each gas the plasma temperatures in each of the dynamic phases, and by inference also in the compressed radiative phase, are identical for all machines, big and small, when optimized.

We next note that the quantity S is dependent on $D = I/a$ linearly whilst it depends only on the half power of ρ . Note also that over a two decade range of stored energy the optimized operational pressure has a range of only 2¹. Thus in a relative sense the density ρ and hence the quantity D may in the first approximation be considered also as constant when comparing different machines, all optimized. This clearly agrees with the design tendency to increase the anode radius proportionally

with the available drive current. But there is also a fundamental significance.

For each gas, since we are dealing with the same compressed temperature and essentially the same density, radiation yield will depend on the product of compressed plasma volume and lifetime. Again since we are dealing with the same dynamical speeds and compressed temperatures any reasonable modeling^{4,7,14} will show that each dimension of the pinched plasma is proportional to the anode radius, as is the lifetime of the compressed plasma. Thus radiation yield is proportional to a^4 . And since D is essentially constant for each gas, radiation yield, at least for neutrons and SXR, is proportional to I^4 . Such a scaling is energetically possible since whenever energy is taken from the circuit by the plasma such an energy extraction will reflect in a lowering of the current. Such a self-regulating mechanism will self-consistently limit the extraction of energy from the circuit.

Thus for a given stored energy, yield performance is related to current. Circuit inductance needs to be minimized. Our modeling also indicates the importance of minimizing the ratio of generator impedance to total impedance for efficient transfer of energy to the plasma pinch. Practically this is again accomplished by minimizing all the inductances from the capacitor bank through the switches right up to the collector flanges of the plasma focus head. Thus improving circuit performance should improve yield performance.

For applications, whilst the peak rates of yield may have significance for some time-resolved experiments, for other applications such as SXR lithography for microelectronics application there is a need for high average yield rates sustained over at least a duration of minutes, even for demonstration purposes. Thus ability to operate at high repetition rates in a prolonged burst is necessary.

The length of the anode is also of crucial importance^{2,7}. Computation and experience agree that a strong focus with optimum energy coupled into the focus pinch so as to emit intense radiation, is achieved when the radial compression starts (end of axial phase) at a time t_{ax} where t_{ax} is equal to t_r , t_r being a hypothetical risetime of the capacitor bank with a value between the short-circuited risetime and the risetime of the circuit loaded hypothetically with the full axial load. As a rule of thumb the short-circuited risetime may be used for a first estimate of the optimum anode length.

Thus for the deuterium focus with an optimum average axial speed of say 5.5 cm/ μ sec the anode length should be 5.5 cm per μ sec of short-circuited bank risetime. For the neon focus taking the optimum average axial speed to be 4.5 cm/ μ sec would give us an indicative optimum anode length of 4.5cm for every μ sec of short-circuited bank risetime.

What about the value of $D = I/a$? From a survey of experiments it is found that the current per unit anode radius has a design range of 150-220 kA/cm, for

optimum neutron yield. We have used this range also as an indicative design range for our SXR facilities.

Based on the above considerations we have developed two high repetition rate compact plasma focus facilities, the NX1 and the NX2 to be powerful SXR sources for microelectronics lithography⁸⁻¹³.

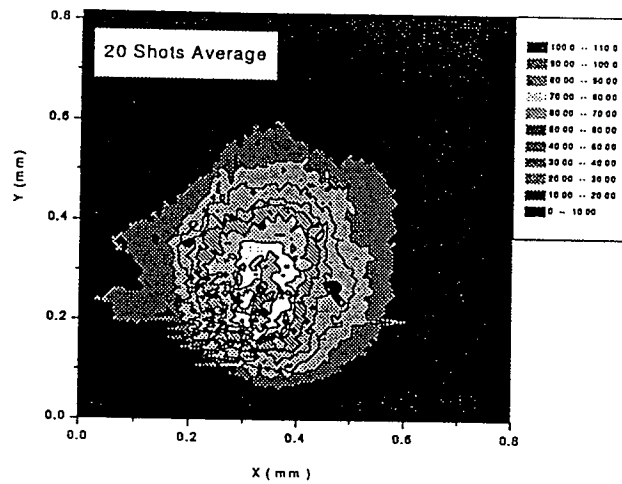


Fig. 1 End-on x-ray pinhole image (equi-density contour of 20 shot overly).

By considering drive parameters, operational speeds and yield performance we had developed two plasma focus devices into powerful SXR sources, the NX1 and NX2, for microelectronics lithography. Although the NX1 appeared to be the more efficient machine, with a wall plug conversion efficiency into SXR of up to 4%, we have made our first attempts at SXR lithography using the NX2 source since the NX2 had water cooled electrodes and hence could be operated in longer bursts at higher repetition rates. The requirements for a point SXR microelectronics lithography source may be summarised as follows:

- a. point source with dimension less than 1mm (viewed end on).
- b. emission in the wavelength range 0.8-1.4nm.

We have fulfilled (a) (Fig. 1)¹⁵ and (b) (Fig. 2)⁶.

For industrial throughput purposes there is a third requirement.

- c. Average SXR power of 1kW at source over 4π delivered over a prolonged burst.
The NX2 produces 20J per shot at up to 16 shots per second giving up to 300W

of SXR power. For demonstration purposes even operation at the 50W level allows convenient accumulation of the required exposure dose.

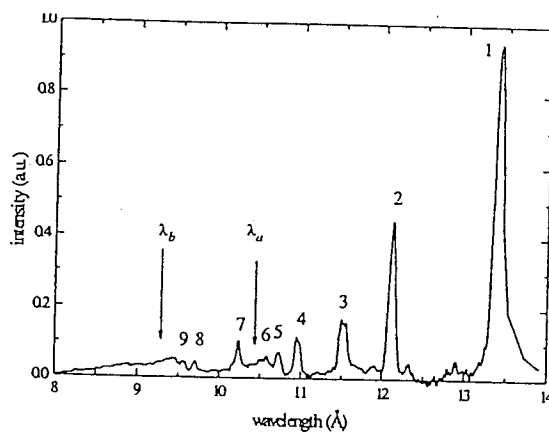


Fig. 2 Neon plasma x-ray spectrum.

APPARATUS

The NX2 is a 2kJ focus operated in Neon. The capacitor bank consists of 48 capacitors with a total capacity of 30 μ F. These are arranged in a square, 12 capacitors on each side of the square connected to the plasma focus via a rail gap switch by parallel plates, folded to save space. A general view is shown in Fig. 3. The capacitors are charged to 11.5kV by ALE model 802 chargers with a total charging capacity of 32kW. The short circuit rise time is 1 μ sec. The on-load current peaks at 400kA at a repetition rate of up to 16 shots per sec.

The design (Fig. 4) enables measurement of SXR yield via the upper beam lines at the same time as the lithographic exposure is made in the chamber below the plasma focus electrodes. The system is completely shielded against electromagnetic radiation and has a footprint of 1.6m $\times$ 1.6m. A schematic of the stainless steel water cooled electrodes is shown in Fig. 4. Cooling of the electrodes is achieved by ducts in the anode and outer squirrel cage cathode through which chilled water flows. A quartz disc is found necessary to protect the inside base of the anode against the electron beam emitted from the plasma focus. A 3.5mm hole in the centre of the quartz disc and through the anode extracts SXR onto the lithography assembly (Fig. 4) in the lithography chamber. The plasma focus chamber is evacuated by a turbo-molecular pump. During focus operation, the turbo molecular pump is isolated and a continuous flow of neon is admitted into the upper section of the plasma focus chamber whilst a rotary pump, connected to the lower end of the lithography chamber pumps out the neon through the anode SXR extraction hole. In this way using a choking aperture

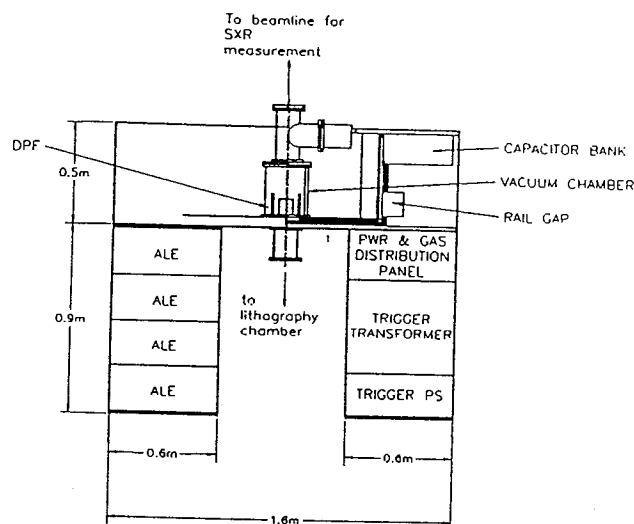


Fig. 3 General view of the NX2.

(1.5mm in diameter) at the anode extraction hole a low pressure (10^{-2} mbar) may be maintained in the lithography chamber whilst operating the focus chamber at the correct focusing pressure of 4-5mbar.

The lithography assembly (see Fig. 4) uses a clamping magnet to attract a steel washer thus evenly clamping a mask to a resist coated wafer. The SXR passing through the mask falls on the resist. The clamped mask-resist structure is centred in a light-tight structure with an entrance aperture closed by $10\mu\text{m}$ Be foil which allows in SXR but blocks out UV and the visible spectrum. The SXR from the plasma focus point source is extracted through the hole at the bottom of the anode and passes through an array of magnets, which deflects the electron beam to the side, before entering the lithography assembly via the beryllium window.

EXPERIMENT AND RESULTS

Experiments in x-ray lithography include a range of positive and negative resists exposure with specially designed test x-ray masks. The high resolution test mask consists of a $0.5\mu\text{m}$ thick Ni absorption layer with smallest elements dimensions below $0.1\mu\text{m}$ on 100 nm thick Si_3N_4 membrane. The high contrast masks have a similar design but the absorption layer is $0.3\text{-}0.6\mu\text{m}$ Au with smallest line width from 0.2 to $0.4\mu\text{m}$ depending on Au thickness.

The x-ray yield is monitored, using a photoconducting diamond detector (PCD), during the exposure and the exposure stopped when the total x-ray yield

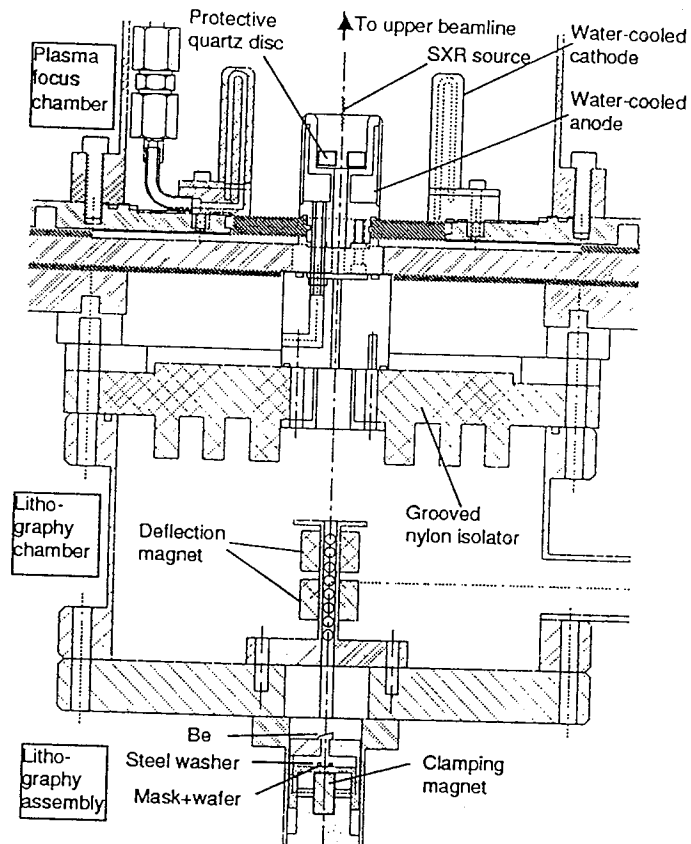


Fig. 4 Detail of experimental setup.

was considered sufficient for an exposure.

Positive resists, PMMA495 and ERP40 (from NII MV, Russia) with low sensitivity, but high resolution and good development flexibility, were used with high resolution masks to show that mask membrane vibration during the high rep-rate pulsed discharge does not affect the exposure resolution.

The aim of experiment was to demonstrate the possibility of forming $0.2\ \mu\text{m}$ elements in chemically amplified negative resists AZPN114 and SAL601. The Au mask and wafer covered with $0.5\ \mu\text{m}$ resist layer were clamped with a magnet to provide a small gap and to avoid mask shift during exposure. To get high resist sensitivity, a Post Exposure Baking (PEB) scheme with 2 minutes at 110°C on hotplate was used. This PEB provides resist resolution better than $0.1\ \mu\text{m}$, as seen from sharp corners of the $0.2\ \mu\text{m}$ width structure in AZPN114 resist, seen in Fig. 5(a), but makes the

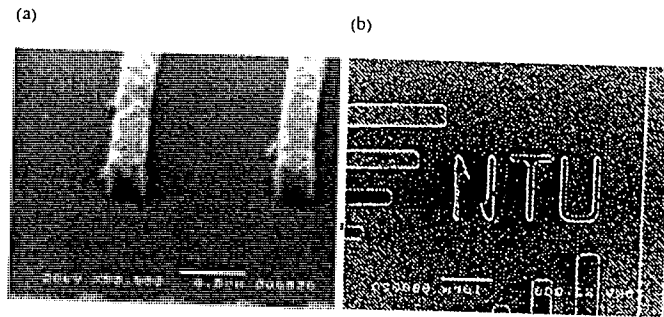


Fig. 5 SEM pictures of test structures produced in AZPN114 with x-rays from NX2.

exposure time approximately twice shorter in comparison with the recommended (1 min at 100°C) PEB parameters. The structures in AZPN114 resist shown in Fig. 5(b) is a mirror image of the test mask structure.

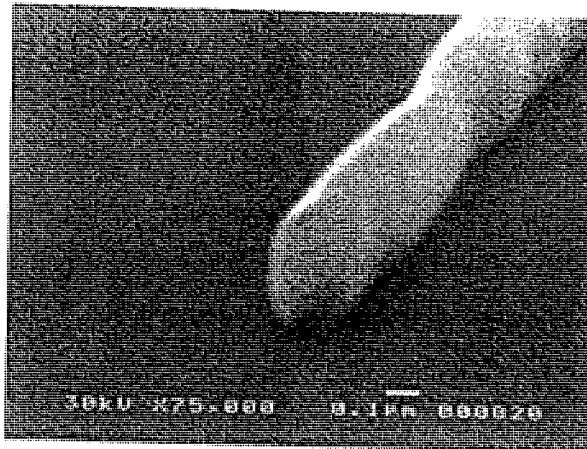


Fig. 6 SEM picture of small structure replicated in AZPN114 using the NX2.

Fig. 6 shows a line with less than $0.2\mu\text{m}$ width the rounded edges show that this is near the limit of the resolution. Such small structures can be made only on relatively thin layers of resist.

CONCLUSION

We have designed two powerful point soft x-ray sources at the 300W level (into 4π). Using one of these two sources, we have demonstrated the transfer of $0.2\mu\text{m}$ structures

from masks to resist. It would be useful to extend the wavelength range of the source e.g. to 0.3-0.5 nm in order to develop other applications which requires high resolution, high aspect ratio micro structures.

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Experiments on speed-enhanced neutron yield from a small plasma focus

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In order to operate a plasma focus at high axial sheath velocities, the geometry of the inner electrode (anode) of a 3 kJ Mather-type device was modified. Double-stage stepped-anode configurations were tested with the speed-enhanced region sufficiently long for a significant increase in speed but not long enough to allow the development of force-field flow-field separation at the end of the axial phase. Peak axial speeds up to $15 \text{ cm } \mu\text{s}^{-1}$ were achieved. The neutron and soft X-ray productions were found to be sheath-velocity-dependent. A new scaling law for the non-beam component of the neutron yield is proposed.

1. Introduction

The most important areas for developing immediate practical applications using a plasma focus are those that employ the device as a pulsed radiation (i.e. neutron or soft X-ray) source. Therefore special attention has to be given to studies of radiation mechanisms. Based on these studies, new methods for enhancing the radiation yield could be developed.

An analysis of data for Mather-type plasma-focus devices for their wide range of sizes, with the energy stored in the driver ranging from 1 kJ to 1 MJ (Haines 1982; Kies 1988; Herold 1990; Conrads 1992; Bernard *et al.* 1994) shows the following experimentally observed features.

- (i) The total neutron yield scales with the focus current as $Y_n \propto I^4$.
- (ii) Plasma focus devices can be optimized either for large X-ray output or for high neutron production.
- (iii) For neutron-optimized operating conditions, the following properties are seen.
 - (a) They all have the same limited peak axial sheath velocity v_{axial} of $10 \text{ cm } \mu\text{s}^{-1}$ and radial on-axis collapse speed of $25 \text{ cm } \mu\text{s}^{-1}$; this fixes the forward shock temperature on axis at $1.4 \times 10^6 \text{ K}$, and the on-axis reflected-shock temperature at $3.6 \times 10^6 \text{ K}$. Further compression brings the temperature of the gross plasma column to just under 1 keV (Lee 1988, 1990).
 - (b) They are all driven by a standard value of a drive parameter $(I_p/a) \rho_0^{-1/2}$ (i.e. the peak drive current per unit anode radius divided by the square root of the fill density) of $89(\pm 8) \text{ kA cm}^{-1} (\text{Torr D}_2)^{-1/2}$ (Lee and Serban 1996) (for simplicity, the gas density is replaced by pressure and the drive parameter is written as $(I_p/a) p^{-1/2}$). This ensures for all machines the same value of the drive magnetic field in the axial phase

and the same compressed energy density in the focus phase, leading to the same high temperature in all devices (Lee 1990, 1994).

(c) They all have a maximum density of the pinched plasma in the region of $(1-5) \times 10^{19} \text{ cm}^{-3}$ (Lee *et al.* 1988).

(d) They all operate in a narrow range of deuterium filling pressures of several torr.

(iv) They have a plasma impedance about 0.3Ω (Bernard *et al.* 1994).

The neutron scaling law shows that the larger plasma focus devices produce more neutrons. This increased neutron yield appears to be due only to a combination of the larger volume of the focused plasma and the consequent increase in the lifetime of the focused region. Any realistic modelling of the plasma focus will show that each linear dimension of the approximately cylindrical focus or pinch region is proportional to the anode radius (Lee 1983, 1988; Lee and Serban 1996). Since all plasma focus devices are conventionally designed with nearly the same drive parameter, it follows that the volume of the focused or pinched plasma is proportional to I_p^3 . The lifetime of plasma confinement is limited by the magnetohydrodynamic transit time. This transit time is a function only of the smallest linear pinch dimension, and hence of I_p , since the energy densities that control the relevant magnetohydrodynamic speeds are practically identical, as discussed above. Combining these scalings of volume and confinement time immediately gives the experimentally observed scaling law $Y_n \propto I^4$.

A good focusing effect is usually obtained in plasma focus experiments when the peak axial sheath velocity is within the limited range of $6-10 \text{ cm } \mu\text{s}^{-1}$ and the drive parameter is about $89 \text{ kA cm}^{-1} (\text{Torr D}_2)^{-1/2}$ (Lee & Serban 1996). The lower speed limit is easily understood in terms of poor coupling of the magnetic piston with the driven plasma layer, indicated by a low magnetic Reynolds number R_m (Lee *et al.* 1991), or in terms of low specific energy (Pouzo *et al.* 1988). For the higher speed limit, it appears that the high R_m leads to an effective separation of the magnetic piston from the plasma layer. The plasma layer then collapses radially, whilst the magnetic piston is still driving axially (Lee 1994). Such a force-field flow-field separation is not conducive to an intense focus. Other possible mechanisms responsible for the upper speed limit are due to

- (i) plasma-anode interactions or, more specifically, the ion (and sometimes, electron) current component;
- (ii) the development of Rayleigh–Taylor instabilities;
- (iii) at high velocities, the mean free path increasing and subsequently the shock becoming diffusive, hence making the drive ineffective.

In the light of these factors, the idea of driving the plasma with speeds exceeding the ‘magic’ value of $10 \text{ cm } \mu\text{s}^{-1}$, but at the same time trying to overcome the difficulties mentioned above and to achieve good focusing effect, became challenging. Of course, one of the possibilities for increasing the speed is to reduce the gas filling pressure, but in this way one switches from one operating regime to another, and the effects are already known. In fact, a change of pressure is the practical way to optimize a given machine (fixed geometry) to operate in a certain regime.

In our work we studied the performance of a plasma focus driven by peak axial sheath velocities up to 10–15 cm μs^{-1} without changing the gas filling pressure or the charging voltage. Our first objective was to characterize the focus operating with the standard electrode geometry and to correlate various plasma parameters like thickness and inclination of the sheath, size, location and temperature of the pinch, development of macroinstabilities, X-ray production, and neutron yield.

Secondly – and this was the new element introduced by our experimental work – in order to increase the drive parameter and at the same time to limit the force-field flow-field separation, we used a stepped anode structure, which we call a composite anode (see Fig. 1). The first part of the axial phase uses a regular anode designed for the standard $(I_p/a)p^{-1/2}$, but shorter than required to match the discharge peak. This regular anode is attached to a stepped-down anode of smaller radius. This is the speed-enhanced section with increased value of $(I_p/a)p^{-1/2}$, which should be long enough to increase the speed significantly above 10 cm μs^{-1} , but short enough to limit the force-field flow-field separation.

Our hypothesis is that a good focusing effect occurring at higher speeds implies the achievement of higher temperatures of the pinched column. This will automatically lead to an enhanced radiation output. A possible explanation of this effect is based on an idea proposed by Lee (1988, 1994). He suggested that removing the speed limitation would ultimately result in a vastly improved scaling law $Y_n \propto I^8$, which could enhance the prospects of the plasma focus as a fusion contender.

Operating the focus at higher velocities, and hence higher temperatures, the thermonuclear component Y_{th} of the total neutron production is enhanced. It can easily be shown that $Y_{th} \propto I^4 v_{axial}^4$, and the beam–target component of the neutron yield $Y_{bt} \propto I^{4.5} v_{axial}^{-1.5}$.

The total neutron yield is $Y_n = Y_{th} + Y_{bt}$. If the experiments do not limit the speed of operation then Y_{th} will increase above the I^4 scaling whilst Y_{bt} will have a scaling law poorer than $I^{4.5}$. In the limit keeping the anode radius constant whilst increasing the current,

$$Y_{th} \propto I^8, \quad Y_{bt} \propto I^3.$$

The following conclusions may be drawn from such an analysis: operating at higher speeds, above 10 cm μs^{-1} , should

- (i) increase the thermonuclear component of the neutron yield preferentially to the beam–target component;
- (ii) make the scaling law more favourable than I^4 , with the ultimate, most favourable scaling law being $Y \propto I^8$ (Lee 1994; Lee and Serban 1994).

In view of such analysis, a further objective of our work was to obtain indications regarding how neutron production scales with speed.

2. Apparatus

The evolution, dynamics, and discharge characteristics of a 3 kJ Mather-type plasma focus device were studied using two different electrode configurations (see Fig. 1). The outer electrode used as cathode was not modified. The two basic kinds of geometries of the anode were:

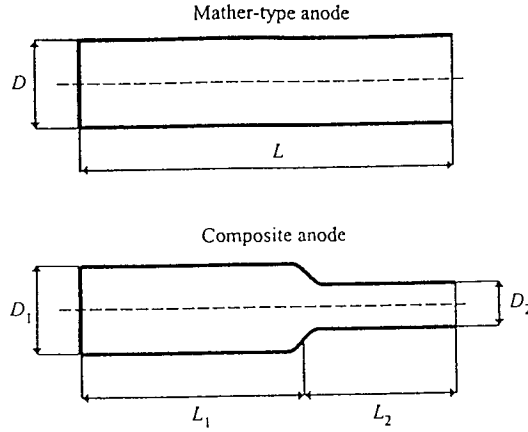


Figure 1. Anode configurations: one-piece Mather-type anode (top) and stepped-down composite anode (bottom).

Table 1. One-piece Mather-type anode configurations (OPA).

Name	L (mm)	D (mm)
SPF-165/19	165	19
OPA-185/15	185	15
OPA-180/17	180	17
OPA-175/17.5	175	17.5

Table 2. Composite-anode configurations (CCA). All dimensions are in mm.

Name	L_1	D_1	L_2	D_2
CCA-120/19 + 50/15	120	19	50	15
CCA-103/19 + 70/15	103	19	70	15
CCA-93/19 + 80/15	93	19	80	15
CCA-90/19 + 100/15	90	19	100	15
CCA-95/19 + 90/14	95	19	90	14
CCA-65/19 + 120/45	65	19	120	15
CCA-45/19 + 140/15	45	19	140	15

- (i) a one-piece Mather-type anode (OPA; Fig. 1 and Table 1);
- (ii) a stepped anode called a composite anode (CCA; Fig. 1 and Table 2).

The first part of this stepped anode was a regular Mather-type anode designed for our plasma focus device, but cut shorter than required to match the discharge peak. The diameter of the first part of the anode was 19 mm (see Table 2). This corresponded to the diameter of the original anode of the focus device designed for operating at 15 kV. Thus we do not change the conditions for the first part of the discharge, i.e. the breakdown, lift-off and axial propagation phases. This part was attached to a stepped-down anode of smaller radius. This second stage of the anode is referred to as the speed-enhanced section, which we attempt to adjust in length and diameter. All the anodes used were hollow at the open end.

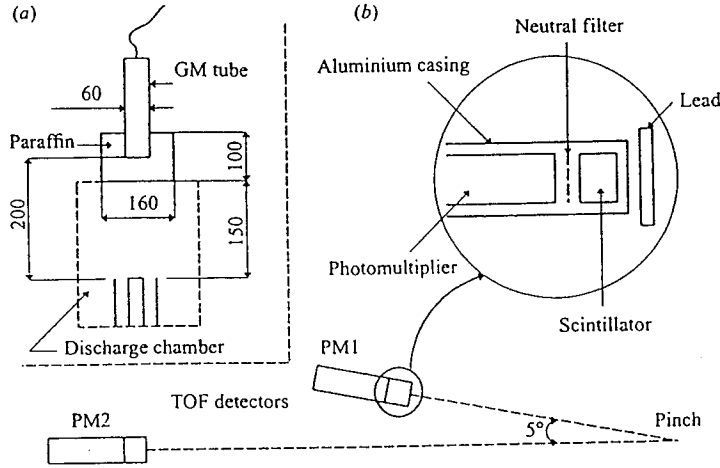


Figure 2. Schematic of experimental arrangements for neutron measurements: (a) neutron yield (all dimensions are in mm); (b) time-resolved neutron flux and time-of-flight.

The diagnostic techniques employed include current and voltage measurements, shadowgraphic investigations, time-resolved neutron measurements and total neutron yield, and axial sheath velocity measurements. The plasma electron temperature during the pinch phase was determined using the filter ratio method.

Measurements of the total neutron yield were carried out using the indium foil activation technique. A schematic of the experimental set-up is illustrated in Fig. 2(a). The calibration factor of our system (BICRON Labtech Analyzer with GM tube) was 3.4×10^5 neutrons/count. Time-resolved neutron flux measurements were carried out with two time-of-flight (TOF) detectors. A schematic diagram of the experimental arrangement is shown in Fig. 2(b).

Each TOF detector consists of a plastic scintillator NE 102A of 50 mm diameter and 40 mm thickness coupled to a photomultiplier EMI 9813B. The plastic scintillator was wrapped in aluminium foil except for the side facing the window of the photomultiplier. Dow Corning 200 silicon grease was used between the plastic scintillator and the window of the photomultiplier for proper optical coupling.

Assuming a typical plasma-focus discharge producing an average yield of 10^8 neutrons/shot isotropically, the estimated numbers of neutrons reaching the TOF detectors (placed radially at $3.6(\pm 0.04)$ m and $6.1(\pm 0.04)$ m respectively) were approximately 1150 and 400 respectively. Therefore, in order to obtain output signals (to the oscilloscope) of approximately the same amplitude from both TOF detectors, neutral filters were placed between the plastic scintillators and the windows of the photomultipliers (see Fig. 2b).

The TOF detectors were enclosed in aluminium casings. Lead sheets of up to 6 mm thickness were placed in front of the TOF detectors to cut off most of the hard X-rays.

3. Results and discussion

The results of our experiments with basically two types of anode geometries, namely a one-piece anode and a composite or double-stage anode, show that, in terms of radiation output, there are significant differences among the electrode configurations studied. However, for the plasma focus evolution and dynamics, in practice two operating regimes are identified. One corresponds to discharges with single voltage spike. This is an indication of a single compression of the plasma column during the pinch phase. In these cases the neutron output is above the average value for each anode geometry. The other plasma focus regime is associated with multiple voltage spikes, which, in turn, indicate multiple compressions of the pinched column. The neutron productions were generally below the average for each electrode configuration.

The common characteristics of all electrode configurations investigated are as follows.

- (i) The neutron-optimized operating pressure is 450 Pa for a charging voltage of 14 kV.
- (ii) The neutron output of the plasma focus has a strong dependence on the gas filling pressure: the total neutron production has a pronounced maximum at 450 Pa deuterium; the neutron yield drops relatively sharply with increasing gas pressure, while deteriorating less drastically for decreasing pressures.
- (iii) Discharges with high neutron production are always accompanied by low soft X-ray output, but by high emission in the hard X-ray region.

At the same time, correlations of the plasma focus parameters have been made. The purpose was to get a better understanding of the evolution and dynamics of the plasma focus, as well as to benchmark the device for a given electrode configuration and operating conditions. The list of the parameters used includes peak discharge current, peak axial velocity, axial transit time, duration of the radial collapse, pinch lifetime, and neutron yield. Also, the soft X-ray production was correlated with the neutron yield.

The data from discharges having the same peak current, same peak axial velocity, and comparable pinch lifetime, but different axial transit time, show that the neutron yield is higher for shorter duration of the axial phase. As the duration of the initial phases of the discharge, i.e. breakdown and lift-off phases, is included in our axial transit time, we infer that the breakdown phase could have a strong influence on the total neutron production. From discharges with the same peak current, same peak axial speed, and same axial transit time, but different pinch lifetime and duration of the radial collapse phase, we infer that a fast compression followed by a dynamical (with large time and space gradients) evolution during the pinch phase favours large neutron production. Another important feature that was observed is that, for the same peak current and same pinch lifetime, the neutron as well as the soft X-ray yields depend on the sheath velocity.

The evolution and dynamics of the plasma focus with composite anode geometry may be affected by the profile of the joint between the two sections of the inner electrode. It was observed during the preliminary experiments that

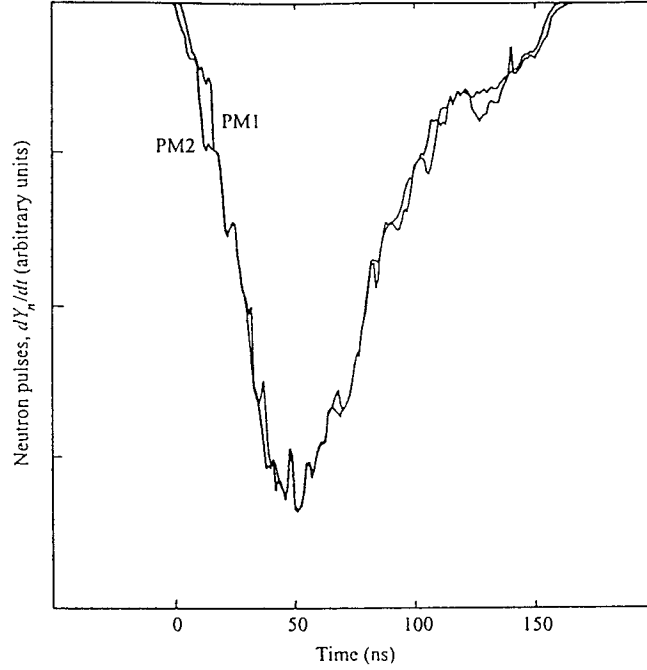


Figure 3. Neutron pulses obtained from the TOF detectors and compensated for their time of flight. Inner trace: signal from PM1. Outer trace: signal from PM2. Configuration: (X'A-93/19+80/15. Discharge at 14 kV and 450 Pa D_2 .

a steep joint aids the development of interchange instabilities. This may destroy the symmetry of the sheath even before the plasma enters the radial phase. Subsequently, the evolution and dynamics of the sheath during the final phase is affected. In order to avoid, or at least reduce, this effect, the profile of the joint has to be smooth and gradual.

Using the peak-to-peak method of analysis of the neutron pulses recorded with the two TOF detectors, an average energy of the neutrons emitted radially of 2.48 MeV was determined for all electrode configurations. Therefore the neutron pulses can be translated back in time according to their flight path. In this way, information on the neutron source was inferred. The result of this procedure is illustrated in Fig. 3. Each signal (from the near detector and far detector respectively) is normalized to the area under the trace, which is proportional to the total neutron yield. By overlapping the neutron signals, one can see the differences that appear at the beginning of the leading edge and the end of the trailing edge of the pulses due to neutron dispersion. Although proper TOF analysis and neutron spectroscopy were not performed because of our experimental limitations, we do not infer that the neutrons are monoenergetic.

On the basis of this result, we infer that the neutron emission commences at $t = 0 (\pm 2 \text{ ns})$. The time reference $t = 0$ is taken at the instant when the plasma column reaches the minimum radius at the end of the radial compression phase. The pinch lifetime t_p is defined as the duration from $t = 0$ to the instant corresponding to the development of the $m = 0$ instability. It was also observed that the neutron signal consists of two pulses, one emitted around $t = 0$ and the other at $t = t_p$, merged together owing to short values of the lifetime of the

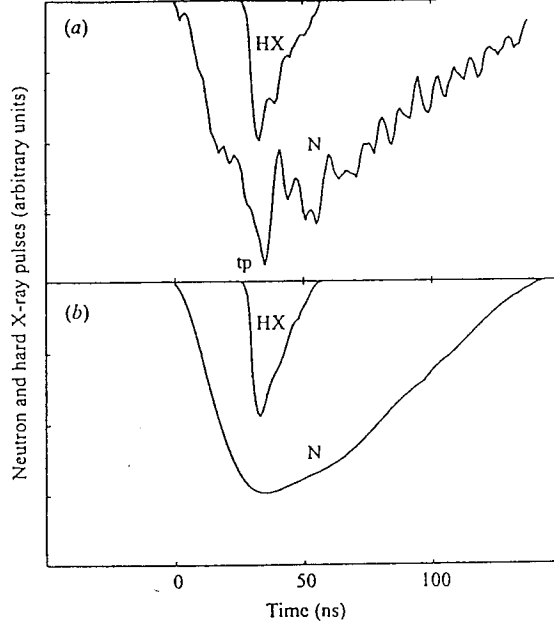


Figure 4. Time-resolved neutron (N) and hard X-ray (HX) pulses from the first TOF detector (PM1). The neutron pulse is compensated for its time of flight: (a) experimental data; (b) the corresponding pulses after smoothing. Configuration: CCA-103/19 + 70/15. Discharge at 14 kV and 450 Pa D₂.

pinch. Therefore one may estimate the number of neutrons emitted during the pinch lifetime by integrating the neutron signal dY_n/dt from $t = 0$ to $t = t_p$. In order to do so, the neutron signals from the TOF detectors have to be compensated for their flight path and overlapped with the hard X-ray pulses. Then the neutron signals (and eventually the hard X-ray signal) are smoothed using high-order polynomial functions. The procedure is illustrated in Fig. 4, where only the neutron signal recorded with the first TOF detector (PM1) is shown. The hard X-rays corresponding to the first plasma compression at $t = 0$ were cut off using lead sheets in front of the detector.

The results of this procedure give values of the percentage of the neutrons emitted during the lifetime of the pinch with respect to the total yield ranging between 4 % and 20 % for the neutron-optimized pressure of 450 Pa deuterium.

The plot of the average total neutron yield as a function of the fourth power of the peak discharge current illustrated in Fig. 5 shows that the neutron scaling law $Y_n \propto I^4$ does not hold exactly for all the electrode configurations tested in our experiments. The reason is that the neutron production mechanism(s) is affected by some factors such as force-field flow-field separation, electrode erosion or changes in the breakdown conditions. One could

- (i) separate the neutron production into two components, i.e. a non-beam component such as the thermonuclear component Y_{th} and a beam-target component Y_{bt} ;
- (ii) study the effect on these yield components of increasing the drive parameter and consequently the axial speed.

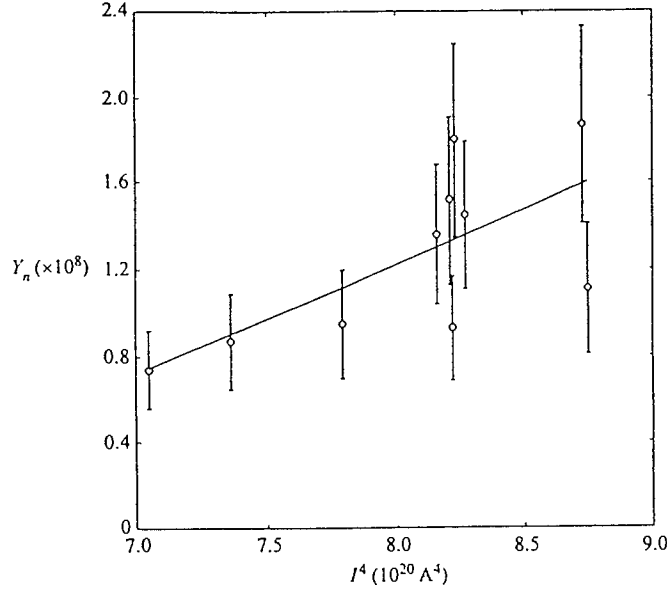


Figure 5. Total neutron yield as a function of the fourth power of the peak discharge current. The circles represent the mean values and the vertical error bars the corresponding standard deviations. Discharges at 14 kV and 450 Pa D₂.

In earlier experimental work (Chakrabarty 1988; Moo *et al.* 1991) on 3 kJ plasma focus devices, the reported value of the ratio Y_{th}/Y_{bt} is of the order of 15/85. It has also been proposed (Lee 1994; Lee & Serban 1994) that the thermonuclear component can be written as follows:

$$Y_{th} = CI_p^4 v_{axial}^4, \quad (1)$$

with C a constant over the range of plasma-focus devices.

We use our data to investigate whether our experiments verified (1).

The results obtained for a neutron-optimized pressure of 450 Pa deuterium are illustrated in Fig. 6. All data were included except those obtained from experiments with the electrode configuration OPA-185/15, CCA-45/19 + 140/15 and CCA-65/19 + 120/15. These were excluded because:

- (i) the breakdown conditions were changed (OPA-185/15);
- (ii) the speed-enhanced section of the anode was too long and led to force-field flow-field separation;
- (iii) the reproducibility of the focus was very poor, thus affecting the mean value of the neutron yield.

The results (see Fig. 6) confirm that the data fit (1).

The value of the constant C in (1) was determined using a linear regression of the data plotted in Fig. 6: $C = 1.8 \times 10^{-34}$ (SI units). Thus (1) can be written in the form

$$Y_{th} = 1.8 \times 10^{-6} I_p^4 v_{axial}^4 \quad (\pm 30\%), \quad (2)$$

with I_p in kA and v_{axial} in $\text{cm } \mu\text{s}^{-1}$ in the range of 7–14 $\text{cm } \mu\text{s}^{-1}$.

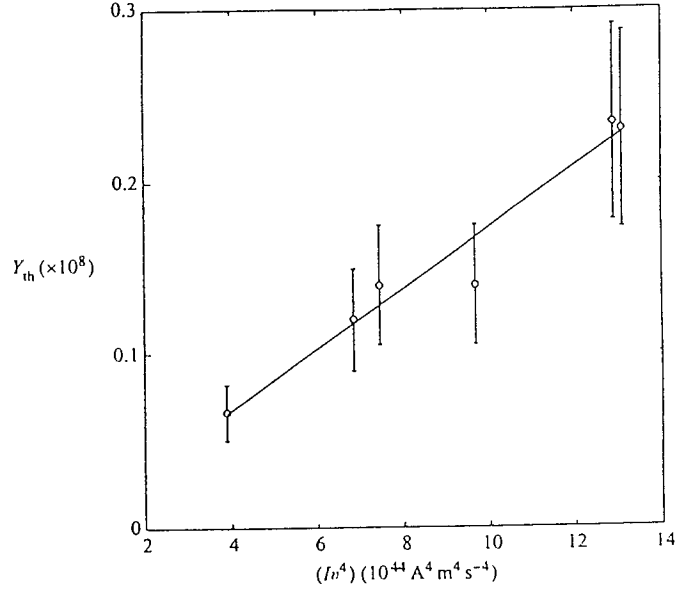


Figure 6. The non-beam component of the neutron yield as a function of $(Iv)^4$, where I is the peak discharge current and v is the peak axial speed. The circles represent the mean values and the vertical error bars the corresponding standard deviation. Discharges at 14 kV and 450 Pa D_2 .

Table 3. Drive parameter $(I_p/a) p^{-1/2}$ and neutron yield at 450 Pa D_2 .

Configuration	v_{axial} (cm μs^{-1})	I_{max} (kA)	$(I_{max}/a) p^{-1/2}$ (kA cm $^{-1}$ (Torr D_2) $^{-1/2}$)	Y_n ($\times 10^8$)
SPF-165/19	8.3	172.0	97.8	1.11
OPA-175/17.5	9.5	171.9	106.2	1.87
OPA-180/17	9.7	169.9	108.1	1.36
OPA-185/15	10.4	162.1	116.8	0.73
CCA-45/19+140/15	10.5	164.7	118.7	0.87
CCA-65/19+120/15	10.6	167.1	120.5	0.95
CCA-103/19+70/15	11.2	169.4	122.1	1.80
CCA-93/19+80/15	11.3	169.5	122.2	1.50
CCA-90/19+100/15	—	169.6	122.3	1.45
CCA-95/19+90/14	11.4	169.4	130.8	0.95

Thus there is evidence within the limited range of our operation that the neutron yield of the plasma focus is enhanced by operating at higher speeds. We also have evidence that the X-ray production is also enhanced.

The values of the drive parameter and the corresponding neutron yield at 450 Pa deuterium filling pressure are listed in Table 3. It can be seen that there are two electrode configurations, namely OPA-175/17.5 and CCA-103/19+70/15, that produce, practically, the same neutron yield of approximately 1.8×10^8 neutrons/discharge. The increase of the drive parameter by 15% and of the axial speed by 17% for the CCA-103/19+70/15 geometry with respect to OPA-175/17.5 does not bring about an increase in the neutron output. One possibility is that, by operating the plasma focus at higher speed, the non-beam

component of the neutron yield, such as that of thermonuclear origin, is enhanced (see (1)), while the beam-target component decreases according to the following expression (Lee 1994; Lee and Serban 1994);

$$Y_{bt} = C' I_p^{4.5} v_{axial}^{-1.5}, \quad (3)$$

where C' is a constant.

It is interesting to compare the performances of CCA-103/19+70/15 and CCA-93/19+80/15 as configurations of the same family of composite anodes. These two anodes have the same length and only a difference of 1 cm in the length of the speed-enhanced section. The configuration with the longer speed-enhanced section has a slightly higher speed, as expected. However, the neutron yield is reduced by 16 %. This degradation of neutron yield could be interpreted as the result of a significant separation of the shock front from the driving magnetic piston during the axial phase. Such a separation is proportional to distance travelled. It appears that increasing the speed-enhanced section from 7 cm to 8 cm results in an increase in that separation sufficient to affect the neutron yield. With sufficient separation, when the shock front is in radial motion, the magnetic piston is still moving axially. Therefore the radial compression is not driven or, if the separation is not too big, the efficiency of the drive is very poor, and leads to a low radiation yield.

A further increase in the length of the speed-enhanced section of the anode (see the data for the CCA-90/19+100/15 and CCA-95/19+90/14 anodes in Table 3) leads to a decrease in the total neutron yield. This is again consistent with the expected effect of force-field flow-field separation on the efficiency of the compression of the plasma column.

On the other hand, a comparison between the two high-neutron-output configurations, namely the OPA-175.17.5 and CCA-103/19+70/15 geometries, in terms of soft X-ray production shows that at higher speeds the soft X-ray emission is enhanced. A data analysis indicates that the plasma temperature during the pinch phase is higher. Assuming that the temperature T is proportional to the square of the velocity v , $T \propto v^2$ (Lee 1994), the temperature increases by almost 40 %. This is in agreement with the earlier interpretation of an enhanced non-beam neutron emission (Lee and Serban 1994).

The plasma focus device can be optimized for either neutron production or soft X-ray output. The optimization procedure has to meet conflicting requirements. An increase in the drive parameter by using a smaller-radius anode is favourable for increasing the plasma temperature, and thus the non-beam neutron component and the soft X-ray yield. At the same time, the pinch lifetime and dimensions are reduced accordingly (Lee and Serban 1996). Therefore the size of the radiation source is smaller. This effect is encouraging for practical applications of the plasma focus, for example as a soft X-ray source for lithography (Burkhalter *et al.* 1992).

4. Conclusions

Regardless of the electrode geometry, the neutron output of our plasma focus device has a strong dependence on the gas filling pressure. The neutron-optimized pressure is 450 Pa. The emission of neutrons begins at the end of the compression phase, when the plasma reaches its minimum radius.

Peak axial sheath velocities of up to $15 \text{ cm } \mu\text{s}^{-1}$ have been achieved (Serban 1995). The radiation output, i.e. both neutron and soft X-ray productions, increases as the speed increases. However, beyond a certain value of the peak axial speed and a certain length of the speed-enhanced section of the anode, the focusing characteristics and reproducibility are affected. We conclude that the length of the speed-enhanced section is critical. This section has to be long enough to increase the speed, but short enough to avoid the separation between the shock front and the magnetic piston. Also, the profile of the joint between the two sections of the anode plays an important role. An abrupt joint will favour the development and rapid growth of interchange instabilities, which will later affect the evolution of the focus during the final phases.

The results of the correlations of the neutron production and soft X-ray emission indicate that higher speeds enhance the temperature of the pinched column. The non-beam component of the neutron flux, taken to be of thermonuclear origin, is correlated with the peak discharge current and peak axial speed. A scaling law $Y_{\text{th}} \propto (I_p v_{\text{axial}})^4$ for the non-beam neutron component has been proposed on the basis of our experimental results within our range of operations. However, this scaling law should be checked with results from other plasma focus devices operating with a broader range of energies.

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Scaling of the Plasma Focus – Viewpoint from Dynamics

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Abstract

The gross dynamics of the plasma focus is discussed in terms of phases. The dynamics of the axial and radial phases is computed using respectively a snowplow and an elongating slug model. A reflected shock phase follows, giving the maximum compression configuration of the plasma focus pinch. An expanded column phase is used to complete the post-focus electric current computation. Parameters of the gross focus pinch obtained from the computation, supplemented by experiments are summarised as follows:

		Deuterium	Neon (for SXR)
minimum radius	$r_{\min}$	0.13a	0.04a
maximum length	z	0.7a	0.8a
radial shock transit	t_{comp}	$5 \times 10^{-6}a$	$4 \times 10^{-6}a$
pinch lifetime	t_p	$2 \times 10^{-6}a$	$1 \times 10^{-6}a$

where, for the times in sec, the value of anode radius, a, is in m. For the neon calculations radiative terms are included. The scaling suggests a speed enhancement effect on neutron yield, enhancing from the conventional I^4 to a superior I^8 scaling law.

1. Introduction

This paper starts with a simple axial-radial model of the Mathers type plasma focus¹ to show that the elongating plasma focus pinch achieves a gross compressed configuration in which its minimum radius and its maximum length are dependent on its anode radius 'a'. Moreover for a given gas there appears to be experimental mechanisms that require the drive magnetic energy density to be constant over a range of the devices from small (kJ) to big (hundreds of kJ). From this it follows that the lifetime of the plasma focus pinch is also dependent on anode radius 'a'. Thus the bigger the anode radius, the bigger are the radius, length and lifetime of the compressed pinch. This dependence on 'a' is alone sufficient to derive the general rule that radiation yield is proportional to I^4 . It also suggests a speed enhancement effect on neutron yield, which however does not appear to apply to soft x-ray (SXR) yield for microelectronics lithography.

2. Model

We use a snowplow model for the axial phase and a slug model for the radial pinch phase²⁻⁴. The end-point of compressions is fixed when the radially out-going reflected shock hits the in-going compressing piston.

2a. Axial phase:

We consider the rate of change of momentum of the current sheath sweeping up mass and equate this to the driving electromagnetic force (see Fig 1a).

$$\frac{d}{dt} \left[\pi (b^2 - a^2) \rho \frac{dz}{dt} \right] = \frac{\mu f_c^2 I^2}{4\pi} \ln c \quad (1)$$

*Invited paper to be presented at International Plasma Focus Symposium at Kudowa, Poland, July 1998

where b is the outer electrode radius, a the inner electrode radius, z the position of the 'snowplow' current sheath, ρ the ambient density, I the driving current, $c=b/a$, and μ the permeability of free space. The two parameters f_m and f_s are the mass swept-up factor and current factor used to account for the experimentally observed mass loss and current loss respectively⁵.

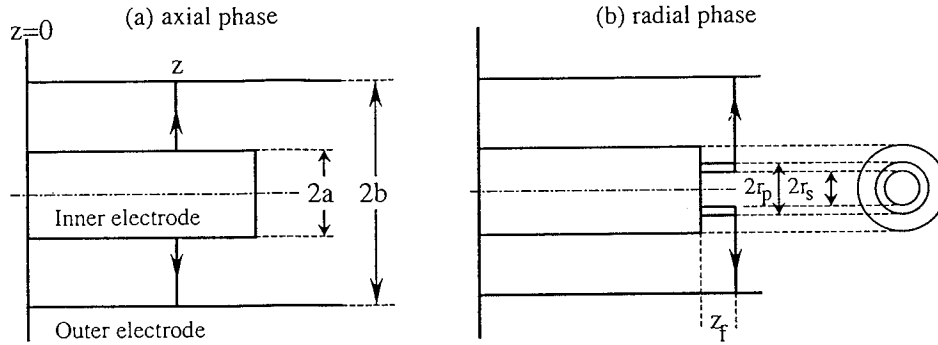


Fig 1: Schematic of (a) axial phase and (b) radial phase

The circuit equation which captures the effect of the changing inductance L_p , due to current sheath motion, on the current I is:

$$\frac{d}{dt} [(L_o + f_c L_p) I] = V_o - \frac{1}{C_o} \int_o^t I dt - r_o I \quad (2)$$

where L_o , C_o and r_o are the fixed circuit inductance, capacitance and stray resistance, and L_p is:

$$L_p = \frac{\mu}{2\pi} z \ln c \quad (3)$$

Equations (1) & (2) may be integrated step-by-step for the instantaneous values of I and z . Appropriate values used for f_m and f_c are found to be $f_m = 0.1$, $f_c = 0.7$.

2b. Radial Phase

In the radial phase (see Fig 1b), because of the compression configuration, less mass loss is observed so a radial mass swept-up factor f_{mr} is introduced. The current factor remains as f_c . We derive the shock speed from the driving magnetic pressure and use the same speed (except for a thermodynamic factor) for the elongation since the same magnetic pressure drives both the radial compression and axial elongation. We allow the current sheath (piston) to separate from the shock front by applying an adiabatic approximation⁶

relating a change in pressure P to a change in volume V , to a fixed mass of gas at any given instant of time t . These 3 equations are then closed with a fourth equation, this being the circuit equation. These equations are written as follows:

$$\frac{dr_s}{dt} = - \left\{ \frac{\mu(\gamma+1)}{\rho f_{mr}} \right\}^{\frac{1}{2}} \frac{f_c I}{4\pi r_p} \quad (4)$$

$$\frac{dz_f}{dt} = - \frac{2}{\gamma+1} \frac{dr_s}{dt} \quad (5)$$

$$\frac{dr_p}{dt} = \frac{\frac{2}{\gamma+1} \left(\frac{r_s}{r_p} \right) \frac{dr_s}{dt} - \frac{r_p}{\gamma I} \left(1 - \frac{r_s^2}{r_p^2} \right) \frac{dI}{dt} - \frac{1}{\gamma+1} \frac{r_p}{z_f} \left(1 - \frac{r_s^2}{r_p^2} \right) \frac{dz_f}{dt}}{\frac{\gamma-1}{\gamma} + \frac{1}{\gamma} \frac{r_s^r}{r_p^2}} \quad (6)$$

$$\frac{d}{dt} [(L_o + f_c L_p) I] = V_o - \frac{1}{C_o} \int I dt - r_o I \quad (7)$$

where in the radial phase

$$L_p = \frac{\mu}{2\pi} z_o \ln c + \frac{\mu}{2\pi} z_f \ln \left(\frac{b}{r_p} \right) \quad (7a)$$

The four equations (4) – (7) may be integrated step-by-step for the instantaneous values of r_s , r_p , z_f & I . For deuterium, γ is taken as 5/3. This phase is completed when the shock front hits the axis i.e. $r_s = 0$ with velocity $(dr_s/dt)_{on-axis}$.

2c. Reflected Shock Phase

When the shock front hits the axis, because the focus plasma is collisional, a reflected shock develops (position r_r) which moves radially outwards, whilst the radial current sheath piston continues to move inwards (see Fig 2).

This phase is simulated with the following equations:

$$\frac{dr_r}{dt} = f_{RS} \left(\frac{dr_s}{dt} \right)_{on-axis} \quad (8)$$

where we usually take f_{RS} as 0.3 empirically.

$$\frac{dz_f}{dt} = -\frac{2}{\gamma+1} \left(\frac{dr_s}{dt} \right)_{\text{on-axis}} \quad (9)$$

$$\frac{dr_p}{dt} = -\frac{r_p}{\gamma l} \left(1 - \frac{r_r^2}{r_p^2} \right) \frac{dI}{dt} - \frac{1}{\gamma+1} \frac{r_p}{z_f} \left(1 - \frac{r_r^2}{r_p^2} \right) \frac{dz_f}{dt} \quad (10)$$

$$\frac{\gamma-1}{\gamma} + \frac{1}{\gamma} \left(\frac{r_r}{r_p} \right)^2$$

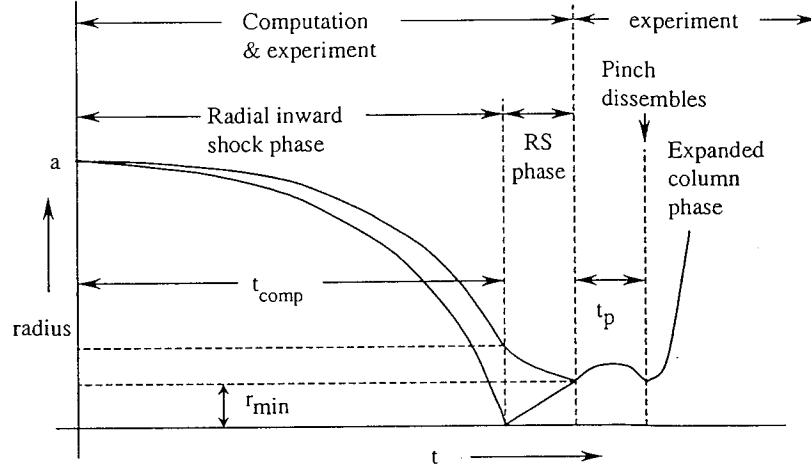


Fig 2. Schematic of radial phases

The circuit equations may be used unchanged from (7) supplemented by (7a). Equations (8), (9), (10) and (7) may be integrated step-by-step for r_r , z_f , r_p and I .

When the out-going reflected shock hits the in-going piston the compression enters a radiative phase in which for gases such as neon e.g. radiation cooling may actually enhance the compression. For deuterium we assume the radiative phase is not significant to the dynamics. We treat this point as the point of maximum compression with minimum gross radius $r_{\min}$ and maximum plasma pinch length z_p . If we just want the gross parameters of the plasma focus pinch the calculations may end here.

2d. Expanded Column Phase

To simulate the current trace beyond this point we allow the column to suddenly attain the radius of the anode, and use the expanded column inductance for further integration.

3. Normalization:

The equations are normalised in the following manner²⁻⁴:

$$\tau = \frac{t}{t_o}, \quad \zeta = \frac{z}{z_o}, \quad \iota = \frac{I}{I_o}, \quad \delta = \frac{r_o}{Z_o} \quad \text{where } Z_o = \sqrt{\frac{L_o}{C_o}}$$

$$\kappa_s = \frac{r_s}{a}, \quad \kappa_p = \frac{r_p}{a}, \quad \zeta_f = \frac{z_f}{a}$$

$$t_o = \sqrt{L_o C_o} \text{ and } I_o = V_o / Z_o$$

Axial Phase:

The normalized axial phase equations are:

$$\frac{d^2 \zeta}{d\tau^2} = \frac{\alpha^2 \iota^2 - \left(\frac{d\zeta}{d\tau} \right)^2}{\zeta} \quad (11)$$

$$\frac{d\iota}{d\tau} = \frac{1 - \int \iota d\tau - f_c \beta \frac{d\zeta}{d\tau} \iota - \delta \iota}{1 + f_c \beta \zeta} \quad (12)$$

to compute ζ and ι ; with two scaling parameters:

$$\beta = \left[\frac{\mu}{2\pi} z_o \ln c \right] / L_o$$

which is the ratio of the full axial phase tube inductance to the external fixed inductance.
Ratio of characteristic electrical discharge time to characteristic axial transit times is:

$$\alpha = t_o / t_a$$

$$\text{where } t_a = \left[\frac{4\pi^2 (c^2 - 1)}{\mu \ln c} \right]^{1/2} \frac{z_o \sqrt{f_m}}{f_c} \frac{\sqrt{\rho}}{(I_o / a)}$$

giving a characteristic axial transit speed of $v_a = z_o / t_a$ of

$$v_a = \left[\frac{\mu \ln c}{4\pi^2 (c^2 - 1)} \right]^{1/2} \frac{f_c}{\sqrt{f_m}} \frac{(I_o / a)}{\sqrt{\rho}} \quad (13)$$

We note the dependence of v_a on $(I_o / a) / \sqrt{\rho}$ which is designated as the drive parameter S .

Radial Phase

Normalised radial phase equations are:

$$\frac{d\kappa_s}{d\tau} = -\alpha\alpha_1 \frac{1}{\kappa_p} \quad (14)$$

$$\frac{d\zeta_f}{d\tau} = -\frac{2}{\gamma+1} \frac{d\kappa_s}{d\tau} \quad (15)$$

$$\frac{d\kappa_p}{d\tau} = \frac{\frac{2}{\gamma+1} \frac{\kappa_s}{\kappa_p} \frac{d\kappa_s}{d\tau} - \frac{\kappa_p}{\gamma 1} \left(1 - \frac{\kappa_s^2}{\kappa_p^2}\right) \frac{d\tau}{d\tau} - \frac{1}{\gamma+1} \frac{\kappa_p}{\zeta_f} \left(1 - \frac{\kappa_s^2}{\kappa_p^2}\right) \frac{d\zeta_f}{d\tau}}{\frac{\gamma-1}{\gamma} + \frac{1}{\gamma} \frac{\kappa_s^2}{\kappa_p^2}} \quad (16)$$

$$\frac{d\tau}{dt} = \frac{1 - \int 1 d\tau + \frac{\beta_1}{F} f_c \frac{\zeta_f}{\kappa_p} \frac{d\kappa_p}{d\tau} 1 + \frac{\beta_1}{F} f_c \ln\left(\frac{\kappa_p}{c}\right) \frac{d\zeta_f}{d\tau} 1 - \delta 1}{1 + f_c \beta - f_c \frac{\beta_1}{F} \zeta_f \ln\left(\frac{\kappa_p}{c}\right)} \quad (17)$$

$$\text{where } \beta_1 = \frac{\beta}{\ln c}, F = \frac{z_o}{a}$$

and the ratio of the characteristic axial transit time to characteristic pinch time

$$\alpha_1 = \frac{t_a}{t_p} = \left[(\gamma+1)(c^2-1) \right]^{1/2} \frac{F \sqrt{f_m}}{2\sqrt{\ln c}}$$

$$\text{Hence } t_p = \frac{4\pi}{[\mu(\gamma+1)]^{1/2}} \frac{\sqrt{f_{mr}}}{f_c} \frac{\sqrt{\rho}}{(I_o/a)} a$$

and characteristic pinch time a/t_p is

$$v_p = \frac{[\mu(\gamma+1)]}{4\pi} f_c \frac{I_o/a}{\sqrt{\rho}} \quad (18)$$

We note that v_p has the same dependence on drive parameter S as V_a .

4. Parameters and Scaling

The UNU/ICTP PFF is a 3 kJ plasma focus ⁷ designated as the United National University/International Centre for Theoretical Physics Plasma Focus Facility. This device was developed during UNU/ICTP training programmes and is now established in

6 countries for postgraduate training and research. To compute the above model for the UNU/ICTP PFF we note its operational parameters:

$$\begin{aligned}
 C_o &= 3 \times 10^{-5} \text{F} & L_o &= 1.1 \times 10^{-7} \text{H} \\
 a &= 0.95 \times 10^{-2} \text{m} & b &= 3.2 \times 10^{-2} \text{m} & z_o &= 0.16 \text{m} \\
 c &= 3.37 & F &= 16.84 \\
 \text{Hence } t_o &= \sqrt{L_o C_o} = 1.82 \times 10^{-6} \text{s} & Z_o &= \sqrt{L_o / C_o} = 0.06 \Omega
 \end{aligned}$$

Typical operation is at 14 kV with ambient pressure of 3.5 torr deuterium giving:

$$\begin{aligned}
 \rho &= 8.2 \times 10^{-4} \text{kgm}^{-3} & V_o &= 1.4 \times 10^4 & \text{Also } r_o &= 0.012 \Omega \\
 \text{Hence } I_o &= V_o / Z_o = 2.33 \times 10^5 \text{A} & \delta &= r_o / Z_o = 0.2 \\
 \text{we take } f_c &= 0.7 & f_m &= 0.1 \\
 f_{mr} &= 0.3 & v_a &= 1.15 \times 10^5 \text{m/s} \\
 \text{Hence } t_a &= 1.38 \times 10^{-6} \text{s} & v_p &= 1.6 \times 10^5 \text{m/s} \\
 t_p &= 6.0 \times 10^{-8} \text{s} \\
 \text{Hence} & & \alpha_1 &= 23.2 \\
 \alpha &= 1.31 & \beta_1 &= 0.29 \\
 \beta &= 0.35
 \end{aligned}$$

We also use $\gamma = 5/3$ (specific heat ratio for fully ionized deuterium)

The above values of α , β , δ , f_c , f_m are used with equations (11) and (12) to compute the axial phase dynamics for ι and ς . For the radial phase dynamics additional parameters from the above list namely, α_1 , γ , β_1 , F , c are used together with the 4 equations 14 – 17 to compute the radial phase dynamics for κ_s , κ_p , ζ_f and ι . In the reflected shock phase we take the reflected shock speed ratio $f_{rs} = 0.3$.

Even without numerical computation, the normalization of the axial and radial phases equations has shown us the following regarding the characteristic times and speeds. We note that in the design of plasma focus devices the geometrical ratio c is between 2 and 3 so that the factor $[(c^2-1)/\ln c]^{1/2}$ remains within a small range. Thus basically: $t_a \sim z_o/S$ and $t_p \sim a/S$ and both the axial and radial speeds v_a and v_p are proportional to the drive parameter S .

Over a range of machines, from small to big, it is experimentally observed that the drive parameter is constant for neutron optimized operation in deuterium. This is consistent with observed constant speed over the range of devices. Hence the characteristic times scale with dimension z_o for the axial phase and 'a' for the radial phase.

Moreover it is implied in the equations 14-16 that at any point in the radial trajectory the values of r_s , r_p and z_f are proportional to 'a'. Hence in the position of maximum compression, which gives the minimum radius $r_{\min}$ of the piston position, the gross parameters $r_{\min}$ and z_p are both proportional to anode radius 'a'.

5. Results of computation and discussion.

Computation for the trajectories and electric current yield the following results. Fig 3 shows the axial phase dynamics in terms of axial position and speed presented in real quantities. It shows that the current sheath reaches the end of the axial phase at $2.87 \mu\text{s}$ with a peak speed of $8.6 \text{ cm}/\mu\text{s}$.

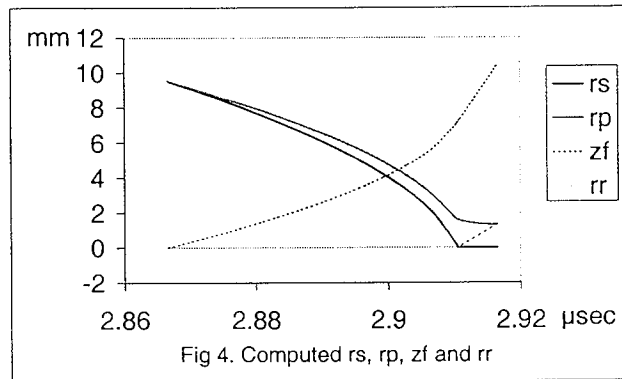
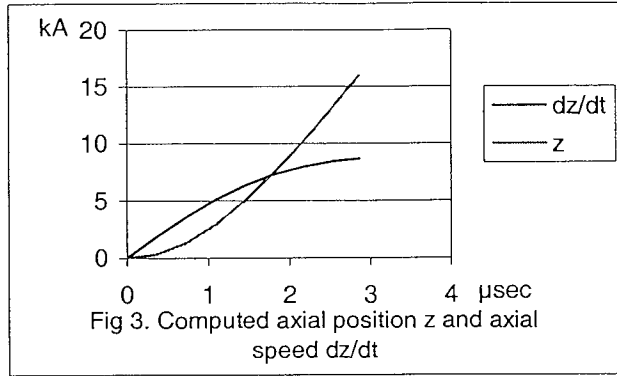


Figure 4 shows the radial phase dynamics. The shock front and the piston start together at $r=a$; the length of the focus pinch is zero at this time. The shock front accelerates onto the axis, hitting the axis 40 ns from the start of the radial phase. At this time the piston position is 1.6mm from the axis and the length of the lengthening focus column is 7.1 mm. According to this computation the speed of the on-axis shock front exceeds $50 \text{ cm}/\mu\text{s}$. The piston speed, which had peaked at $30 \text{ cm}/\mu\text{s}$, reduces sharply as the shock approaches the axis. We note the limitation of the radial model as follows.

Implicit in this radial model is the assumption of instantaneous communication between the piston and the shock front ie an assumption of infinite signal speed. This assumption results in the computed speeds being too high. If we consider the actual communication delay due to the finite small disturbance speed between the piston and shock front (of the order of ns, dependent on plasma slug temperature) the shock front would at any instant feel the considerably smaller pressure of the piston at an earlier time, and likewise the piston would feel the effect of the shock front moving at a slower speed at an earlier

position. This delay effect incorporated into the model, would considerably slow down both the shock front and piston, as they near the axis, to peak values of 25-30 cm/ μ s for the shock front on-axis and to about 20 cm/ μ s a short time before the shock front hits the axis. As the reduction in speeds is only significant near the axis (final 3 mm of shock front travel) the shock transit time is increased only slightly.

When the shock front hits the axis, a reflected shock develops and moves radially outwards. The piston continues to compress inwards until it hits the out-going reflected shock front. We define this point where the piston meets the reflected shock as the point of maximum gross compression, and label this radial position $r_{\min}$. Experimental observations using shadowgraphs complemented by electrical and x-ray measurements, indicate that beyond this point of time the plasma radius remains at about the value of $r_{\min}$ for a short period (some 20ns for the UNU/ICTP PFF) before the pinch disassembles rather violently. For deuterium this model is not extended specifically to compute the dynamics of this phase. For neon we have included this as a radiative phase, adding radiative terms into the computation. Indeed for neon, the radiative terms are energetically significant and even affect the dynamics to give evidence of further compression due to radiative cooling..

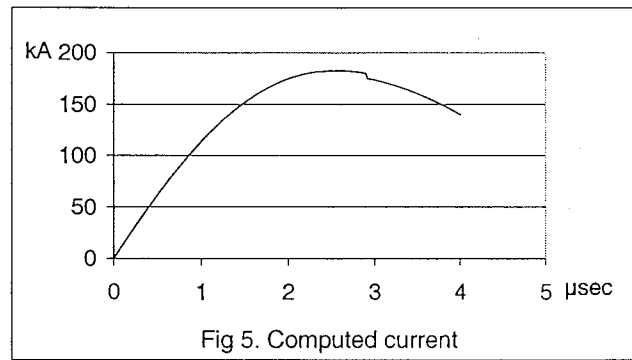


Figure 5 shows the computation of the electric current. This computation was extended to the post-focus phase by using a simple expanded column approximation. The current agrees well with experimentally observed Rogowskii coil measurements.

The key computed pinch parameters for the deuterium focus are as follows:

$$r_{\min} = 0.13 \text{ a} \quad (18)$$

$$z_p = 0.7 \text{ a} \quad (19)$$

$$t_{\text{comp}} = 5 \times 10^{-6} \text{ a} \quad (20)$$

We have not computed t_p but this has been measured experimentally as ⁸:

$$t_p = 2 \times 10^{-6} \text{ a} \quad (21)$$

The above results have been verified experimentally^{8,13} with shadowgraphs and measurements of current, voltage, neutron and SXR of the UNU/ICTP PFF operated in deuterium.

6. Scaling of Yield

For a thermalised plasma we can generally assign density n and temperature T . If the particles of density n interact among themselves with a cross section $C(T)$, generally depended on T , we may write down a general radiation yield, Y , relationship as follows:

$$Y \sim n^2 (\text{volume}) (\text{lifetime}) C \quad (22)$$

For the plasma focus, given the dimensional and temporal dependence as shown in equations (18), (19) and (21) we have

$$Y \sim n^2 a^4 C \quad (23)$$

6a. Constant S operation

A survey of plasma focus devices have shown that in deuterium the drive parameter⁸ is $S = 90$ kA per cm per (torr)^{1/2} of deuterium over a range large range of energy from 3kJ – 200kJ. This corresponds to the well-know phenomenon that similar speeds are observed in small devices as well as in large devices. For example the peak axial speeds for neutron-optimised operation is experimentally observed to be 8 – 10 cm/μs. This has also been expressed as an average axial speed of 5-5.5 cm/μs. Similarly the radial speeds peak at 25-30 cm/μs for all devices, big or small. This peak speed occurs as the radial in-going shock goes on-axis. Such constant speeds observed over such a range of device energies indicate that at any point of the plasma focus operation, e.g. end of axial phase or end of inward shock phase as the inward radial shock goes on axis, the temperature in a small focus is the same as the temperature in a big focus. By extension it is inferred that the temperature at the point of maximum compression is also the same for a small focus as for a big focus. This is of course consistent from the viewpoint of energy densities. The quantity S is the magnetic energy density driving the system. Hence since the driving magnet energy is constant over the range of devices, it is consistent that the temperatures generated is also constant over the range of devices.

Given this observed constancy we have:

$$\frac{(I/a)}{\rho^{1/2}} = \text{constant} \quad (24)$$

$$\text{Hence } I \sim a\rho^{1/2} \quad (25)$$

For a deuterium focus, the pinched gas is fully ionised and the number density of deuterium ions in the pinch is proportional to the ambient density ρ .

Hence applying equation (25) to Eq (23) and noting that since $T=\text{constant}$ over the range of devices, the cross section C is also constant and we have⁹:

$$Y \sim I^4 \quad (26)$$

This yield law really applies to the thermonuclear neutron yield. Experimentally for a small neutron-optimised plasma focus it has been shown¹⁰ that the thermonuclear

component of the neutron yield is only 15%, the other 85% being ascribed to beam-target mechanisms. Nevertheless we note that these yield proportions are occurring at a plasma ion temperature of about 1 keV and a beam energy of about 50 keV.

6b. Speed-enhancement of neutron yield

This leads to the concept of speed enhancement^{9,12}. If the driver parameter S is increased, the drive energy density increases, the speed increases and we may expect the focus pinch ion temperature also to increase. This leads to a dramatic increase in neutron yield since in the range of 1 – 10 keV, the neutron fusion cross-section is a rapid function of T with $C \sim T^n$ n being greater than 4. And since $T \sim v^2$, if we keep 'a' constant as the drive current is increased, we increase the drive parameter S . This will give us a thermonuclear yield component better than

$$Y \sim I^8 \quad (27)$$

Increase in speed will also increase the energy of the beam component. The beam component will however not have a significant increase since above 50 keV the cross section C barely increases with T . This means that as operational speed is increased, the plasma focus neutron yield becomes more thermonuclear. For example an increase in speed by 20% increases the focus pinch temperature by more than 40%, with the thermonuclear yield increasing by more than 5 times, whilst the beam-target component barely increases. This means that even a 20% increase in the drive parameter for the UNU/ICTP PFF could not only significantly increase its neutron but also make this yield predominantly thermonuclear.

However it is not a simple matter to increase the drive speed. Experiments have shown that if the peak axial speed is pushed above 10 cm/ μ s, plasma focus quality simply deteriorates. A force-field flow-field decoupling mechanism³ has been proposed to account for the deterioration of the focus quality. According to shock theory for a gas with specific heat ratio of 5/3, the contact surface or piston should separate from the shock front 1 cm for every 4 cm travelled by the shock front. At lower speeds, although deuterium is already fully ionised at 4 cm/ μ s, there is still considerable diffusion of the magnetic field into the plasma all the way to the shock front so that effectively the centre of drive force field is not significantly behind the centre of the mass field. However at a speed above 9 or 10 cm/ μ s, the electrical conductivity is sufficient to limit the field penetration resulting in a separation of the centre of the force field from the centre of the mass field. This separation grows with distance travelled. If this separation becomes of the order of the anode radius, then when the shock wave sweeps around the anode in the radial compression, the piston is still travelling axially a radius away and when the shock hits the axis the piston may still not have started its radial compression. Such a compression will be weak. It is postulated that this force-mass decoupling mechanism^{3,11} becomes significant above the 'speed-limit' of 9-10 cm/ μ s observed for deuterium focus operation.

An experiment^{12,13} was carried out to achieve this speed increase yet overcome the decoupling by keeping the 'speed-enhanced' region short. A stepped-anode was used

consisting of a 'normal' radius section designed with the normal S value, followed by a short 'speed-enhanced' section for which the S value was increased by a reduction of 'a'. By this means speeds up to 15cm/ μ s was achieved with focussing. Neutron-yield enhancement was indicated.

However this experiment was severely limited in its scope since 'speed-enhancement' was achieved not by an increase of I at fixed 'a', rather by effectively fixing I and reducing 'a'. This was due to the limitations imposed by the UNU/ICTP PFF in its electrical range of operation. It is proposed that speed-enhancement experiments should be carried out in a machine with fixed 'normal' 'a'; and to increase I above 'normal' values.

6c Scaling for neon operation

The plasma focus is operated in neon to generate SXR in the wavelength range¹⁷ of 0.8 – 1.4 nm. This wavelength range is found suitable for microelectronics lithography¹⁴ from the point of view of near optimum contrast using existing mask technology. We have performed calculations^{15,16} using the axial-radial model described above but including radiation terms (free-free, free-bound and bound-bound) into the dynamical equations as well as SXR yield equations. These calculations indicate that the focus pinch temperature needs to be adjusted to 300 – 400 eV for optimum yield in the correct wavelength range which arises from He-like and H-like Neon ions. We have selected 350 eV which corresponds to an axial speed of 4.5 cm/ μ s. For the UNU/ICTP PFF we found that optimum yield is obtained at 14 kV operation when an ambient pressure of 1 torr is used. Because the neon is still ionising (rather than fully ionised) its effective specific heat ratio may be approximated as 1.4. This gives it a thinner slug layer and a smaller compressed radius. Some of the parameters of the neon focus pinch are calculated as:

$$\begin{aligned} r_{\min} &= 0.04a \\ z_{\max} &= 0.8a \\ t_{\text{comp}} &= 4 \times 10^{-6}a \end{aligned}$$

These agree with experimental observations. We have also estimated from experiments:

$$t_p = 1 \times 10^{-6}a$$

Since the pinch temperature needs to be fixed at 350 eV no speed-enhancement is possible for the neon focus operated for microelectronics lithography purposes.

7. Conclusion

We conclude from computation, supplemented by experimental observations that the plasma focus pinch has gross parameters that scale according to anode radius 'a' in the following manner:

	Deuterium
Neon (for SXR)	

minimum radius	$r_{\min}$	0.13a	0.04a
maximum length	z	0.7a	0.8a
radial shock transit	t_{comp}	$5 \times 10^{-6}a$	$4 \times 10^{-6}a$
pinch lifetime	t_p	$2 \times 10^{-6}a$	$1 \times 10^{-6}a$

where, the times are in sec, when the value of anode radius, a, is in m.

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ARGON ION INDUCED CHANGES IN ANTIMONY TELLURIDE THIN FILMS USING DENSE PLASMA FOCUS DEVICE

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1. Introduction

The Dense Plasma Focus (DPF) has been established as an intense source of fusion neutrons, x-rays, electrons and energetic ions with several hundred *keV* [1]. This paper reports the use of the highly energetic, pulsed argon ion beam (from the 3.3kJ UNU/ICTP PFF)[2], for modifying antimony telluride (Sb_2Te_3) films. Antimony telluride is used as a thermoelectric material is being investigated as a phase change optical material.

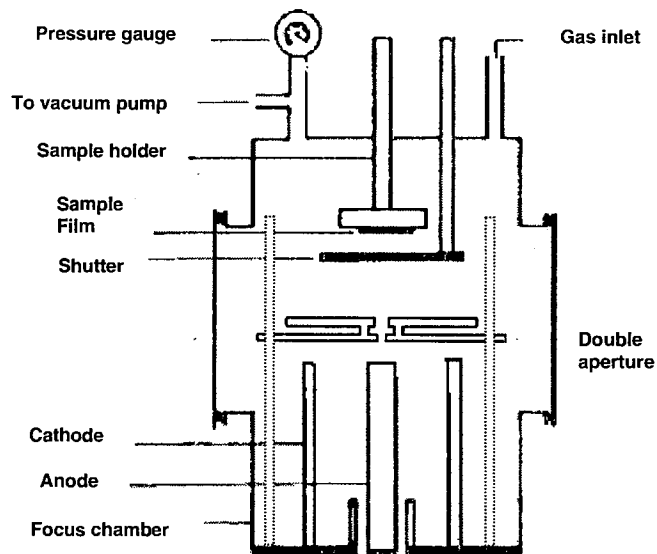


Figure 1. Experimental setup.

2. Experiment

The thin films (0.41 μm thick) were deposited, at University of Delhi, on glass substrates using thermal evaporation technique. The experiment was set up as shown in Figure 1. The samples were placed downstream of the anode using an axially movable sample holder to vary the exposure distance and hence the ion fluence. A combination of two apertures of

Experiment

The thin films ($0.41\mu\text{m}$ thick) were deposited, at University of Delhi, on glass substrates using thermal evaporation technique. The experiment was set up as shown in figure 2. The samples were placed downstream of the anode using an axially movable sample holder to vary the exposure distance and hence the ion fluence. A combination of two apertures of diameter 3mm and 4mm , separated by a distance of 1.0cm , were placed at 2.0cm beyond the anode to attenuate blast wave effects. The focus was operated in 1mbar of argon with a 14kV charging voltage

Results and analysis

The exposed samples were then analysed using Scanning Electron Microscope(SEM), Atomic Force Microscope(AFM), X-ray Diffractometer(XRD), X-ray Photoelectron Spectrometer (XPS).

Figure 2 shows typical SEM micrographs of samples at a few different distances.

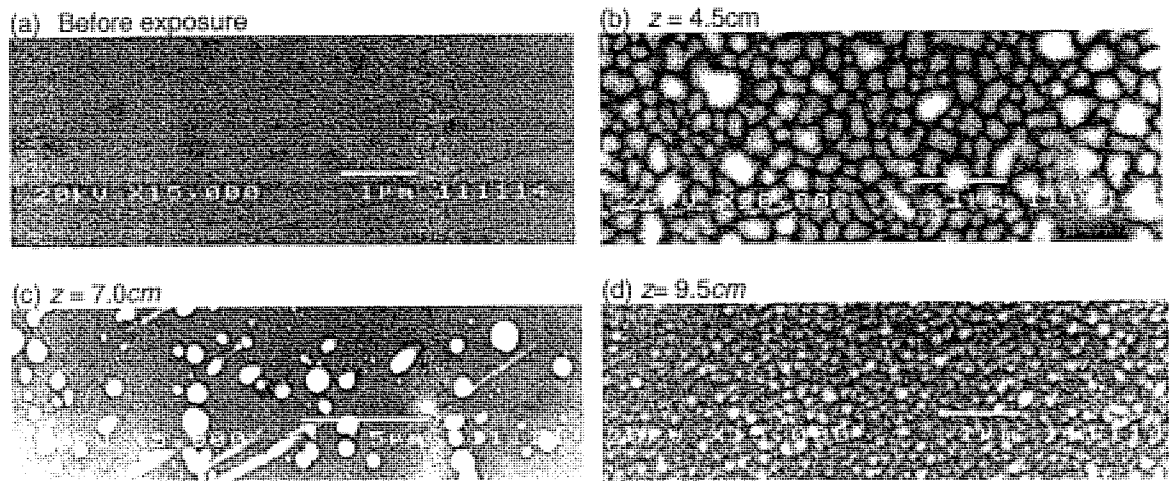


Figure. 2 (a) to (d) SEM micrographs of Sb_2Te_3 films on glass substrate

Figure 3 shows a typical AFM scan of an exposed sample(5cm). The surface roughness was obtained in this way from the various samples.

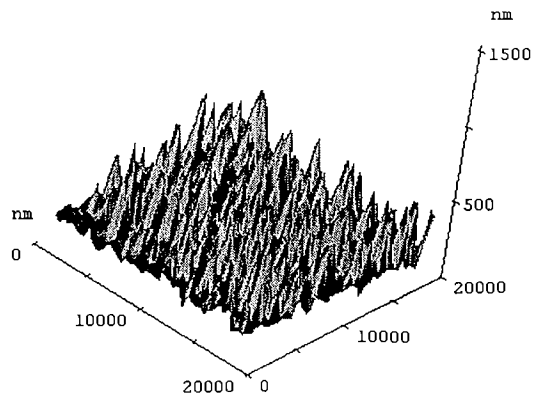


Figure 3. AFM image of a sample exposed at 5cm

Figure 4 shows some raw XRD scans(using Cu K α radiation) of the samples exposed at various distances. Information about the crystal structure is inferred by comparing with a database of known peaks. It is possible to identify about three peaks for each structure

Peaks from the bonded and unbonded tellurium and antimony were identified from the XPS (Table 1). No peaks due to unbonded antimony was observed It was also found that there was some bonding with oxygen. In interpreting the results, it must be noted that the surface roughness must be taken into consideration.

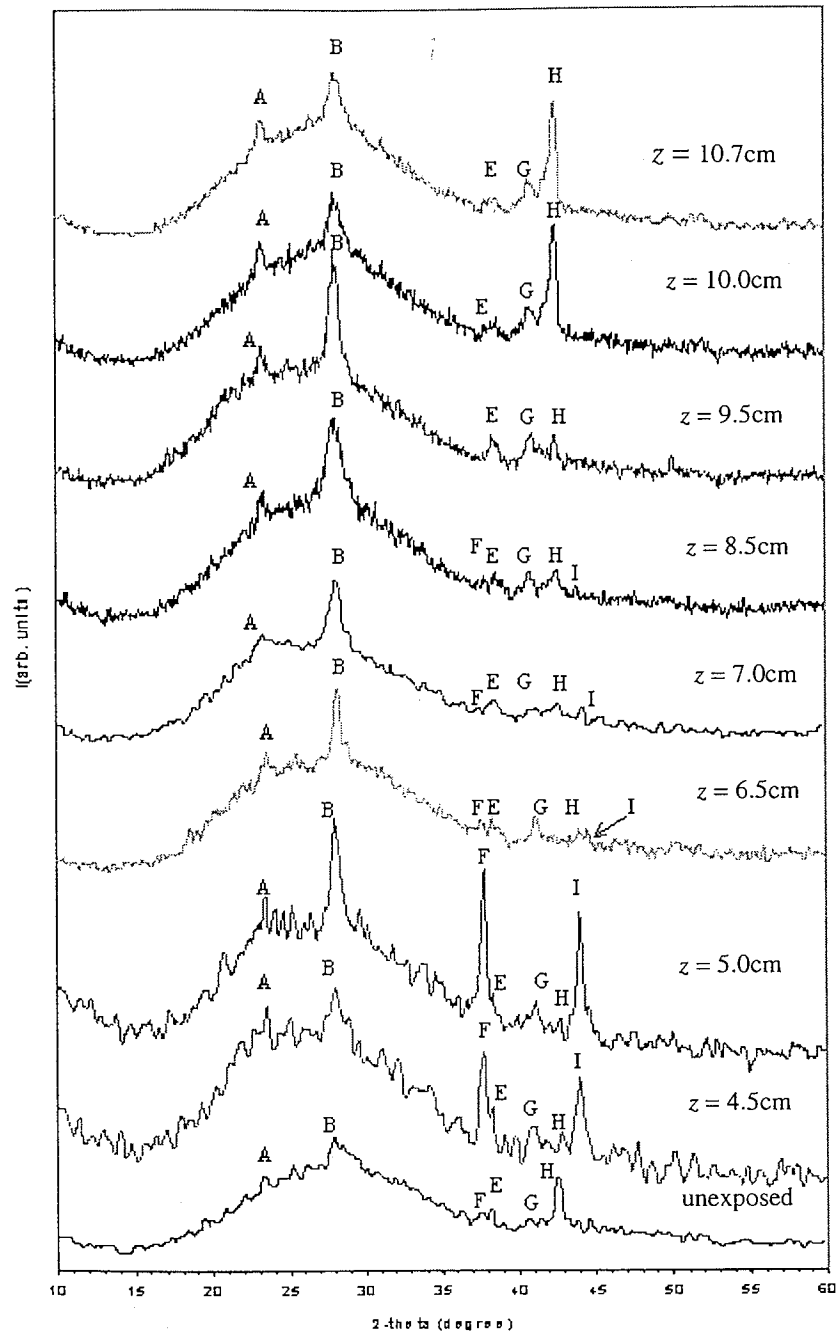


Figure 4. XRD scans. The alphabets indicates identified lines

Region: Te3d (Te3d _{5/2} , Bonded Te)				Region : Te3d (Te3d _{5/2} , Pure Te)		
<i>z(cm)</i>	<i>Position(eV)</i>	<i>Intensity(a. units)</i>	<i>Area</i>	<i>Position(eV)</i>	<i>Intensity(a. units)</i>	<i>Area</i>
5.0	576.1	3 927	804	572.9	419	58
7.0	576.2	10 505	2 092	573.1	1 030	155
10.7	576.4	3 001	690	573.0	408	88
Unexposed	576.1	6 879	1 429	572.8	2131	405
Region : Sb3d, O1s. (Sb 3d _{3/2})				Region : Sb3d, O1s. (Sb 3d _{5/2})		
<i>z(cm)</i>	<i>Position(eV)</i>	<i>Intensity(a. units)</i>	<i>Area</i>	<i>Position(eV)</i>	<i>Intensity(a. units)</i>	<i>Area</i>
5.0	539.8	811	165	530.4	1587	349
7.0	539.8	2270	390	530.4	6444	1241
10.7	539.7	2953	598	530.4	6280	1338
Unexposed	539.6	7466	1240	530.1	11 942	2101

Table 1: XPS results of various analysed region.

Conclusion

The XRD studies revealed an increase in the crystallization of Sb₂Te₃ crystals for films placed at further distances from the anode. For films exposed closer to the anode, other antimony telluride crystals were also found to be induced. AFM and SEM studies indicate that the surface of the films which were exposed at greater distances were reasonably smooth. Preliminary studies using the XPS also indicate a potential use of DPF for increasing bonds in materials.

Acknowledgements

One of us, R.S. Rawat, thank the AAAPT (Asian African Association for Plasma Training) for a grant which has made the research collaboration for this work possible.

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HIGH REPETITIVE X-RAY PINHOLE CAMERA BASED ON CCD AND ITS APPLICATION IN PLASMA X-RAY SOURCE

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Abstract. Based on CCD Camera and Computer technology, a high repetitive x-ray pinhole camera system has been developed and successfully used in our plasma x-ray source for capturing the X-ray pinhole images. This pinhole camera system can be operated in repetition rate of up to 10 Hz. The repetition rate can be preset. The x-ray pinhole images are captured and stored in computer automatically. For synchronization, the pulsed plasma focus x-ray source and pinhole camera system are controlled (triggered) by the same computer, the software is written in C language.

1. Introduction

We have developed a high repetition (16Hz), high power (300W) plasma focus soft x-ray source for microelectronic lithography [1,2]. Because the size of the point-like soft x-ray source is one of the limiting factors to the lithography resolution, we have developed a high repetition rate pinhole camera based on CCD (Charged Coupled Device) for studying the variation of sizes of this point-like soft x-ray source. This pinhole camera system can be operated at a repetition rate of up to 10 Hz. The repetition rate can be preset in the range of 0.01Hz to 10Hz and the number of images to be taken in one burst (or for pulsed soft x-ray source --- plasma focus device how many shots to be fired in one burst) can be preset with the computer. The x-ray pinhole image are captured and stored in the computer automatically. For synchronization, the plasma focus device and pinhole camera systems are controlled (triggered) by the same computer, the software is written in C language. The soft x-ray pinhole images can be analyzed in the computer either singly or by overlaying several images together. This pinhole camera system has been successfully used in our plasma focus x-ray source.

2. Experimental setup

This pinhole camera system has been developed based on CCD and computer. It consists of easily obtained components which includes: a CCD (the glass cover was removed), a video card for computer, and a personal computer as well a program written in C language. The block diagram of pinhole camera system and plasma soft x-ray source is shown in Figure 1.

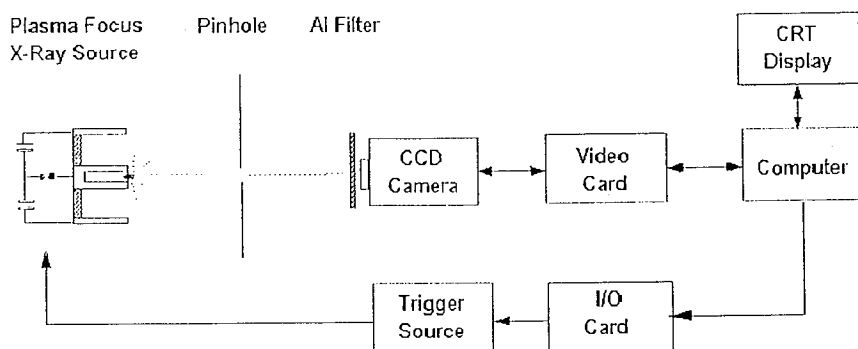


Fig 1. Block Diagram of Pinhole camera system based on CCD and Plasma x-ray source

The CCD camera used in this experiment was a Pulnix TM 6EX which has a high-resolution (756×574 pixels, pixel size $8.3\ \mu\text{m} \times 8.39\ \mu\text{m}$) silicon based 1/3 inch format CCD chip. The glass cover of the CCD was replaced with $25\ \mu\text{m}$ Al filter. The transmission of the Al filter is given in Figure 2. The spectra of x-ray emitted from our Plasma x-ray source are given in Figure 3. Image processing routines were then carried out on the stored

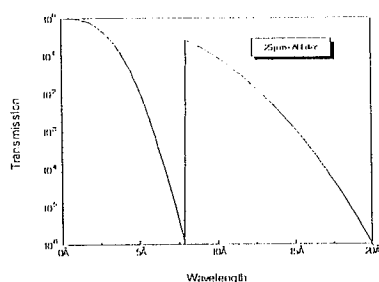


Fig. 2 Transmission of Al Filter

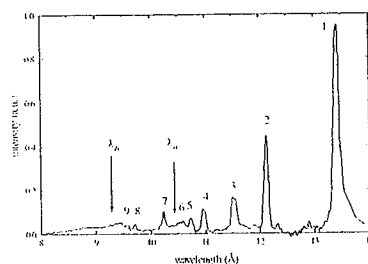


Fig. 3 X-ray emission spectrum of neon plasma

images to extract a variety of information such as pixel value for intensity information. The image captured by CCD is transferred to computer through the video capture card and

displayed on the monitor. The image data can be stored both in the memory of the image memory board and on the floppy disk or hard disk. The data are processed by a personal computer. This system permits flexible processing of the data and its presentation in various formats, such as overlay of many images, contour of image as well as a 3D display.

The pulsed plasmas focus x-ray source was triggered by the computer through a I/O card and trigger source.

3. Results and discussion

Some of pinhole images are presented in Figures 4 to 7. The images of single shot are shown in Figs. 4 and 5. In the Figure 4, one hot spot was found. Multi hot spot was found in Figure 5. Overlay of 20 images and 50 images are shown in Figs. 6 and 7, respectively.

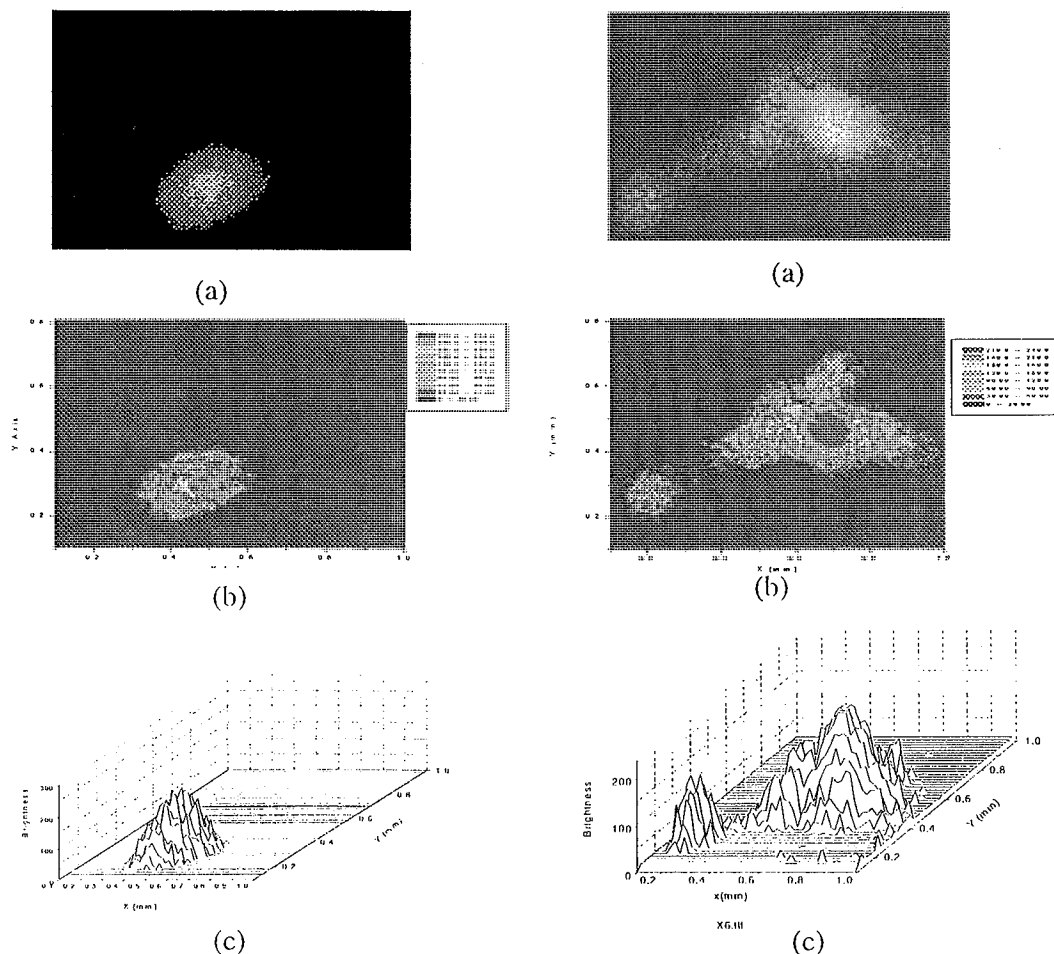


Fig.4 The pinhole image (single shot)
(a) Image (b) Contour (c) 3D View

Fig.5 The pinhole Image (single shot)
(a) Image (b) Contour (c) 3D View

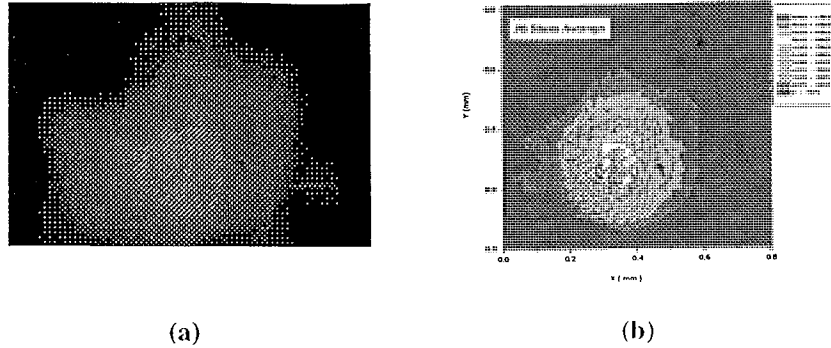


Fig. 6. X-ray Image (20 shots overlay) (a) Image (b) Contour

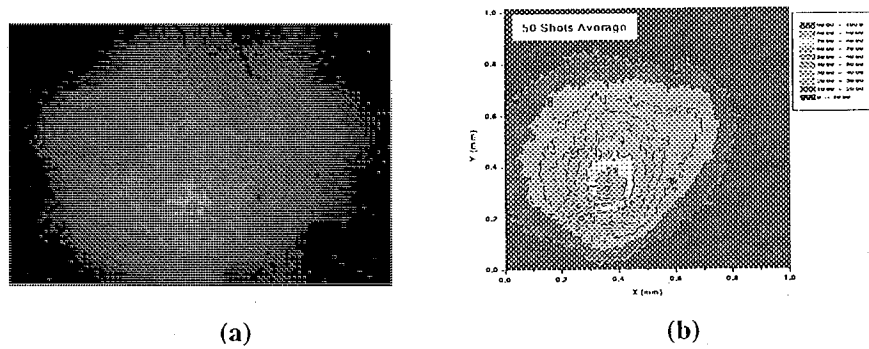


Fig. 7 X-ray Image (50 shots Overaly) (a) Image; (b) Contour

Compared to the traditional method, such as using the x-ray film to record the image, this pinhole camera based CCD is fast and more convenient , whether in recording the image or data processing.

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SXR RADIATION MODELING FOR NEON PLASMA FOCUS

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Abstract

Based on Corona model and our experimental results, a radiative plasma focus model was developed. Reflected shock phase and radiative phase are added to the earlier model to simulate the x-ray emission from the plasma focus. The model was applied to the 3 kJ plasma focus (UNU/ICTP PFF) and electron temperature of 360 eV, density of 10^{26} m^{-3} , pinch column with 8 mm length / 0.4 mm diameter were computed for the uniform radiative compression. Radiation from this compression was also computed. Line radiation comprises 70% of the total x-ray emission which is $\sim 10 \text{ J}$. These results show good agreement with the experimentally measured values.

1. Introduction

A simple plasma focus (PF) model has been developed in earlier work [1-4]. Using a snow-plow model in the axial rundown phase and a slug model in radial phase, this model is capable of yielding trajectory and structure of plasma. The details of this model can be referred to reference [1] and thus will not be described here. This paper reports the improvement done on this model and is focused on the soft x-ray (SXR) radiation part.

2. Radiative plasma focus model

To simulate the radiation from the plasma focus (PF), two additional phases are brought in to give now four phases, i.e., axial-phase, radial-inward-shock-phase, reflected-shock-phase and slow-compression-phase (or radiation-phase), as illustrated schematically in Fig.1 (axial phase not shown in this figure). When the shock front hits the axis of symmetry, the magnetic piston (MP) continues to move inwards until a reflected shock (RS) front meets the MP, at which the pinch comes to a minimum radius and slow-compression-phase starts. A few nanoseconds later the pinch disassembles.

Radiation loss is now considered in the model [5]. Using the First Law of Thermodynamics we can rewrite the equation for the piston radial motion as follows,

$$\frac{dr_p}{dt} = \left[\frac{-r_p}{\gamma} \frac{dI}{dt} - \frac{1}{\gamma+1} \frac{r_p}{z_f} + \frac{4\pi(\gamma-1)}{\mu\kappa_f} \frac{r_p}{I^2} \frac{dQ}{dt} \right] \left(\frac{\gamma-1}{\gamma} \right)$$

Where $Q = Q_{joul} - Q_{rad}$ is the total heat energy absorbed by the plasma, Q_{joul} the joule heating and Q_{rad} the radiation loss. The radiation rate dQ_{rad}/dt consists of line radiation, recombination and little Bremsstrahlung for neon plasma. The corresponding power densities of these three kinds of emission are listed below (all in unit of $W.m^{-3}$)

$$P_l = 3.95 \times 10^{-35} \frac{Z_n^4}{T_{eV}} N_e N_i$$

$$P_r = 5.5 \times 10^{-37} N_e T_{eV}^{-1/2} \sum_z N_z z^4$$

$$P_b = 1.69 \times 10^{-38} N_e T_{eV}^{1/2} \sum_z N_z z^2$$

where N_z is the concentration of ions in z th ionised state, z the charge number of ions, T_{eV} the electron temperature in eV and Z_n the atomic number.

By solving the equations of motion together with circuit equation the work done (W), the kinetic energy (E) and the heat energy (Q) are computed for each time step and the internal energy (U), thus the plasma temperature, is computed using:

$$U = W + Q - E$$

The radiation phase is computed for 10 ns, as observed experimentally for our 3kJ PF.

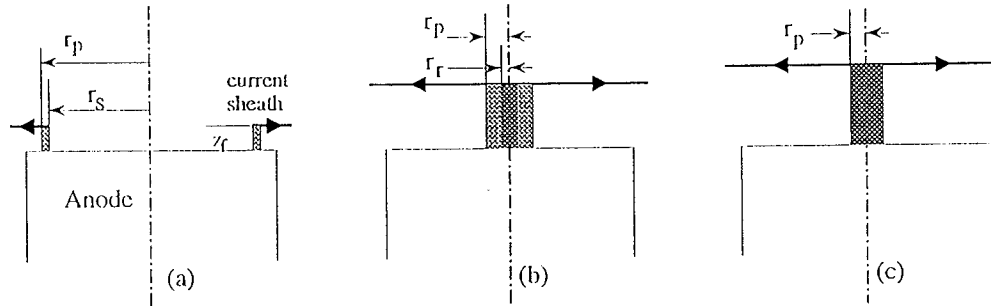
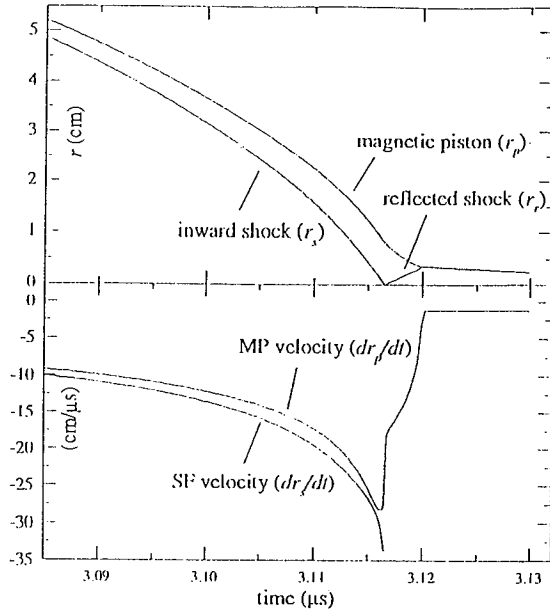


Figure 1. Schematic of plasma focus phases (axial phase not shown here). (a) radial inward shock phase; (b) reflected shock phase; (c) slow compression phase (radiation phase)

3. Results

The trajectory of the plasma sheath in radial phase and its velocity are shown in Fig.2. The model gives the final radial velocity of the imploding plasma sheath ~ 30 cm/ μ s and pinch length ~ 8 mm. By introducing a reflected shock phase a minimum compression radius of ~ 0.4 mm is obtained, which agrees with results from shadowgraphy and schlieren photography done on this same machine.

**Figure 2.**

Upper plot: trajectories of radial inward shock (r_s), reflected shock (r_r) and magnetic piston (r_p).

Lower plot: inward shock speed (dr_s/dt) and magnetic piston speed (dr_p/dt)

(SF: shock front,

MP: magnetic piston)

Conditions: discharge at 13 kV neon at 2.5 mbar.

The temperature of 360 eV and electron density of $\sim 10^{26} \text{ m}^{-3}$ are computed, as shown in Fig.3. The neon plasma is highly ionised, as can be seen in Fig.3(b). Fig.3(c) shows the comparison among the line radiation rate, recombination emission rate and the Bremsstrahlung rate, the joule heating rate is also shown. We see that the line radiation dominates the total radiation yield which in this particular case is 10 J.

4. Conclusion

The simple radiative plasma focus model gives a clear picture of the dynamics in the radial phase as well as quantitative results of the x-ray emission from neon plasma focus. With the finite speed of small disturbance and reflected shock included into the model we obtained more realistic physical picture of the radial inward compression and minimum compression radius. An electron density of 10^{26} m^{-3} and an electron temperature of 360 eV are computed using the model. For neon plasma at this temperature the line radiation is found to be the strongest feature, whereas the Bremsstrahlung is relatively weak. As the joule heating rate is small compared to the radiation loss, radiative collapse is predicted by this model.

These results show good agreement with the experimentally measured values and form part of the data base for the development of a high performance, high repetition rate SXR source for lithography applications, which is now in operation in the plasma SXR source laboratory of Nanyang Technological University.

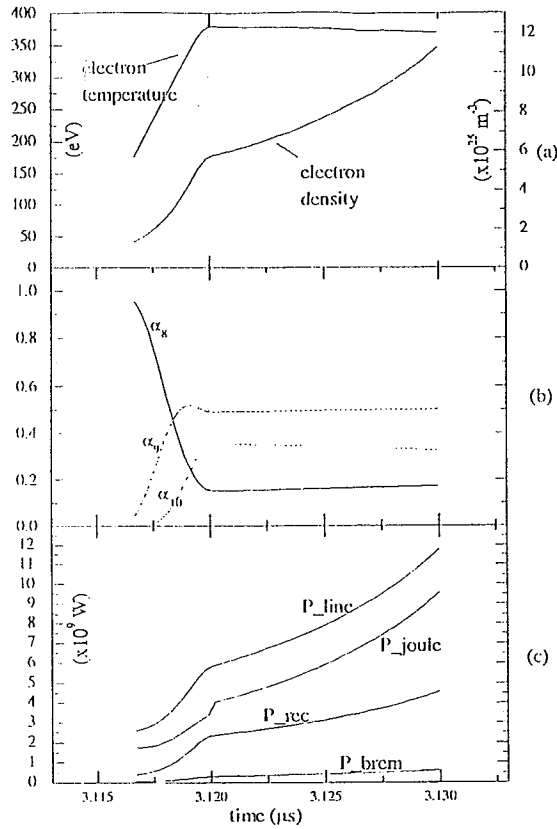


Figure 3.

(a) electron temperature and density.

(b) fraction of 8th, 9th, and 10th ionised state for neon ion.

(c) P_{line} , P_{rec} and P_{brem} are emission rates from line radiation, recombination and Bremsstrahlung respectively; P_{joule} is the joule heating rate.

Conditions: discharge at 13 kV neon at 2.5 mbar.

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A Novel Technique for Measuring the Pulsewidth of Nanosecond Laser Pulses

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Abstract—This paper presents a simple, low-cost, and novel technique for measuring the temporal pulse shape of a nanosecond laser pulse accurately and consistently. The measurement configuration consists of a focusing lens, a tapered rod, and a digital noise filter. Using this setup, the pulsewidth of a nitrogen laser has been determined experimentally. Compared with an unaided measurement configuration, the new setup reduces the maximum deviation from 24.5% to 6.2% and the standard deviation from 7.6% to 1.4%, respectively.

Index Terms—Laser beams, laser measurements, laser stability, measurement, pulse measurements, pulsed lasers.

I. INTRODUCTION

IT IS IMPORTANT to measure accurately and consistently the pulsewidths of pulsed nanosecond lasers such as excimer lasers, the nitrogen laser, and the Q-switched Nd:YAG laser. For example, in excimer laser keratectomy, the control of the laser duration is important in determining the amount of ablation of the cornea tissues [1]. Similarly, the temporal characteristics of the laser pulse are vital in applications such as shadowgraphy, schlieren photography, microlithography, and micromachining [2].

In the literature, most researchers have reported on the use of a combination of a fast photodiode coupled to a storage oscilloscope (or a transient-event digitizer) for the measurement of pulsewidths [3], [4]. Occasionally, an expensive streak camera may be employed [5].

Generally speaking, the pulsewidth of a laser depends on the pumping configuration and the resonator parameters. For example, in the case of a nitrogen laser, the temporal pulse shape depends largely on the voltage of the discharge circuit and the pressure of the lasing gas. However, it is very difficult to obtain an accurate and consistent measurement of the pulse shape of a nanosecond laser pulse because of the following.

- 1) The laser pulse is of a short duration, and the pulse profile may vary from one shot to another. Therefore, to capture the pulse shape accurately, a precision transient-event digitizer or digital oscilloscope with very high sampling rate, in the range of gigasamples per second or higher, is required to capture the laser pulse shape reliably.

- 2) Owing to the short pulse duration, a miniature photodiode has to be used for pulse detection. Otherwise, the carrier transit time will become very long and degrade the temporal measurements [6].
- 3) The spatial energy distribution of a nitrogen or excimer laser beam is generally non-Gaussian and nonuniform. Consequently, for accurate and consistent measurement of the temporal pulse shape, the laser beam has to be focused neatly onto the tiny photodiode to even out the effects of different parts of the beam. Proper alignment of the focused laser beam and the photodetector is, thus, crucial.

In this paper, we report on a new technique for the consistent measurement of laser pulsewidths. The results are compared to those obtained using a few other methods.

II. EXPERIMENTAL LAYOUT

The pulsed laser used in our experiment is a nitrogen laser developed in our laboratory (Blumlein-circuit, transverse flow, electrically excited, corona preionization, 2.8-mm electrode gap) [2]. As the radiative lifetime of nitrogen's transition from the $C^3\pi_u$ upper lasing state to the $B^3\pi_g$ lower lasing state varies from about 40 ns at a few mbars to about 2 ns at one bar [7], fast high-voltage electrical discharges are required to excite the nitrogen molecules. Part of the kinetic energy of an electron is transferred to a nitrogen molecule by elastic collision

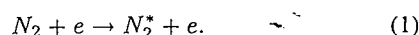


Fig. 1 shows a schematic diagram of the experimental layout. Through numerical control, a PC is used to vary the operating voltage from 9.0 to 11.1 kV, and the gas operating pressure from 250 to 1000 mbar. Laser emission at the wavelength of 337.1 nm is confirmed using an Oriel 77400 spectrograph with 0.2-nm resolution.

The output beam from the N_2 laser is split into two paths for simultaneous measurements of pulsewidth and pulse energy. The uncoated wedge reflects about 4% of the laser beam to the photodiode (MG13DAH001 with a detection area of 0.04 mm² and a rise time of 0.35 ns). A HP54720D transient-event oscilloscope, sampling at 8 GSa/s and having a rise time of 0.175 ns, is used to record the laser pulses and, subsequently, download the data to the PC via the built-in HPIB interface.

The HP scope also provides an optional digital noise filter for the incoming signals. The digital low-pass filter, called the finite impulse-response (FIR) filter, will attenuate the

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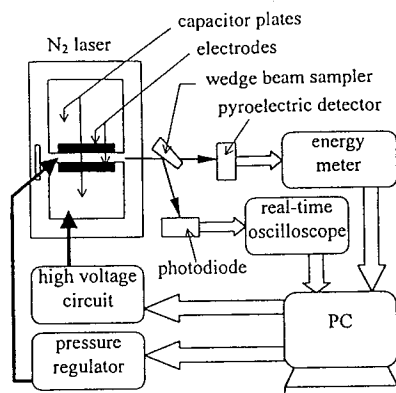


Fig. 1. Schematic diagram of experimental layout.

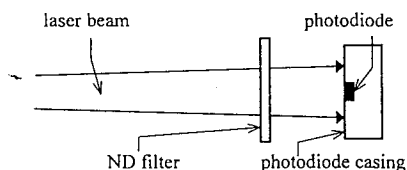


Fig. 2. Direct unaided method for pulswidth measurement.

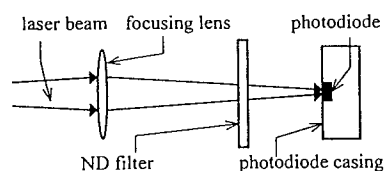


Fig. 3. Pulswidth measurement with a focusing lens.

high-frequency components with an approximate Gaussian response. This effectively reduces both the noise floor in the scope and any noise spikes riding on the input signal, although the effective signal bandwidth is narrowed from 2 GHz to 400 MHz [8].

III. MEASUREMENT CONFIGURATIONS

Fig. 2 shows the setup for direct unaided measurement of the laser pulse. The laser pulse is shone directly onto the photodiode after passing through a neutral-density (ND) filter that attenuates the intensity level of the signal to a suitable level for photodetection.

Fig. 3 shows an improved measurement setup that makes use of an equiconvex focusing lens made of fused silica. It has been found that the alignment of the photodetector with respect to the focused beam is very critical.

Fig. 4 shows the measurement setup that makes use of a 1-m-long multimode optical fiber as the beam homogenizer. It can be observed that the ND filter is no longer required, as the beam intensity at the photodetector can be adjusted by varying slightly the distance between the tip of the fiber and the photodetector.

Fig. 5 shows the novel measurement setup that makes use of a focusing lens in conjunction with a tapered rod acting as a

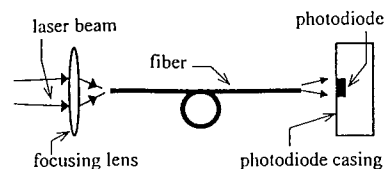


Fig. 4. Pulswidth measurement with an optical fiber.

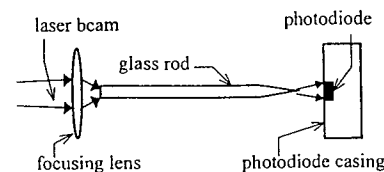


Fig. 5. Pulswidth measurement with a tapered glass rod.

TABLE I
PULSEWIDTHS OBTAINED USING VARIOUS MEASUREMENT SETUPS

Measurement Setup	Pulse width of 20 pulses		
	Mean (nsec)	Maximum Deviation (%)	Standard Deviation (%)
Unaided Direct Method	1.50	24.5	7.6
Unaided Direct Method with Digital Noise Filtering	1.64	14.1	3.9
Focusing Lens with Digital Noise Filtering	1.73	9.8	2.9
Optical Fiber with Digital Noise Filtering	1.89	7.6	2.0
Tapered Glass-Rod with Digital Noise Filtering	1.70	6.2	1.4

beam homogenizer and a light pipe. The tapered rod was pulled over a flame in the laboratory. The taper angle is roughly 5° . Again, no ND filter is required, as the beam intensity at the photodetector is adjusted by varying the distance between the tip of the tapered rod and the photodetector.

IV. RESULTS AND DISCUSSIONS

Table I summarizes the results of pulswidth measurement using the various techniques: 1) the direct unaided method; 2) the direct unaided method with digital noise filtering; 3) the focusing lens method with digital noise filtering; 4) the optical fiber method with digital noise filtering; and 5) the tapered rod method with digital noise filtering. Twenty laser pulses were recorded for each setup at a discharge voltage of 11.1 kV and a nitrogen pressure of 1 bar. The mean, maximum deviation (defined as the difference between the maximum and minimum values normalized by the mean), and standard deviation are calculated for each set of readings.

In the direct unaided method, the photodetector is sampling the laser beam directly from the exit port of the nitrogen laser. As shown in Table I, the average pulswidth is 1.50 ns, the maximum deviation is 24.5%, and the standard deviation is 7.6%. The average pulse energy, detected by a Molec-tron EM500 energy meter with a J-25 pyroelectric probe, is

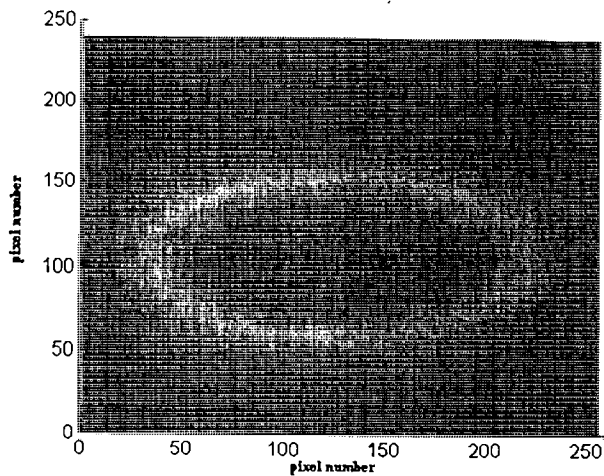


Fig. 6. Intensity profile of raw beam (discharge voltage = 11.1 kV, nitrogen pressure = 1 bar).

typically 0.23 mJ. The divergence of the beam is estimated to be 2° approximately.

The mode shape, i.e., the transverse intensity distribution of the laser beam, is assessed using a Spiricon LBA-100A beam diagnostic system. The laser beam falls onto a Cohu 4810 CCD camera, and the intensities captured are analyzed and displayed on the monitor. The intensity profile can also be output in the form of a data file. Fig. 6 shows the intensity distribution of a typical nitrogen laser pulse captured by the beam profiler. It can be observed that the intensity distribution of the raw beam is nonuniform, but approximates a bivariate normal distribution. Energy spikes exist mainly at the center of the beam. Also, using the same apparatus, we have determined that the pointing instability of the nitrogen laser output, i.e., beam jitter, is approximately 0.22 mrad (at 95% confidence interval). Therefore, the shot-to-shot variation over a small detector area of 0.04 mm^2 becomes fairly substantial.

The digital noise filter improves pulsewidth measurement, with the maximum deviation being reduced from 24.5% to 14.1% and the standard deviation being reduced from 7.6% to 3.9%. The reason is that the high-frequency noise that may exist at the peak of the pulse is filtered. The pulsewidth at full width at half maximum (FWHM) can then be determined more accurately. However, it can be observed that the mean pulsewidth is lengthened by 0.14 ns. This is mainly caused by an increase in the rise time of the instrument by reducing the bandwidth (BW) of the oscilloscope from 2 GHz to 400 MHz. The rise time (t_r) is related to the BW by [6]

$$t_r = \frac{0.35}{\text{BW}}. \quad (2)$$

Therefore, the theoretical rise time is increased from 0.175 ns for $\text{BW} = 2 \text{ GHz}$ to 0.875 ns for $\text{BW} = 400 \text{ MHz}$.

A further experiment performed using this measurement setup reviews that the average pulsewidths for 20 pulses taken at different parts of the beam may vary by 0.20 ns (at 95% confidence interval) over a direct beam area of $3.5 \text{ mm} \times 3.5$

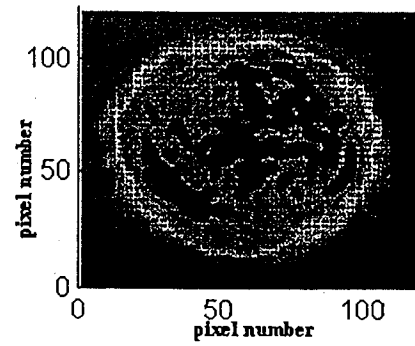


Fig. 7. Intensity profile of laser beam after exiting from optical fiber (discharge voltage = 11.1 kV, nitrogen pressure = 1 bar).

mm. Hence, variation of the mean pulsewidth by as much as 0.20 ns should not be considered as overly alarming.

Using a focusing lens with digital noise filtering improves the consistency of the measurements, with the maximum deviation being reduced to 9.8% and the standard deviation being reduced to 2.9%. The improvement results from a bigger portion of the beam being captured and measured by the tiny photodetector.

Putting one end of a 1-m-long optical fiber at the focus of the converging lens allows the beam to be homogenized by mode propagation and multiple reflections in the multimode fiber. This results in the maximum deviation being reduced to 7.6% and the standard deviation being reduced to 2.0%. Fig. 7 shows the intensity distribution of the laser beam emerging from the tip of the optical fiber. A large portion of the beam is homogenized, but there exist sporadic energy peaks all over the beam.

Since the optical fiber has a core diameter of $50 \mu\text{m}$, a numerical aperture of 0.25, and a refractive index of 1.46, it works out that the modal dispersion (or the longest geometrical path difference for different ray angles in the fiber) will account for about 0.07 ns of pulse dispersion. Therefore, the increase in the mean pulsewidth is due to a combination of having temporal pulse dispersion in the fiber and having a larger portion of the beam being sampled.

It should be noted that other commercial laser beam homogenizers might be attempted to achieve better measurement consistency. These devices include “fly’s eye” lenses, light ducts, and diffractive optical elements. However, such products are generally quite expensive.

The use of a tapered-end circular glass rod improves further the consistency of pulsewidth measurements. The maximum deviation and the standard deviation are reduced to 6.2% and 1.4%, respectively. The glass rod acts as a beam homogenizer and light conduit, so that the effect of pointing instability is largely eliminated. Fig. 8 shows the intensity profile of the laser beam after emerging from the tapered end of the glass rod. The rays that enter the rod bounce off the sides of the glass wall for at least four times, thus homogenizing the beam to a certain extent. In this setup, since the numerical aperture of the input beam is about 0.18, the increase in average pulsewidth due to beam propagation in the tapered glass rod is only about 0.006 ns.

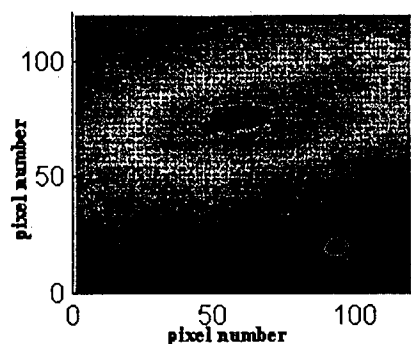


Fig. 8. Intensity profile of laser beam after exiting from tapered rod (discharge voltage = 11.1 kV, nitrogen pressure = 1 bar).

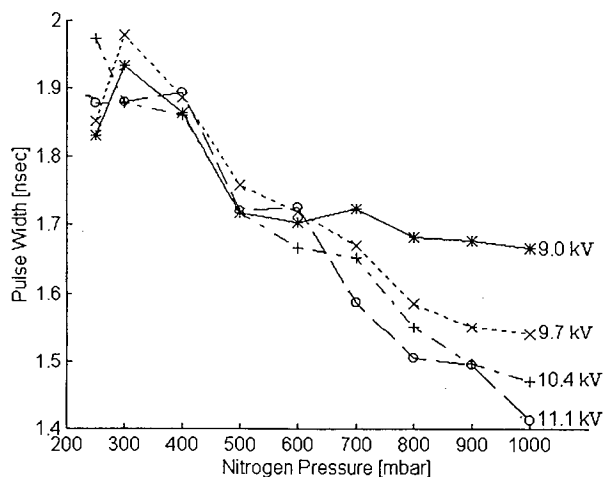


Fig. 9. Pulsewidth measurement at various discharge voltages and nitrogen pressures using the unaided direct method.

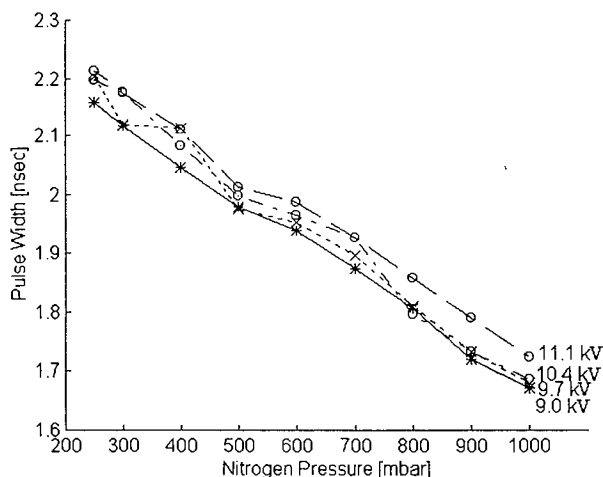


Fig. 10. Pulsewidth measurement at various discharge voltages and nitrogen pressures using the proposed tapered-rod method.

Fig. 9 shows the pulsewidth measurements using an unaided measurement setup for various nitrogen gas pressures at different discharge voltages. The same measurements were retaken using the proposed measurement method (focusing

lens + tapered glass rod + digital noise filter), and the results are plotted in Fig. 10. The improvement in data reliability and data interpretation is evident. Such improvement in measurement consistency is essential in designing hardware or software control schemes to stabilize the output of a nanosecond laser.

V. CONCLUSION

This paper has presented a novel, low-cost, simple, and practical technique for measuring the pulsewidth of a nanosecond pulsed laser beam. Compared with an unaided measurement setup, the use of our proposed measurement configuration (focusing lens + tapered rod + digital noise filter) improves markedly the reliability of the data collected. In our experiment with a nitrogen laser, the maximum deviation has been reduced from 24.5% to 6.2%, and the standard deviation from 7.4% to 1.4%. This is achieved by partial homogenization of the raw beam, and by elimination of the adverse effect of beam jitter. The lengthening of the pulse due to modal dispersion is negligible.

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Sing Lee (M'96), photograph and biography not available at the time of publication.

The collisional energy transfer between the $D^1\Pi$ and $d^3\Pi$ states of the NaK dimer induced by argon buffer gas

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Abstract. By using the 514.5 nm line of a cw argon-ion laser, the discrete spectrum of $D^1\Pi \rightarrow X^1\Sigma^+$ transitions and the continuum spectrum of $d^3\Pi \rightarrow a^3\Sigma^+$ transitions of the NaK dimer in a heat pipe could be observed in the range of 500–700 nm. The collision-induced enhancement effects of the intensities $I_{d \rightarrow a}$ and the quenching effect of the intensities $I_{D \rightarrow X}$ by collisions with argon buffer gas at different pressures were measured experimentally. Based on the stationary collisional model and lifetime measurements, the quenching cross sections and cross sections for collision-induced energy transfer between the $D^1\Pi$ and $d^3\Pi$ states could be estimated.

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Recently, the bound–free emissions of alkali diatomic molecules such as Na_2 , K_2 , Li_2 [1–3] have been of great interest because of their excimer types of nature. It has been suggested that such continuum bands might be used as a source of tunable high-power lasers. The hetero-nuclear NaK molecule is unusual among the alkalis in that most of the singlet states are strongly perturbed by triplet states. As there is a lack of $g-u$ symmetry, this facilitates the direct observation of the excited triple states [4]. Moreover, the lowest triplet state ($a^3\Sigma^+$) is so weakly bound ($D_e = 203.1 \text{ cm}^{-1}$ at $R_e = 5.457 \text{ \AA}$) [5] that a broad continuum emission could be expected for transition from upper bound triple states to the free ground state ($a^3\Sigma^+$). Several experiments and computation works [5–7] on NaK molecules have found that the potential curves for the $D^1\Pi$ and $d^3\Pi$ states are quite close and the perturbations between them are very strong. The radiative transition to the $a^3\Sigma^+$ state would occur following a radiative excitation to the $d^3\Pi$ state, which is allowed by spin–orbit interaction between the $^1\Pi$ and $^3\Pi$ [6]. In this report, we present the results of the studies of laser-induced fluorescence of NaK dimers prepared in a heat-pipe oven. The effective lifetimes of the $D^1\Pi$ state and the collisional-populated $d^3\Pi$ state have been measured at different argon

gas pressures by a time-resolved technique. The cross sections of collisional energy transfer between the $D^1\Pi$ and $d^3\Pi$ states of NaK are properly evaluated.

1 Experimental

The experimental set-up, which has been described in detail in previous papers [8, 9], is also shown, for the sake of completeness, in Fig. 1. The heat-pipe oven consists of a cross-stainless-steel tube with inner diameter 2.5 cm and length 35 cm. Its inner walls are covered along the heating zone by two layers of a nickel mesh for re-circulating the condensed metal vapour. The heat-pipe can be operated in such a way that its central part contains a homogeneous zone of sodium and potassium vapours, while the four outer parts are filled with the argon buffer gas at different pressures, which were monitored with a Barocel capacitance manometer. The temperature in the central heating zone is measured by thermocouples as a function of the electrical input heating power. For this experiment, the potassium–sodium alloy metal (which contained 98% potassium as pure and 2% sodium as impurity) was enclosed in the pipe and could evaporate while above its boiling point. The vapour densities of the components K, Na, K_2 , Na_2 , and NaK at the heat-pipe temperature of 250 °C are respectively, $9.8 \times 10^{14} \text{ cm}^{-3}$, $1.3 \times 10^{13} \text{ cm}^{-3}$, 1.8×10^{12} , $2.1 \times 10^{10} \text{ cm}^{-3}$, and $3.1 \times 10^{12} \text{ cm}^{-3}$ [10, 11]. At a constant temperature, if the argon gas pressure rises above the metal vapour pressure, the argon will diffuse into the central part of the heat-pipe, and NaK–Ar collisions occur.

In Fig. 1a, the 514.5 nm line of a cw Ar^+ laser with total linewidth of 10 GHz (Innova-70-3, Coherent Corp., USA) was chopped and focused into the central part of the heat-pipe. The fluorescence was picked up at right angles to the incident laser beam, and spectra were measured with a HRD-1 double monochromator (J.Y Corp., France) equipped with a couple of holographic gratings (1200 gr/mm) and an R928 photomultiplier tube. The signal from the PMT was fed into a lock-in amplifier (SRS530, USA) for signal amplification and recovery. For the time-resolved measurements shown in Fig. 1b, we used the 3rd-harmonic radiation at 355 nm of

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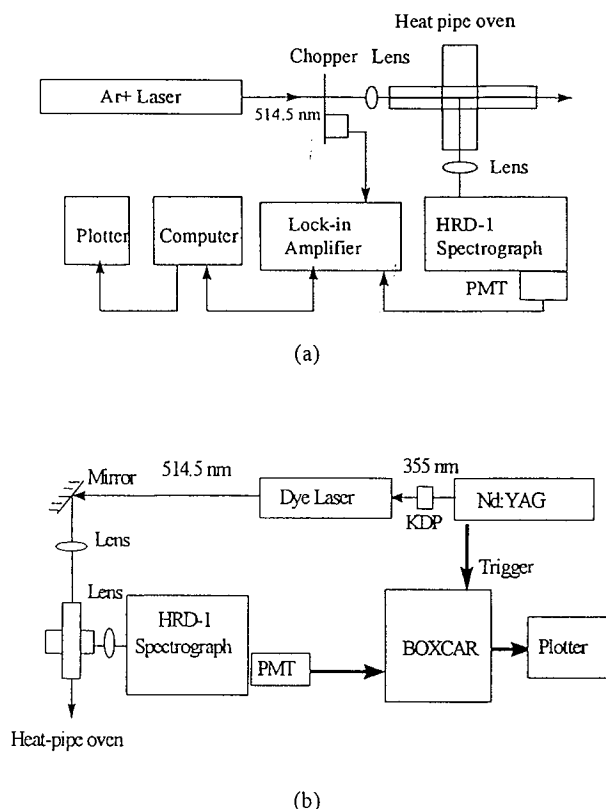


Fig. 1a,b. Experimental setup for laser-induced fluorescence, a steady-state fluorescence measurement, b time-resolved fluorescence measurement

the Q-switched Nd:YAG laser (Quanta-Ray, DCR-3, Spectra-Phys. Inc., USA) to pump the dye (Coumarin-500) laser. The dye laser was tuned at 514.5 nm. The pulse duration was 2.5 ns, linewidth 0.1 cm^{-1} , pulse energy 5 mJ, and repetition rate 10 Hz. The output of the PMT was fed into a boxcar integrator (M4400, EG & G, PARC, USA) with a time-gated width of 2 ns, and all the data were stored and processed by a microcomputer. The trigger pulses were activated prior to the lasing to assure proper synchronisation of the excitation and collection of emission.

The intensity response of the detection system was calibrated with a quartz-halogen lamp (QTH 6333, Oriel Inc., USA), and the spectral calibration Hg(Ne) lamp (Model 6034, Oriel Inc., USA) was used for wavelength calibration of the spectrometer. The spectral accuracy of this system was better than 0.1 Å.

2 Results and discussion

The NaK emission spectrum between 500–700 nm excited by the cw argon-ion laser at $\lambda = 514.5$ nm is shown in Fig. 2. The spectra consist of the discrete spectra in the range 500–590 nm, and the weak continuum spectra between 600 nm and 700 nm, peaking at around 670 nm and 620 nm. In our previous study [8], the assignments of the fluorescence components to specific $D^1\Pi(v', j') \rightarrow X^1\Sigma^+(v'', j'')$ transitions was carried out in detail using the known constants

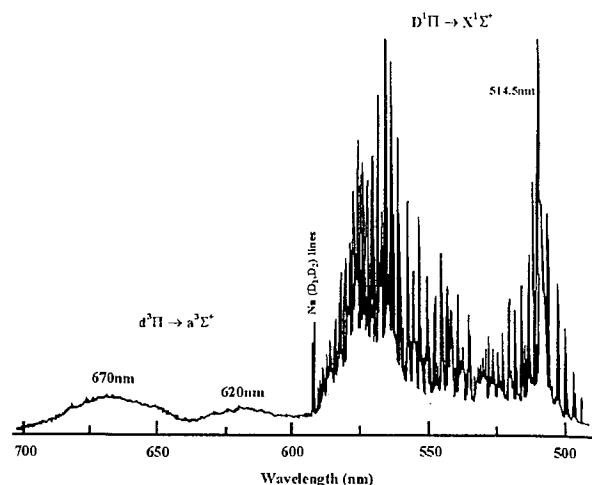
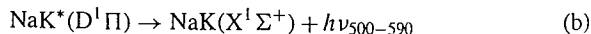
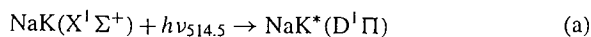


Fig. 2. Laser-induced fluorescence spectrum of NaK excited by the 514.5 nm of a cw Ar^+ laser. ($P_{\text{Ar}} = 1.3$ Torr, $T = 260^\circ\text{C}$)

of NaK molecules given in [12, 13]. We have determined that the observed spectra in the region 500–590 nm is ascribed to the $D^1\Pi \rightarrow X^1\Sigma^+$ transitions of NaK molecules. Three series of Q-branch transitions were involved in the emission: (i) the strong fluorescence of $D^1\Pi(v=1, j=67) \rightarrow X^1\Sigma^+(v, j=67)$ transitions, (ii) the medium fluorescence of $D^1\Pi(v=1, j=95) \rightarrow X^1\Sigma^+(v, j=95)$ transitions and (iii) the weak fluorescence of $D^1\Pi(v=3, j=122) \rightarrow X^1\Sigma^+(v, j=122)$ transitions. The weak continuum spectra in the red range (600–700 nm) is ascribed to the $d^3\Pi \rightarrow a^3\Sigma^+$ transition (bound $\rightarrow$ free emission) which is the result of the strong perturbation between the $D^1\Pi$ and $d^3\Pi$ states [7], and the collision-induced transfer from the $D^1\Pi$ to $d^3\Pi$ states [14].

In the absence of the foreign gas, the fluorescence intensity of $d^3\Pi \rightarrow a^3\Sigma^+$ transition is rather weak compared to that of the $D^1\Pi \rightarrow X^1\Sigma^+$ transition. When the argon gas was added and the gas pressure increased, the fluorescence intensity of the $d^3\Pi \rightarrow a^3\Sigma^+$ transition increased, whereas the intensity of the $D^1\Pi \rightarrow X^1\Sigma^+$ transition decreased. The dependence of the fluorescence intensity at 536.3, 536.0, 535.4, and 670 nm on the argon gas pressure at the temperature $T = 348^\circ\text{C}$ is shown in Fig. 3 (Note that these spectral lines at 536.3 nm, 536.0 nm, 535.4 nm, and 670 nm are corresponding to the transitions of $D^1\Pi(v=1, j=67) \rightarrow X^1\Sigma^+(v=12, j=67)$, $D^1\Pi(v=1, j=95) \rightarrow X^1\Sigma^+(v=11, j=95)$, $D^1\Pi(v=3, j=122) \rightarrow X^1\Sigma^+(v=11, j=122)$ and $d^3\Pi \rightarrow a^3\Sigma^+$, respectively [8]). This indicates that at the constant temperature the collisions between Ar atoms and NaK molecules can greatly decrease the population of the $D^1\Pi$ state, while enhancing the energy transfer from the $D^1\Pi$ to $d^3\Sigma^+$ states. The effect of collisional energy transfer on populating the $d^3\Pi$ state is significant particularly for the use of higher pressures of argon gas. The above-mentioned kinetic processes can be expressed as



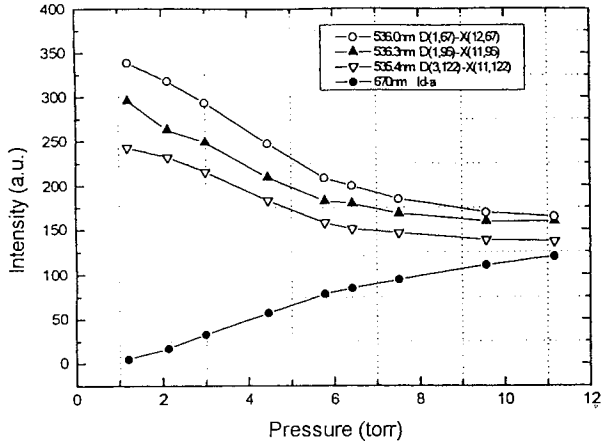
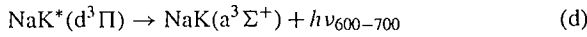
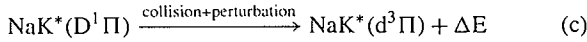


Fig. 3. The fluorescence intensity versus argon gas pressure at $T = 348^\circ\text{C}$



ΔE is the change in kinetic energy ($< 200\text{ cm}^{-1}$) [4, 13]. This small energy gap enables a considerable energy transfer between the $\text{D}^1\Pi$ and $\text{d}^3\Pi$ states under a collisional environment.

With excitation by a pulsed dye laser at 514.5 nm and tuning of the double monochromator to the positions of selected fluorescence transitions (i.e. 536.3 nm, 536.0 nm, 535.4 nm, and 670 nm), time-resolved decay curves could be determined as a function of argon pressure at a fixed temperature. Figure 4 gives the typical decay curves of the $\text{D}^1\Pi$ and $\text{d}^3\Pi$ states at an argon gas pressure $P_{\text{Ar}} = 1.2$ Torr and a temperature $T = 348^\circ\text{C}$. The time-resolved spectroscopy of these bands showed that there was a time delay (5–10 ns) for the $\text{d}^3\Pi \rightarrow \text{a}^3\Sigma^+$ transition (670 nm) compared to the $\text{D}^1\Pi \rightarrow \text{X}^1\Sigma^+$ transitions (536.0 nm, 536.3 nm, and 535.4 nm). This further confirms that the population of the $\text{d}^3\Pi$ state is mainly due to the collisional transfer from the $\text{D}^1\Pi$ state. From the

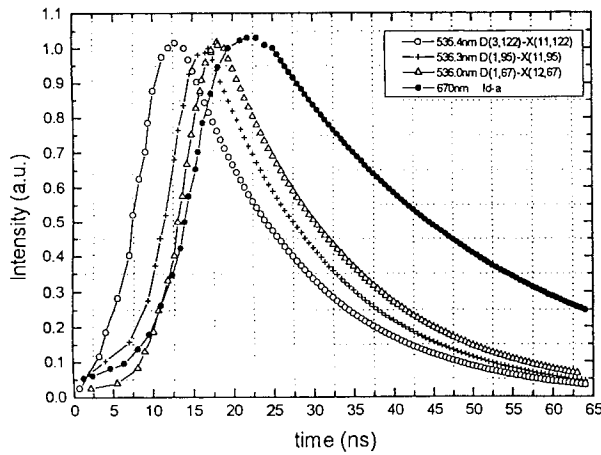


Fig. 4. The fluorescence decay curves of the $\text{D}^1\Pi$ and $\text{d}^3\Pi$ states of NaK ($P_{\text{Ar}} = 1.2$ Torr, $T = 348^\circ\text{C}$)

Stern–Volmer plot of the inverse effective lifetimes [15]

$$\frac{1}{\tau_{\text{eff}}} = \frac{1}{\tau_{\text{rad}}} + n\sigma\bar{V} = \frac{1}{\tau_{\text{rad}}} + \sqrt{\frac{8}{\pi\mu kT}} \sigma P \quad (1)$$

where P is gas pressure ($P = nkT$) at a temperature T with a mean relative velocity $\bar{V} = (8kT/\pi\mu)^{1/2}$ of the collision partners ($\text{NaK}^* + \text{Ar}$) with reduced mass $\mu = \mu_{\text{NaK}}\mu_{\text{Ar}}/(\mu_{\text{NaK}} + \mu_{\text{Ar}})$, and σ is the quenching cross section. The radiative lifetimes of the $\text{D}^1\Pi$ and $\text{d}^3\Pi$ states can be measured at a constant temperature by varying the pressure of argon buffer gas, and therefore the total quenching cross sections from (1). The fitted radiative lifetimes τ_{rad} and the quenching cross sections σ are listed in Table 1.

The fluorescence intensity $I_{\text{d-a}}(t)$ for the $\text{d}^3\Pi \rightarrow \text{a}^3\Sigma^+$ transition of NaK shown in Fig. 4 (at 670 nm) is proportional to the population density $N_{\text{d}}(t)$ of the $\text{d}^3\Pi$ state. It can be described by the rate equation:

$$\frac{dN_{\text{d}}}{dt} = N_{\text{D}}(t)C_{\text{D-d}} - N_{\text{d}}(t)(A_{\text{d}} + C_{\text{d}}), \quad (2)$$

where N_{D} is the population of the feeding level in the $\text{D}^1\Pi$ state, and A_{d} and C_{d} are the probabilities of radiative and collisional induced transitions depopulating the $\text{d}^3\Pi$ state. $C_{\text{D-d}} = n\sigma_{\text{d}}\bar{V}$ is the probability of collision-induced transitions from the $\text{D}^1\Pi$ to $\text{d}^3\Pi$ states at a density n of collision partners ($\text{NaK}^* + \text{Ar}$).

Under stable cw excitation of the $\text{D}^1\Pi$ state at the constant temperature of the heat-pipe, a stationary population of the $\text{d}^3\Pi$ state can be achieved by collisional transfer, and (2) can be re-written as

$$\frac{dN_{\text{d}}}{dt} = 0 = N_{\text{D}}(t)C_{\text{D-d}} - N_{\text{d}}(t)(A_{\text{d}} + C_{\text{d}}) \quad (3a)$$

i.e.

$$N_{\text{d}} = N_{\text{D}} \frac{C_{\text{D-d}}}{A_{\text{d}} + C_{\text{d}}} \quad (3b)$$

Then, the collisional transfer probability $C_{\text{D-d}}$ can be determined from the intensity ratio $R_{\text{D-d}}$ of the fluorescence intensities from the $\text{D}^1\Pi$ and $\text{d}^3\Pi$ states by changing the argon pressure at a fixed temperature T .

$$R_{\text{D-d}} = \frac{I_{\text{d-a}}}{I_{\text{D-X}}} = \frac{N_{\text{d}}A_{\text{d}}}{N_{\text{D}}A_{\text{D}}} = \frac{C_{\text{D-d}}}{A_{\text{D}} + C_{\text{d}}A_{\text{D}}/A_{\text{d}}} \quad (4)$$

Figure 5 represents the intensity ratio $R_{\text{D-d}}$ of the $\text{D}^1\Pi$ ($v = 1, j = 67; v = 1, j = 95; v = 3, j = 122$) levels to the

Table 1. Lifetimes, quenching cross sections and energy transfer cross sections for $\text{D}^1\Pi$ and $\text{d}^3\Pi$ states by $\text{NaK}^* + \text{Ar}$ collisions

State	radiative lifetime $\tau_{\text{rad}}/\text{ns}$	quenching cross section σ/nm^2	transfer cross section $\sigma_{\text{d}}/\text{nm}^2$
$\text{D}^1\Pi(v = 1, j = 67)$	16.1 ± 0.8	2.28 ± 0.5	0.76 ± 0.3
$\text{D}^1\Pi(v = 1, j = 95)$	15.2 ± 0.6	2.12 ± 0.7	0.87 ± 0.5
$\text{D}^1\Pi(v = 3, j = 122)$	14.7 ± 0.6	1.95 ± 0.3	1.22 ± 0.6
$\text{d}^3\Pi$	28.6 ± 1.8	0.93 ± 0.2	

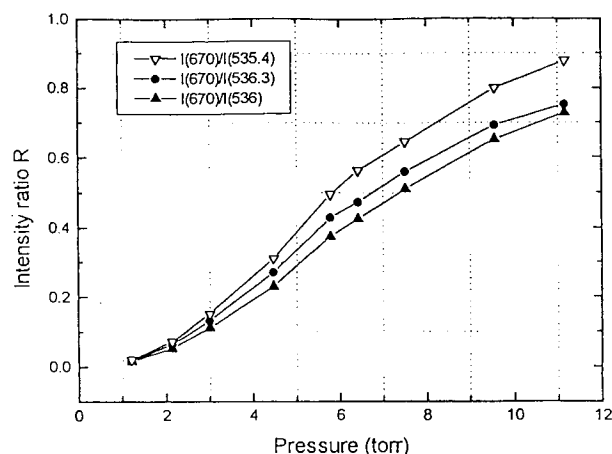


Fig. 5. The intensity ratio R versus argon gas pressure at $T = 348^\circ\text{C}$

$d^3\Pi$ states as a function of argon pressure at a temperature $T = 348^\circ\text{C}$. The slope of the intensity ratio R_{D-d} yields the transition rate for the $\text{NaK}^* + \text{Ar}$ collisions, and the fitting results of these measurements for the cross sections of collisional transfer transitions ($D^1\Pi \rightarrow d^3\Pi$) are also summarised in Table 1.

From Table 1, it can be seen that the cross section for collisional transfer from the $D^1\Pi$ ($v = 3, j = 122$) level to the $d^3\Pi$ state is larger compared to the $D^1\Pi$ ($v = 1, j = 67; v = 1, j = 95$) levels. This is mainly due to the smaller energy gap between the $D^1\Pi$ ($v = 3, j = 122$) and $d^3\Pi$ states and the stronger perturbations between them [4, 12]. It also can be found that the lifetime of the $d^3\Pi$ state is longer than that of $D^1\Pi$ levels whereas its quenching cross section is smaller compared to the $D^1\Pi$ levels. This suggests that the bound triple state $d^3\Pi$ is a promising upper state for the $d^3\Pi \rightarrow a^3\Sigma^+$ laser oscillation.

3 Conclusion

Clear bound-free emissions ($d^3\Pi \rightarrow a^3\Sigma^+$) in the region of 600–700 nm could be observed arising from the collisional energy transfer between the $D^1\Pi$ and $d^3\Pi$ states of NaK, and the energy transfer process could be further enhanced if the higher pressure of argon buffer gas was used. The results obtained in this study indicated that the combination of time-resolved fluorescence measurements and cw excitation for the determination of fluorescence intensity as a function of argon gas pressure in a heat-pipe is an efficient method for observing the diverse energy transfer processes and for determining the cross sections for the collisional transitions.

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THE EFFECT OF HIGH AXIAL SHEATH VELOCITY ON NEUTRON YIELD IN PLASMA FOCUS

EXPERIMENTAL DEVICES

KEYWORDS: *plasma focus, neutron yield, focus velocity*

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To study the effect of higher axial sheath velocities on neutron production, the geometry of the inner electrode (anode) of a 3-kJ Mather-type plasma focus device was modified. Double-stage stepped-anode configurations were tested with a speed-enhanced region long enough for a significant increase in speed but not long enough to allow the development of force-field flow-field separation at the end of the axial phase. Peak axial speeds up to 15 cm/ μ s were achieved without modifying the deuterium filling pressure and charging voltage. The neutron and soft X-ray productions were found to be dependent on sheath velocity. A new scaling law for the nonbeam component of the neutron yield was proposed.

INTRODUCTION

Plasma focus devices are very efficient pulsed-radiation sources of neutrons and X rays (soft and hard) that could be used for practical applications. Therefore, efforts are now devoted to studies of radiation mechanisms and methods to enhance the radiation yield.

Our analysis of published data for Mather-type plasma focus devices in their wide range of sizes,¹⁻⁵ i.e., energy stored in the driver, from 1 kJ to 1 MJ, shows the following experimentally observed features: Plasma focus devices can be optimized either for large X-ray output or for high neutron production, and for neutron-optimized operating conditions they all

1. operate in a narrow range of deuterium-filling pressures of several torr
2. have a maximum density of pinched plasma of 1 to 5×10^{19} cm⁻³ (Ref. 6)

3. have the same limited peak axial sheath velocity v_{axial} of 10 cm/ μ s and radial on-axis collapse speed of 25 cm/ μ s
4. are driven by a standard value of a drive parameter $(I_p/a)/\sqrt{p_o}$, the peak drive current per unit anode radius divided by the square root of the fill density, of 89 (± 8) kA/cm/(Torr D₂)^{1/2} (Ref. 7) [for simplicity, gas density is replaced by pressure, and the drive parameter is written as $(I_p/a)/p^{1/2}$]
5. follow the total neutron yield scaling law with the focus current $Y_n \sim I^4$.

The constancy of the drive parameter ensures for all machines the same value of drive magnetic field in the axial phase and the same compressed energy density in the focus phase, leading to the same high temperature in all devices.^{8,9} The constancy of the plasma sheath velocities fixes the forward shock temperature on-axis at 1.4×10^6 K and the on-axis reflected shock temperature at 3.6×10^6 K; further compression brings the temperature of the gross plasma column to just under 1 keV (Refs. 8 and 10). The neutron scaling law shows that the larger plasma focus devices produce more neutrons. This increased neutron yield appears to be due only to a combination of the larger volume of the focused plasma and the consequent increase in lifetime of the focused region. It was shown that each linear dimension of the approximately cylindrical focus or pinch region is proportional to the anode radius.^{7,9,11}

Good focusing effect is usually obtained in plasma focus experiments when the peak axial sheath velocity is within the limited range of 6 to 10 cm/ μ s and a drive parameter of ~ 89 kA/cm/(Torr D₂)^{1/2} (Ref. 7). The lower speed limit is easily understood in terms of poor coupling of the magnetic piston with the driven plasma layer, indicated by a low magnetic Reynolds number Re_m (Ref. 12), or in terms of low specific energy.¹³ For the higher speed limit, it appears that the high Re_m leads to an effective separation of the magnetic piston from the center of the plasma layer. The plasma layer then collapses

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radially, while the magnetic piston is still driving axially.⁹ Such a force-field flow-field separation is not conducive to an intense focus. Other possible mechanisms responsible for the higher speed limit are due to plasma/anode interactions (the ion and sometimes electron current component), the development of Rayleigh-Taylor instabilities, and at high velocities, the mean free path increases and, subsequently, the shock becomes diffusive; hence, the drive is ineffective.

Because of these factors, our main goal was to drive the plasma with axial speeds exceeding the "magic" value of 10 cm/ μ s, to try, at the same time, to overcome the aforementioned difficulties, and to achieve a good focusing effect. Our idea was not to increase the speed by reducing the gas filling pressure or increasing the charging voltage, because in this way, one switches from one operating regime to another, and the effects are already known. Our experiments were designed to study the performance of the plasma focus driven by peak axial sheath velocities up to 15 cm/ μ s.

First, we characterized the plasma focus operating with the standard electrode geometry and correlated various parameters like thickness and inclination of the plasma sheath, size and temperature of the pinch, development of macroinstabilities, X-ray output, and total neutron production.

Second, and this was the novel element of our work, to increase the drive parameter while limiting the force-field flow-field separation, we used a stepped anode structure, which we call a composite anode (see Fig. 1). The first part of the axial phase uses a regular anode de-

signed for the standard $(I_p/a)/p^{1/2}$ but shorter than required to match the discharge peak. This regular anode is attached to a stepped-down anode of smaller radius. This is the speed-enhanced section with increased value of the drive parameter, which should be long enough to increase the speed significantly above 10 cm/ μ s but short enough to limit the force-field flow-field separation, because from shock theory, we expect this separation to depend on the distance of travel.

Our hypothesis is that a good focusing effect occurring at higher speeds implies the achievement of higher temperatures of the pinched column. This will lead to an enhanced neutron output. A possible explanation of this effect is based on an idea proposed by Lee.^{9,10} He suggested that removing the speed limitation would result ultimately in a vastly improved scaling law of $Y_n \sim I^8$, which could enhance the prospects of the plasma focus as a fusion contender.

The total neutron yield can be written as $Y_n = Y_{th} + Y_{b-t}$, where Y_{th} and Y_{b-t} are the thermonuclear and the beam-target components, respectively. It can be easily shown that $Y_{th} \sim I^4 v_{axial}^4$, and the beam-target component of the neutron yield $Y_{b-t} \sim I^{4.5} v_{axial}^{-1.5}$. Therefore, by operating the plasma focus at higher velocities, hence higher temperatures, the thermonuclear component is enhanced. If the experiments do not limit the speed of operation, then Y_{th} will increase above the I^4 scaling, while Y_{b-t} will have a scaling law poorer than $I^{4.5}$. In the limit keeping the anode radius constant while increasing the current,

$$Y_{th} \sim I^8 \quad \text{and} \quad Y_{b-t} \sim I^3.$$

This analysis shows that operating the focus at higher speeds would increase the thermonuclear component of the neutron yield preferentially to the beam-target component and make the scaling law more favorable than I^4 , with the ultimate, most favorable scaling law being $Y \sim I^8$ (Refs. 9 and 14). In view of this analysis, a further objective of our work was to obtain indications regarding the way that neutron production scales with peak axial speed v_{axial} .

EXPERIMENTAL SETUP

Two types of inner electrode (anode) were used (see Fig. 1) in our experiments. The outer electrode (cathode) was not modified. The two basic kinds of geometries of the anode were a one-piece Mather-type anode (OPA), presented in Fig. 1 and Table I, and a stepped anode called the composite anode (CCA), illustrated in Fig. 1 and Table II. The first part of this stepped anode was a regular 19-mm-diam Mather-type anode designed for our 3 kJ/15 kV plasma focus device but cut shorter than required to match the discharge peak. This part was attached to a stepped-down anode of smaller radius. This second stage of the anode is referred to as the

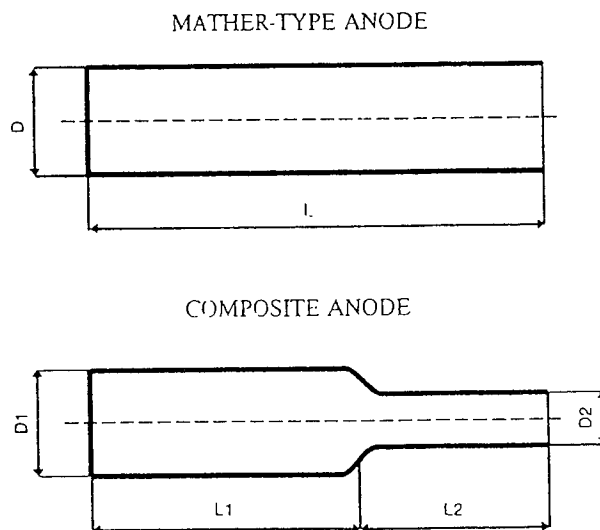


Fig. 1. Anode configurations: one-piece Mather-type anode (top) and stepped-down composite anode (bottom).

TABLE I
One-Piece Mather-Type Anode Configurations

Name	L (mm)	D (mm)
SPF-165/19	165	19
OPA-185/15	185	15
OPA-180/17	180	17
OPA-175/17.5	175	17.5

TABLE II
Composite Anode Configurations

Name	L1 (mm)	D1 (mm)	L2 (mm)	D2 (mm)
CCA-120/19+50/15	120	19	50	15
CCA-103/19+70/15	103	19	70	15
CCA-93/19+80/15	93	19	80	15
CCA-90/19+100/15	90	19	100	15
CCA-95/19+90/14	95	19	90	14
CCA-65/19+120/45	65	19	120	15
CCA-45/19+140/15	45	19	140	15

speed-enhanced section, which we attempt to adjust in length and diameter. All the anodes used were hollow at the open end.

The diagnostic techniques employed include time-resolved neutron and soft X-ray measurements, total neutron yield, peak axial sheath velocity measurements, and single-shot shadowgraphic investigations. The plasma electron temperature during the pinch phase was determined using the filter ratio method.

The measurements of the total neutron yield were carried out using the indium-foil-activation technique. A schematic of the experimental setup is provided in Fig. 2a. The calibration factor of our system^a (BICRON Labtech analyzer with GM tube) was 3.4×10^5 n/count. Time-resolved neutron-flux measurements were carried out with two time-of-flight (TOF) detectors. A schematic of the experimental arrangement is shown in Fig. 2b. Each TOF detector consists of an NE 102A plastic scintillator of 50-mm diameter and 40-mm thickness coupled to an EMI 9813B photomultiplier. Assuming a typical plasma focus discharge that produces an average yield of 10^8 n/shot isotropically,¹⁵ the estimated number of neutrons reaching the TOF detectors (placed radially at 3.6 ± 0.04 m and $6.1 \pm$

^aBICRON Labtech analyzer with Geiger-Müller tube.

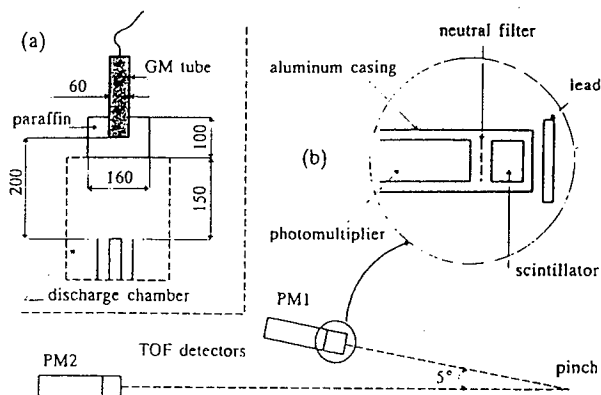


Fig. 2. Schematic of experimental arrangements for neutron measurements: (a) neutron yield and (b) time-resolved neutron flux and TOF.

0.04 m, respectively) is 1150 and 400, respectively (see Fig. 2b). Lead sheets up to 6 mm thick were placed in front of the TOF detectors to cut off most of the hard X rays.

RESULTS AND DISCUSSION

More than 1500 shots were fired at 14 kV for all the electrodes tested. The deuterium filling pressure ranged from 400 to 600 Pa.

The results of our experiments show that the radiation output depends on the electrode configurations studied, but, in terms of plasma focus evolution and dynamics, only two operating regimes are identified. One corresponds to the discharges with single-voltage spike as an indication of a single compression of the plasma column during the pinch phase. In these cases the neutron output is above the average value for each anode geometry. The other plasma focus regime is associated with multiple-voltage spikes, which, in turn, indicate multiple compressions of the pinched column. The neutron productions were, generally, below the average for each electrode configuration.

The common characteristics of all electrode configurations investigated are as follows:

1. The neutron output of the plasma focus has a strong dependence on the gas filling pressure with a pronounced maximum at 450 Pa; the neutron yield drops relatively sharply with increasing pressure while deteriorating less drastically for decreasing pressures.

2. Discharges with high neutron production are always accompanied by low, soft X-ray output but high emission in the hard X-ray region.

3. By use of the peak-to-peak method of analysis of the neutron pulses recorded with the two TOF detectors, an average energy of the neutrons emitted radially of 2.48 MeV was determined.

To obtain a better understanding of the evolution and dynamics of the plasma focus, as well as to benchmark the device for a given electrode configuration and operating conditions, correlations of the plasma focus parameters have been made. The list of the parameters used includes peak discharge current, peak axial velocity, axial transit time, duration of the radial collapse, pinch lifetime, and neutron yield. Also, the soft X-ray production was correlated with the neutron yield.

Our data show that the neutron and soft X-ray yields depend on sheath velocity: The neutron yield is higher for shorter duration of the axial phase and for a fast compression followed by a dynamic (with large time and space gradients) evolution during the pinch phase. In an earlier work on a large machine (171 kJ), neutron production was correlated with the minimum radius of the plasma column.¹⁶ In the Ref. 16 experiment, radial collapse velocities of ~ 20 cm/ μ s were reported.

To obtain information on the neutron source, the neutron pulses were translated back in time according to their flight path (see Fig. 3). Each signal (from the near detector and far detector, respectively) was normalized to the area under the trace, which is proportional to the total neutron yield. By overlapping the neutron signals, one

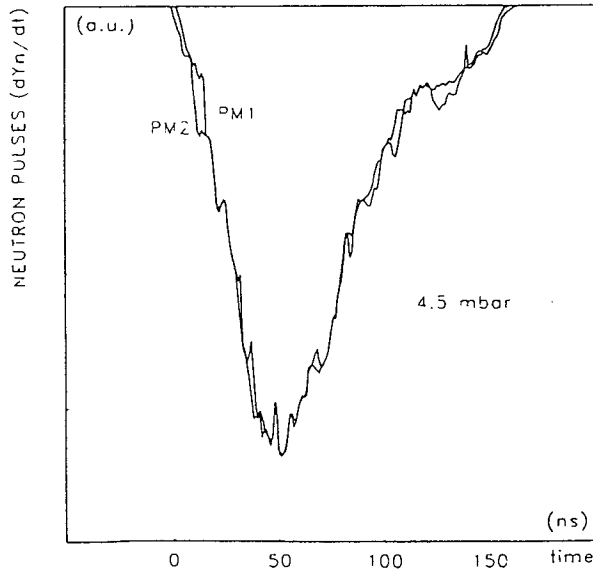


Fig. 3. Neutron pulses obtained from the TOF detectors and compensated for their TOF. Inner trace: signal from PM1. Outer trace: signal from PM2. Configuration: CCA-93/19+80/15. Discharge at 14 kV, 450-Pa D₂.

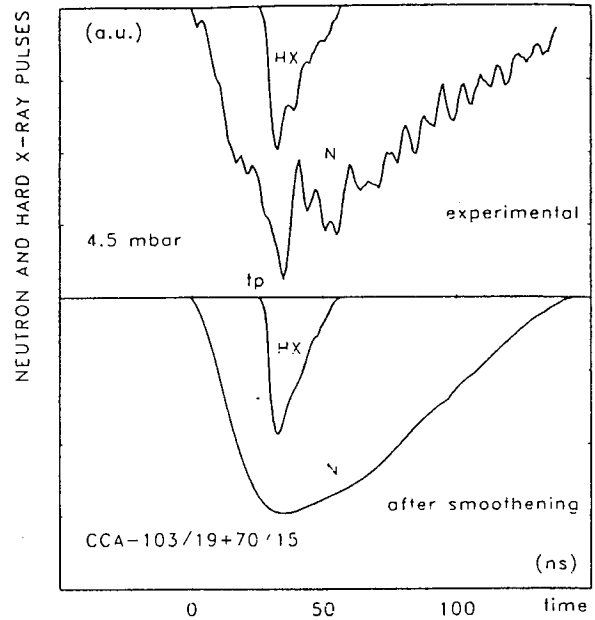


Fig. 4. Time-resolved neutron (N) and hard X-ray (HX) pulses from the first TOF detector (PM1). The neutron pulse is compensated for its TOF. Experimental data (upper plot) and the corresponding pulses after smoothing (lower plot). Configuration: CCA-103/19+70/15. Discharge at 14 kV, 450-Pa D₂.

can see the differences that appear at the beginning of the leading edge and the end of the trailing edge of the pulses due to neutron dispersion. Although proper TOF analysis and neutron spectroscopy were not performed because of our experimental limitations, we infer that the neutrons are not monoenergetic. The neutron emission commences at $t = 0$ (± 2 ns). The time reference $t = 0$ is taken at the instant when the plasma column reaches the minimum radius at the end of the radial compression phase. The pinch lifetime t_p is taken as the duration from $t = 0$ to the instant corresponding to the development of the $m = 0$ instability. The neutron signal consists of two pulses, one emitted around $t = 0$ and the other one at $t = t_p$, merged together due to short values of the lifetime of the pinch.

The number of neutrons emitted during the pinch lifetime was estimated by integrating the neutron signal dY_n/dt from $t = 0$ to $t = t_p$. The neutron signals from the TOF detectors were compensated for their flight path and overlapped with the hard X-ray pulses. Before the numerical integration, the neutron signals (and, eventually, the hard X-ray signal) were smoothed using high-order polynomial functions. The procedure is illustrated in Fig. 4, where only the neutron signal recorded with the first TOF detector (PM1) is shown. The hard X ray

corresponding to the first plasma compression at $t = 0$ was cut off using lead sheets in front of the detector.

The results of this procedure give values of the percentage of the neutrons emitted during the lifetime of the pinch with respect to the total yield ranging from 4 to 20% for the neutron-optimized pressure of 450-Pa deuterium.

The plot of the average total neutron yield as a function of the peak discharge current to the power 4 (I^4) as illustrated in Fig. 5 shows that the neutron scaling law $Y_n \sim I^4$ does not work properly for all the electrode configurations tested in our project. Our explanation is that the neutron production mechanism is affected by factors like force-field flow-field separation, electrode erosion, or changes in the breakdown conditions. For each electrode configuration, 80 to 120 shots were analyzed for the neutron-optimized pressure of 450 Pa.

The total neutron yield consists of two components: the nonbeam component, such as thermonuclear Y_{th} , and the beam-target component Y_{b-t} . We intended to study the effect of the increased drive parameter and, consequently, the axial speed on these yield components. In earlier experimental work^{15,17} on an identical (3-kJ) plasma focus device, the reported value of the ratio $Y_{th}:Y_{b-t}$ is of the order of 15:85. It has also been proposed^{9,14} that the thermonuclear component can be written as follows:

$$Y_{th} = CI_p^4 v_{axial}^4 \quad (1)$$

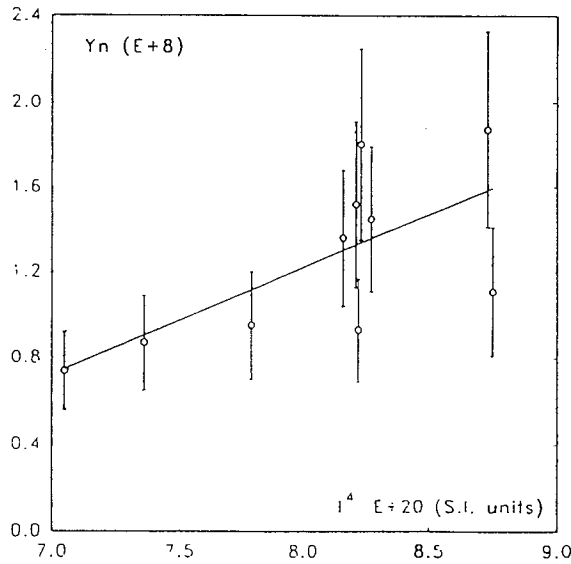


Fig. 5. Total neutron yield as a function of the peak discharge current to the power 4 (I^4). The circles represent the mean values over 80 to 120 shots, and the vertical error bars indicate the corresponding standard deviations. Discharges at 14 kV, 450-Pa D_2 .

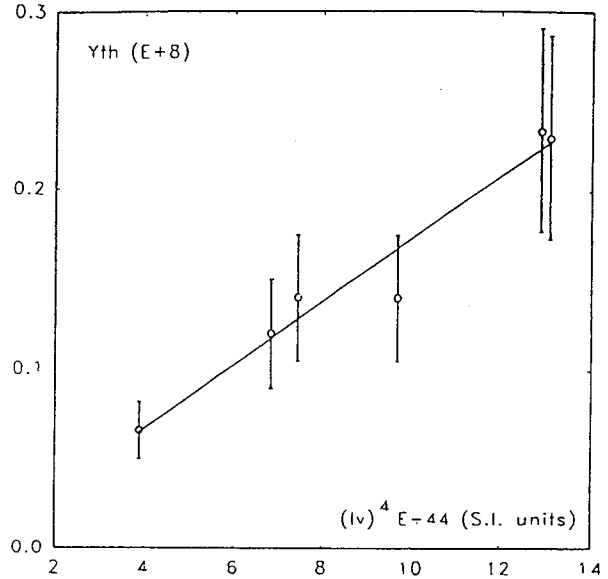


Fig. 6. The nonbeam component of the neutron yield as a function of $(Iv)^4$, where I is the peak discharge current and v is the peak axial speed. The circles represent the mean values over 80 to 120 shots, and the vertical error bars represent the corresponding standard deviation. Discharges at 14 kV, 450-Pa D_2 .

where C is a constant over the range of plasma focus devices. We used our data to investigate whether our experiments verified Eq. (1).

The results confirming that our data obtained for the neutron-optimized pressure fit Eq. (1) are illustrated in Fig. 6. The data from experiments with the OPA-185/15, CCA-45/19+140/15, and CCA-65/19+120/15 electrode configurations were excluded because either the breakdown conditions were changed (OPA-185/15) or the speed-enhanced section of the anode was too long and led to force-field flow-field separation and/or the reproducibility of the focus was very poor, thus affecting the mean value of the neutron yield.

The value of the constant C in Eq. (1) was determined using a linear regression of the data plotted in Fig. 6: $C = 1.8 \times 10^{-34}$ (SI units). Thus, Eq. (1) can be written in the following manner:

$$Y_{th} = 1.8 \times 10^{-6} I_p^4 v_{axial}^4 (\pm 30\%) \quad (2)$$

where I_p is measured in kiloamperes and v_{axial} is measured in centimetres per microsecond in the range from 7 to 14 cm/ μ s.

Thus, there is evidence within the limited range of our operation that the neutron yield of the plasma focus is enhanced by operating at higher speeds. We also have evidence that the X-ray production is also enhanced.¹⁸

The values of the drive parameter and the corresponding neutron yield at 450-Pa deuterium filling pressure are listed in Table III. Note that there are two electrode configurations, OPA-175/17.5 and CCA-103/19+70/15, which produce nearly the same neutron yield of $\sim 1.8 \times 10^8$ n/discharge. The increase of the drive parameter by 15% and of the axial speed by 17% for the CCA-103/19+70/15 geometry with respect to OPA-175/17.5 does not bring an increase in the neutron output. One possibility is that by operating the plasma focus at higher speed, the nonbeam component of the neutron yield, such as that of thermonuclear origin, is enhanced [see Eq. (1)], while the beam-target component decreases according to the following expression^{9,14}:

$$Y_{b-t} = C' I_p^{4.5} v_{axial}^{-1.5}, \quad (3)$$

where

C' = a constant

I_p = peak discharge current

v_{axial} = peak axial velocity.

A comparison of the performance of the CCA-103/19+70/15 and CCA-93/19+80/15 configurations of the same family (with a difference of 1 cm in the length of the speed-enhanced section) shows the effect of the force-field flow-field separation on the neutron output. The configuration with the longer speed-enhanced section has a slightly higher speed as expected, but the neutron yield is reduced by 16%. This could be interpreted as the result of a significant separation of the shock front from the driving magnetic piston during the axial phase. This separation is proportional to the distance traveled. When the shock front is in radial motion, the magnetic piston is still moving axially. Therefore, the radial compression is not driven, or if the separation is not too big, the effi-

ciency of the drive is very poor and leads to a low radiation yield.

The further increase of the length of the speed-enhanced section of the anode (see data for CCA-90/19+100/15 and CCA-95/19+90/14 anodes in Table III) leads to a decrease of the total neutron yield. This again is consistent with the expected effect of the force-field flow-field separation on the efficiency of the compression of the plasma column.

On the other hand, the comparison between the two high-neutron-output configurations, i.e., the OPA-175/17.5 and CCA-103/19+70/15 geometries, in terms of soft X-ray production shows that at higher speed, the soft X-ray emission is enhanced. Data analysis indicates that the plasma temperature during the pinch phase is higher. If we assume that the temperature T is proportional with the square of velocity v , $T \sim v^2$ (Refs. 9 and 16), then the temperature increases by almost 40%. This is in agreement with the earlier interpretation of an enhanced non-beam neutron emission.¹⁴

The plasma focus device can be optimized for either neutron production or soft X-ray output. The optimization procedure has to meet conflicting requirements. The increase of the drive parameter by use of a smaller-radius anode is favorable for increasing the plasma temperature and thus the nonbeam neutron component and the soft X-ray yield. At the same time, the pinch lifetime and dimensions are reduced accordingly⁷; therefore, the size of the radiation source is smaller. This effect is encouraging for practical applications of the plasma focus, e.g., as a soft X-ray source for lithography.¹⁹

CONCLUSIONS

The neutron output of our plasma focus device has a strong dependence on the gas filling pressure. The

TABLE III
Drive Parameter (I_p/a)/ $p^{1/2}$ and Neutron Yield at 450-Pa D₂

Configuration	v_{axial} (cm/ μ s)	I_p (kA)	$(I_p/a)/p^{1/2}$ [kA $\cdot$ cm ⁻¹ (Torr D ₂) ^{-1/2}]	Y_n ($\times 10^8$)
SPF-165/19	8.3	172.0	97.8	1.11
OPA-175/17.5	9.5	171.9	106.2	1.87
OPA-180/17	9.7	169.9	108.1	1.36
OPA-185/15	10.4	162.1	116.8	0.73
CCA-45/19+140/15	10.5	164.7	118.7	0.87
CCA-65/19+120/15	10.6	167.1	120.5	0.95
CCA-103/19+70/15	11.2	169.4	122.1	1.80
CCA-93/19+80/15	11.3	169.5	122.2	1.50
CCA-90/19+100/15		169.6	122.3	1.45
CCA-95/19+90/14	11.4	169.4	130.8	0.95

neutron-optimized pressure at 14 kV is 450 Pa, regardless of the electrode geometry. The neutron emission begins at the end of the compression phase, when the plasma reaches its minimum radius.

Peak axial sheath velocities up to 15 cm/ μ s were achieved.²⁰ The radiation output, i.e., both neutron and soft X-ray productions, was found to depend on sheath velocity. Above a certain value of the peak axial speed and a certain length of the speed-enhanced section of the anode, the focusing characteristics and reproducibility were affected. We concluded that the speed-enhanced section has to be long enough to increase the speed but short enough to avoid the separation between the shock front and the magnetic piston.

Correlations of the neutron production and soft X-ray emission indicate that higher speeds enhanced the temperature of the focus. The nonbeam component of the neutron flux taken to be of thermonuclear origin was correlated with the peak discharge current and peak axial speed. Based on our experimental results within our limited range of operations, the scaling law $Y_{th} \sim (I_p v_{axial})^4$ for the nonbeam neutron component was proposed. However, this scaling law has to be compared with results from other plasma focus devices operating with a broader range of energies.

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ARGON ION INDUCED CHANGES ON ANTIMONY TELLURIDE THIN FILMS USING DENSE PLASMA FOCUS DEVICE

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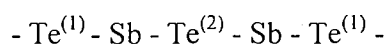
Abstract

The Dense Plasma Focus (DPF) has been established as an intense source of fusion neutrons, x-rays, electrons and energetic ions with several hundred *keV* and above. This paper reports a first time use of the highly energetic, pulsed argon ion beam (from the 3.3kJ/15kV UNU/ICTP PFF), for increasing crystallization in Antimony Telluride (Sb_2Te_3) films. The thin films (0.41 μm thick) were deposited, at University of Delhi, on glass substrates using thermal evaporation technique. The samples were placed downstream of the anode using an axially movable sample holder to vary the exposure distance and hence to vary the ion fluence. A combination of two apertures of diameter 3mm and 4mm, separated by a distance of 1.0cm, were placed at 2.0cm beyond the anode to attenuate blast wave effects. The exposed samples were then analysed using X-ray Diffractometer, Scanning Electron Microscope, Atomic Force Microscope, X-ray Photoelectron Spectrometer, as well as Visible Ultra-violet Spectrometer. The XRD studies revealed an increase in the crystallization of Sb_2Te_3 crystals for films placed at further distances from the anode. For films exposed closer to the anode, other antimony telluride crystals were also found to be induced. AFM and SEM studies indicate that the surface of the films which were exposed at greater distances were reasonably smooth. Initial studies using the XPS also indicate a potential use of DPF for increasing bonds in materials.

1. Introduction

The dense plasma focus (DPF) has not only been established as a source of fusion neutrons and x-rays, but also a source of high fluence, energetic ions of several hundred keV. Various works by the University of Delhi have shown the potential use of argon ions from the DPF for material processing since 1993¹⁻⁴. This is the first time where a DPF, other than the one used in University of Delhi, has been used for the processing of materials. It also reports a first time application of the DPF plasma ions to the crystallization of antimony telluride.

Antimony telluride (Sb_2Te_3) has a melting point of 631°C and a vapour pressure of 1 torr at its melting point. Sb_2Te_3 has a rhombohedral structure but is commonly represented by a hexagonal cell. The hexagonal cell is formed by stacking layers, perpendicular to the c-axis, of like atoms following the sequence:



This sequence is known as a quintet and the hexagonal cell is formed by three quintets. The $\text{Te}^{(1)}-\text{Te}^{(1)}$ bonds are considered to be of Van der Waals type^{5, 6}, while the $\text{Te}^{(1)}-\text{Sb}$ and $\text{Sb}-\text{Te}^{(2)}$ are of the ionic covalent type. Crystalline antimony telluride has been a subject of interest owing to its property as a thermoelectric material and its potential application as a phase change optical recording material.

The performance of a thermoelectric device is related to the figure-of-merit (ZT) of the material. To date, the best ZT at 300K is about 1.0 for p-type $\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3$ alloys and about 0.9 for n-type $\text{Bi}_2\text{Te}_{2.85}\text{Se}_{0.15}$ alloys⁷ and have remained close to unity since the 1960's. This has limited the development of large-scale, solid-state cooling applications. However, a recent study by Venkatasubramanian et. al.⁸ has shown that

superlattice structures of Bi_2Te_3 and Sb_2Te_3 , formed by MOCVD (metalorganic chemical vapour deposition) of alternating layers of Bi_2Te_3 and Sb_2Te_3 films, could have an improved ZT of 2.0 at 300K.

Various literature^{9, 10} have also indicated the possible use of Sb_2Te_3 as a practical, erasable recording media. To achieve reliable disk performances in mass-produced optical disk, the alloy composition must be precisely controlled, hence, the wide composition margin for the single phase Sb_2Te_3 may contribute to good rewritability, making Sb_2Te_3 a promising material for the production of recording media. The reversibility in the change in phase has been reported to be 10^3 to 10^5 cycles. The moderate melting point of Sb_2Te_3 may also contribute to its good rewritability, because the amorphization does not require high power, thus avoiding irreversible deformation in protective layers. The optical characteristics of Sb_2Te_3 films have been reported to change due to an amorphous crystalline phase transition at a temperature lower than 200 °C, with a corresponding change in reflectivity from 45% to 65% by laser radiation¹⁰ ($\lambda = 8000\text{\AA}$). Sb_2Te_3 films have also been found to exhibit room temperature stability as well as long data retention time of more than 10 years while having a short erasure time of less than $1\mu\text{s}$.

Various techniques such as r.f. sputtering⁹ and thermal evaporation¹⁰⁻¹², have been reported for deposition of antimony telluride films on different substrates, but the deposited films are usually amorphous in structure. Post-deposition annealing has been found to improve the crystallinity of the films. However, it is also reported that the films would dissociate if the annealing time is long¹¹, indicating a possible potential use of the

DPF for the post treatment of deposited Sb_2Te_3 films, since heat treatment of the films may be carried out in a very short time at an intense temperature.

2. Experiment

2.1 Preparation of the Sb_2Te_3 films

The thin films of antimony telluride were prepared by vacuum evaporation process using Hind Hivac Vacuum Coating 12A4 at the University of Delhi. 99.9% pure Sb_2Te_3 were ground to approximately 1mm in size and evaporated onto ordinary glass microslides in a vacuum chamber at a pressure of the order of micro torr. All the films were grown at room temperature with a distance of 15cm between the source and the substrate.

The chemical and physical condition of the films depends on the cleanliness of the substrates. Therefore, before deposition, the glass substrates were cleaned in chromic acid for 24 hours, washed with soap solution, then in distilled water and then dried with a hot blower before placing in the vacuum chamber for deposition.

2.2 Post-Deposition Processing with Argon Ions

The DPF device at the Nanyang Technological University/National Institute of Education is a 3.3kJ/15kV Mather type focus¹³ powered by a 30 μF , 15kV fast discharging energy storage capacitor. It is part of an international network of 3.3kJ plasma focus, designated as the UNU/ICTP PFF¹⁴. When the capacitor voltage is applied across the electrodes(see figure 1), an azimuthally symmetric electric discharge will be initiated across the surface of the insulator between the anode and cathode. This current is then lifted off in an inverse pinch manner, and when the conductance of the

current is high enough, the discharge converts into a plasma sheath, which is a double layer structure consisting of the ionization front and magnetic piston¹⁵⁻¹⁷. This plasma sheath is then pushed by the self-generated $\vec{J} \times \vec{B}$ force against the stationary ambient gas to a supersonic speed. This current sheath accelerates down the tube and scoops up the gas it encounters. As it reaches the end of the anode, the current sheath sweeps around the anode and collapses radially inwards with an azimuthal symmetry and a non-cylindrical funnel-shaped profile. When the plasma column collapses close to the minimum radius, the magnetic field starts diffusing into the plasma column. The eventual complete diffusion will lead to an anomalous high plasma resistance. At the same time the inductance of the system increases inducing an electric field in the plasma column. This induced electric field is further locally enhanced by the growing $m=0$ instabilities which finally leads to the acceleration of the electrons towards the anode and the ions in the opposite direction.

Generally the total ion flux from the DPF has been estimated to be between 10^{12} , for a small plasma focus device, to 10^{15} for bigger machines. The argon ions in the 3.3kJ DPF have been reported to have an energy range of 25keV to 8MeV . They are emitted in pulses of approximately 8-10ns (FWHM) in pulse length, with a wide solid angle of 60° . For higher intensity shots, approximately one-half of the ion intensity would be inside a cone of half angle 7° .^{18,19}

In the experiments, the antimony telluride films are each exposed to a single shot of argon ion beam from the DPF at different distances from the anode (z cm). Fig. 1 depicts the schematic experimental setup in this study. A charging voltage of 14kV is used with an argon gas filling pressure of 1mbar.

This setup is essentially the same as the one used at the University of Delhi but improved by the use of the double aperture. It was found, prior to the experiment, that upon exposure of some glass substrates to the plasma in the DPF, surface cracks as well as copper deposition could be seen on the substrates. These cracks are suspected to have been caused by the plasma shockwave, while the copper deposition is believed to be from the copper jet which originates from the copper anode used¹⁹. With the introduction of a single aperture, surface cracking of glass no longer occurred and the copper deposition was greatly reduced. However, spreading of the copper jet after it emerges from the aperture was observed. Hence, the double aperture was used to attenuate the shockwave, as well as further reduce the amount of copper coming onto the surface of the substrate.

The double aperture is mounted between the anode and the target sample. The first aperture, is 3 *mm* in diameter. The second aperture 1cm away is 4 *mm* in diameter. For this study, the position of the double aperture was fixed at a distance of 2cm from the anode. The anode radius is 1cm and in an earlier study¹⁹ it was found that any obstacle placed above the central anode will not affect the DPF dynamics and focusing action if its distance from the end of the anode is not less than the radius of the anode.

An Aluminium shutter is used to avoid unnecessarily exposing the samples to weak ion beams which are produced while optimising the DPF for good focusing.. Generally, good focusing is obtained by the third shot after a fresh filling of argon. The aluminium shutter is then opened, and the sample is exposed to the next shot. After exposure, the chamber is then filled with air and opened to replace a new sample.

Both the exposed and unexposed were then analysed with the XRD, SEM, AFM and XPS.

3. Results

3.1 Adhesion of the films

The Sb_2Te_3 films adhered well to the glass substrates, even after irradiation with the argon ions from the DPF. Prior to this study, C-N films, Sb_2S_3 films ($1.4\mu\text{m}$ in thickness) and Fe_2O_3 films ($1.05\mu\text{m}$ in thickness) deposited on glass substrates were also exposed to argon ions from the DPF. However, upon exposure, it was found that these films buckled and flaked off from the glass. The buckling and flaking of the various films on the glass substrates are believed to be due to excessive compressive stress caused by the intense heat treatment and bombardment by the argon ions on the films. Therefore, stress plays an important factor in determining whether a film is suitable for processing by plasma focus machine.

3.2 Thickness of the films

The thickness of the unexposed films were measured by scanning the edge with a Daktak IIA surface profilometer and found to be $0.41\mu\text{m}$.

The Carl Zeiss Ultraobjective Atomic Force Microscope was used to analyse the thickness of the film which was irradiated at a distance of $z = 5.0\text{cm}$ from the anode by making a scratch at the centre of the film and scanning over the scratch. The one-dimensional plot of the surface profile scanned over the scratch is shown in Fig. 2.

After irradiation, the thickness of the films had decreased to approximately $0.2\mu m$.

3.3 Surface morphology of the films

The surface morphologies of the films were examined both with the SEM and AFM. Fig. 3 depicts the SEM micrographs of the films and Fig. 4 gives the three-dimensional surface profiles together with the corresponding one-dimensional surface profiles of the films.

The SEM micrographs reveals the uneven surfaces of the films which were irradiated with the argon ions, with the exception of the film placed at $z = 10.7cm$ which resembled that of the unexposed film. The significant change in the surface morphology indicates that the surface nucleations are greatly dependent on the temperatures of the films. The micrographs of the films placed at $z = 9.5cm$ and $z = 4.5cm$ reveal islands of crystal grains. Droplet structures were also observed on the films which were place at $z = 5.0cm$ and $z = 7.0cm$, with the $z = 5.0cm$ film having more network structures between the droplets. These droplets can be formed during recrystallisation by the coalescence of the film. Some of the droplets could also be argon bubbles that form when the argon ions, which are embedded in the films, try to escape from the film. The argon ions could also act as nucleation centres for the film.

Further measurements made with the AFM provided a quantitative analysis to the surface morphology of the films. From the estimated differences in heights between the "peaks" and "troughs" of the film (Table 1), it could be seen that the irradiated films were much rougher than the unexposed film. Films that were irradiated at a closer distance to the anode were also rougher than those that are exposed at further distances

from the anode as they were subjected to more energetic and a higher fluence of argon ions, resulting in the rougher surfaces observed.

Table 1: Estimated variations in the heights from the 1-D plots of surface profile

<i>Distance of exposure from the anode, z (cm)</i>	<i>Estimated variation (nm)</i>
Unexposed	~ 2 to 7
5.0	~ 60 to 500
7.0	~ 10 to 450
8.0	~ 15 to 150
8.5	~ 10 to 120
10.7	~ 2 to 50

3.4 XRD Results

The XRD spectra of the films were analysed using a Philips X'Pert X-ray Diffractometer system with $\text{CuK}\alpha$ radiation in a continuous mode with a scanning step of 0.05° per step and a scanning rate of 3s per step. The spectra of the unexposed films and the ion irradiated films at $z = 4.5\text{cm}$, 5.0cm , 6.5cm , 7.0cm , 8.5cm , 9.0cm , and 10.7cm are illustrated in Fig. 5. The results from the analysis of the XRD spectra are shown in Table 2.

Table 2: XRD Peaks

<i>Peak Label</i>	<i>Peak Position</i>			
	<i>2θ(°)</i>	<i>d-spacing(nm)</i>	<i>Compound</i>	<i>Hkl</i>
A	23.3	3.82	Te	1 0 0
B	28.2	3.16	Sb ₂ Te ₃	0 1 5
E	38.6	2.33	Te	1 0 2
F	38.1	2.36	Sb _{0.405} Te _{0.595}	1 0 <u>10</u>
G	40.8	2.22	Te	1 1 0
H	42.6	2.12	Sb ₂ Te ₃	1 1 0
I	44.6	2.03	Sb _{0.405} Te _{0.595}	0 0 <u>15</u>

The XRD spectra indicate that both the unexposed films and films that were irradiated with the ion beams contained crystals of Sb₂Te₃. However, films that were exposed to the argon ions at distances $z = 10.7\text{cm}$ and $z = 10\text{cm}$ showed increased crystallinity when compared with the unexposed films, as indicated by the larger intensities peaks at $d = 3.16$ ($2\theta = 28.2^\circ$) and $d = 2.12$ ($2\theta = 42.6^\circ$). When the films are placed closer to the anode, the crystallization of the Sb₂Te₃ crystals began to decrease while Sb_{0.405}Te_{0.595} crystals began to appear. Maximum crystallization of the Sb_{0.405}Te_{0.595} was attained for the film which was exposed at $z = 5.0\text{cm}$.

3.5 XPS Results

To investigate the elemental composition of the films, XPS scans on the films were conducted as well. The scans on the films were conducted in an UHV (Ultra High

Vacuum) chamber at a pressure of 10^{-9} mbar using the MgK_{α} anode at a take off angle of 75° operating at 120W. An initial wide scan was taken for each film, after which the individual scans corresponding to the C1s, Te3d, Sb3d, O1s regions were then taken. The curves were fitted to locate the peaks and the positions of the peaks were then corrected using the adventitious carbon (C1s) peaks. Results and analysis of the scans done on the various films are shown in Table 3.

Table 3: XPS Results of the Various Regions Analysed**Region: Te3d (Te3d_{5/2}, Bonded Tellurium)**

<i>z(cm)</i>	<i>Position(eV)</i>	<i>Intensity(arb. units)</i>	<i>Area</i>
5.0	576.1	3 927	804
7.0	576.2	10 505	2 092
10.7	576.4	3 001	690
Unexposed	576.1	6 879	1 429

Region : Te3d (Te3d_{5/2}, Pure elemental tellurium)

<i>z(cm)</i>	<i>Position(eV)</i>	<i>Intensity(arb. units)</i>	<i>Area</i>
5.0	572.9	419	58
7.0	573.1	1 030	155
10.7	573.0	408	88
Unexposed	572.8	2131	405

Region : Sb3d, O1s. (Sb 3d_{3/2})

<i>z(cm)</i>	<i>Position(eV)</i>	<i>Intensity(arb. units)</i>	<i>Area</i>
5.0	539.8	811	165
7.0	539.8	2270	390
10.7	539.7	2953	598
Unexposed	539.6	7466	1240

Region : Sb3d, O1s. (Sb 3d_{5/2})

<i>Distance of exposure, z(cm)</i>	<i>Position(eV)</i>	<i>Intensity(arb. units)</i>	<i>Area</i>
5.0	530.4	1587	349
7.0	530.4	6444	1241
10.7	530.4	6280	1338
Unexposed	530.1	11 942	2101

From the XPS spectra, it was observed that both unbonded elemental tellurium as well as bonded tellurium were present in all the films, though only bonded antimony seemed to be present in the films. Films exposed closer to the anode generally had smaller intensity peaks for antimony and tellurium, as sputtering effects become significant when the films are subjected to more energetic and greater fluence of ions

when they are placed closer to the anode. However the intensities of the tellurium peaks were actually larger than that of the unexposed sample, even though there was no extraneous source of tellurium in the experiment. This seemingly contradictory phenomenon may be easily resolved by the following explanation. Recall that the surface of the film exposed at $z = 7.0\text{cm}$ was much rougher when compared with the rest of the films. Hence the photoelectron emission is greater than normal as the spikes and thin edges on the rougher films provide a greater area for the photoelectrons to escape.

Both bonded tellurium and bonded antimony were observed in the films. The slight shifts of both the tellurium peaks to the right indicated the possibility of oxides occurring in the films. The incomplete shifts in the peaks also indicated the elements were only partial bonded to oxygen.

4. Discussion

When the high-energy argon ions are directed onto the surface of the films, various effects including ionization, sputtering as well as displacement of target material could occur. Because of the high energy of the ions, they could also become embedded at a depth before coming to rest (implantation). In the process, they may displace target atoms from their normal lattice sites, ionise atoms or break bonds. The deposited energy and thermal spike effect generates an annealing process, similar to dynamic recrystallisation. The high energy treatment would also cause surface melting of the films, allowing for recrystallisation and other microstructural changes to occur when the film cool down and solidifies. Furthermore, when the energy and fluence of the argon ions approach a critical value, increased crystallisation occurs.

5. Conclusions

This is the first time that material modification has been made with a DPF other than at the University of Delhi. It is also the first time that modification of antimony telluride films has been carried out by argon ions from the DPF. The introduction of the double aperture has not only reduced the damages done to the films but has also limited the amount of copper that is deposited on the samples.

Various conclusions can be made from the studies of the films:

- (a) Stress, especially thermal stress seemed to play a deciding role in determining the suitability of the films to be processed by the DPF, since the films are subjected to very high thermal treatment.
- (b) By varying the ion energy density and ion flux, it was possible to increase the crystallinity of Sb_2Te_3 crystals in the films as well as induced $\text{Sb}_{0.405}\text{Te}_{0.595}$.
- (c) Relative smooth and undamaged films with improved crystallinity were also obtained by exposing the films at relatively large distances from the anode.

To refine the above results, further studies can be conducted. There is also a need to further examine at the atomic levels the various interactions of the argon ions and the target films which causes recrystallisation and bonding.

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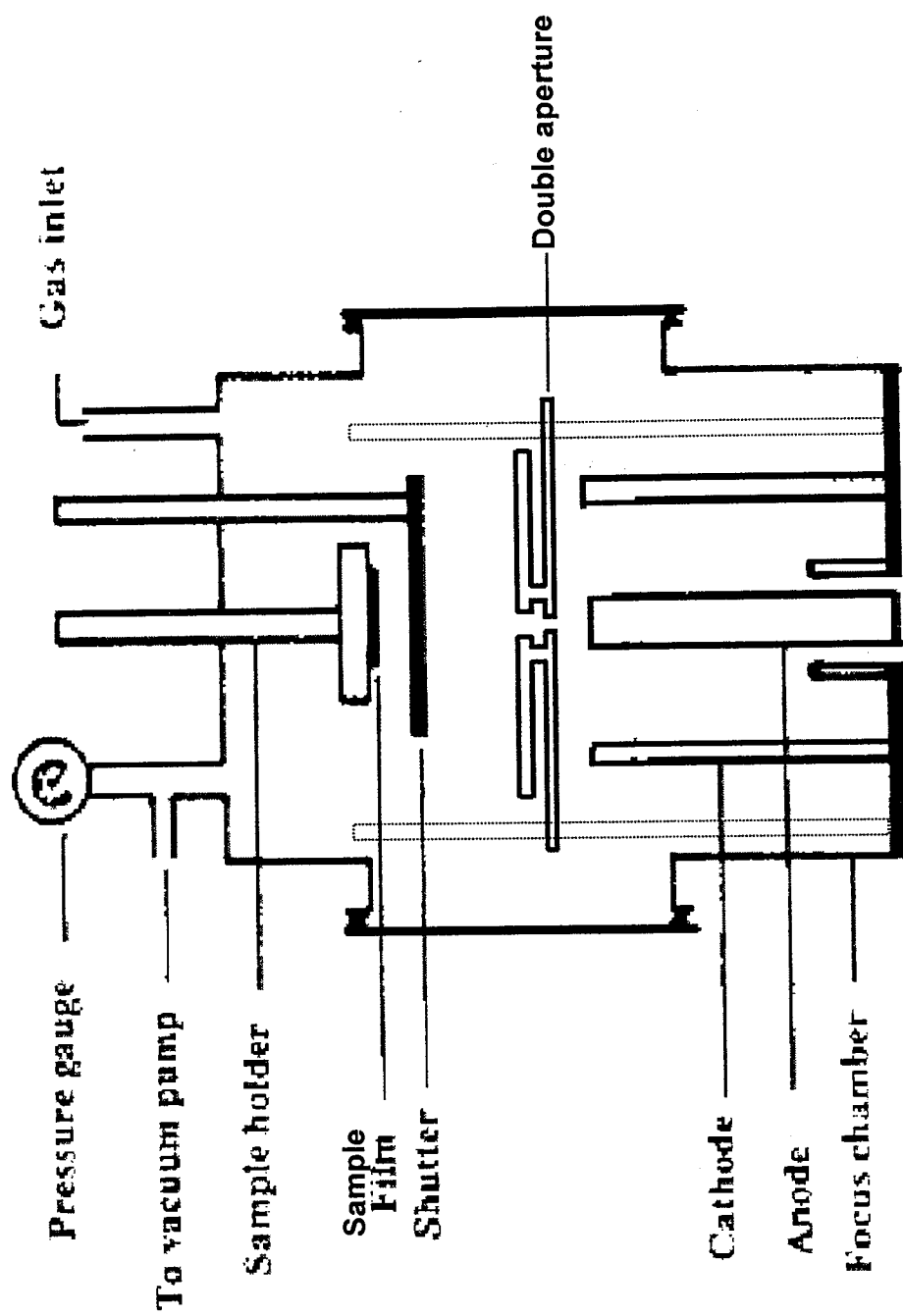


Fig. 1
Experimental Setup

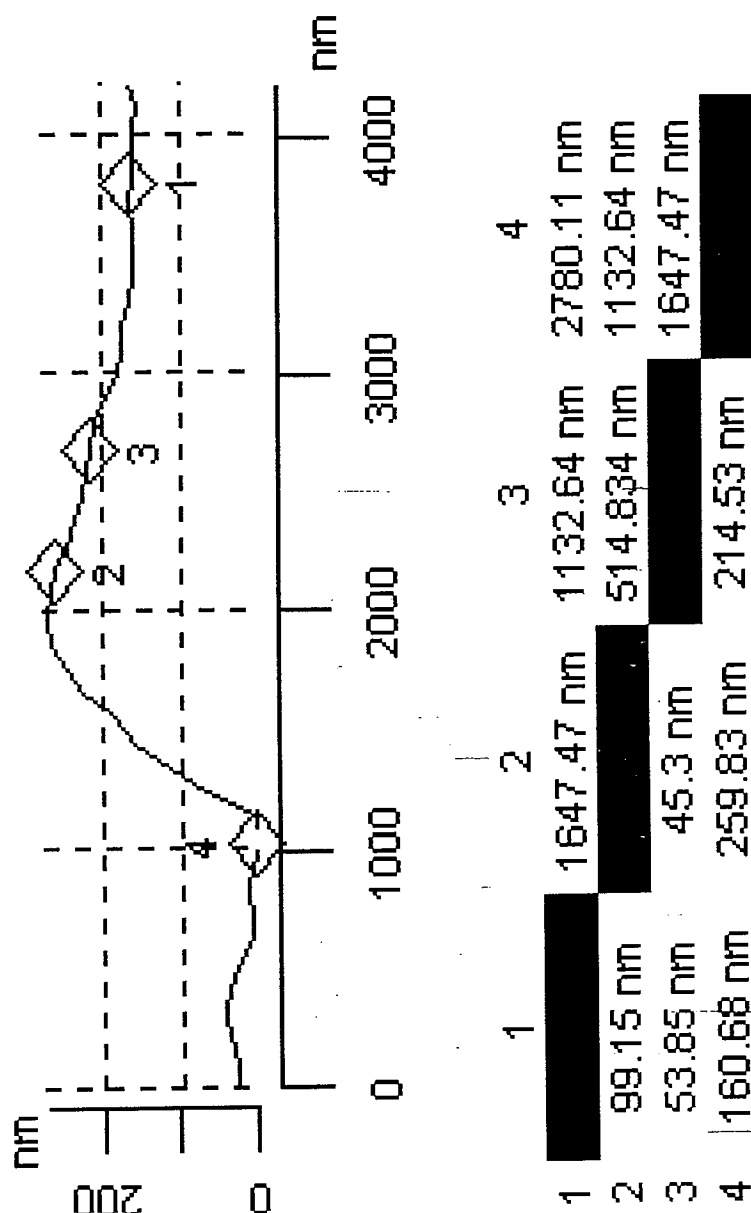
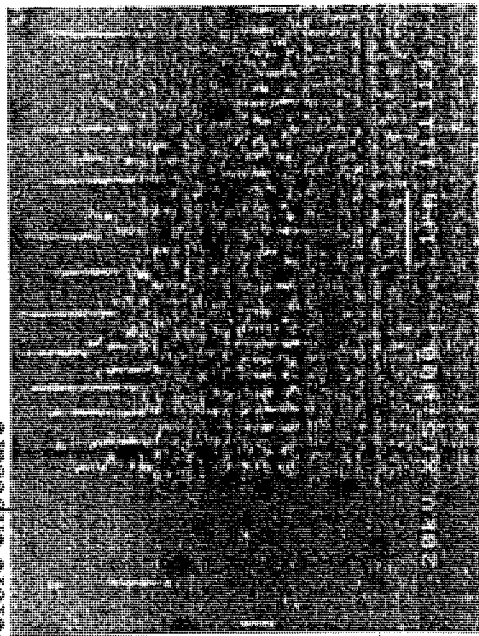


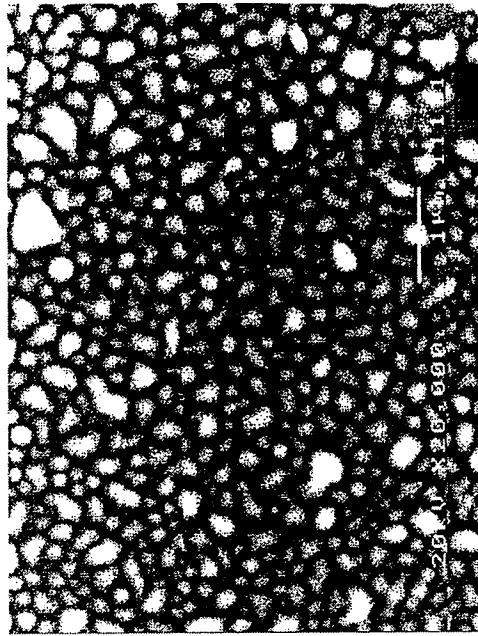
Fig. 2

One dimensional plot of the surface profile scanned over the scratch made on the film exposed at $z = 5.0\text{cm}$

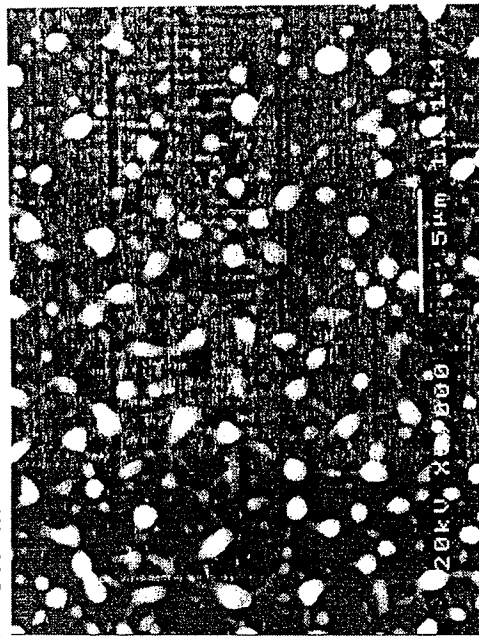
(a) before exposure



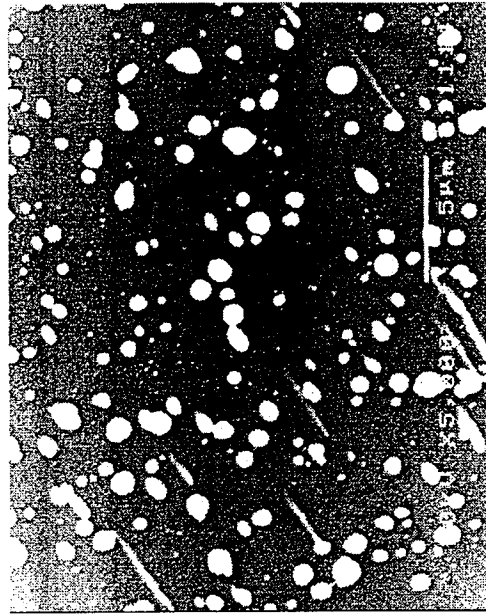
(b) $z = 4.5\text{cm}$



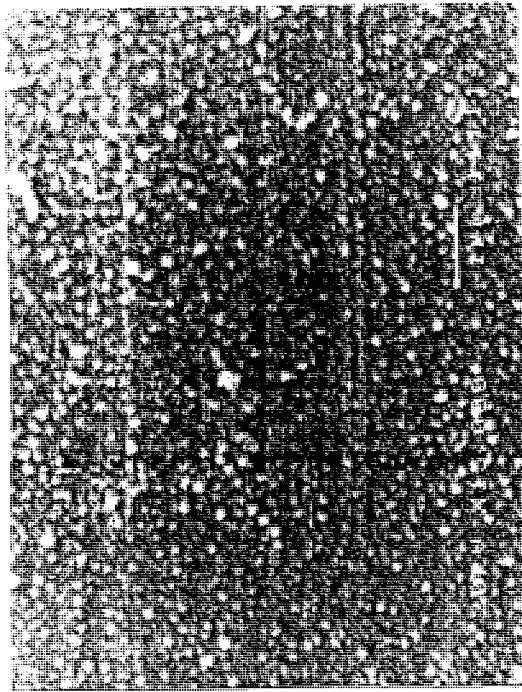
(c) $z = 5.0\text{cm}$



(d) $z = 7.0\text{cm}$



(e) $z=9.5\text{cm}$



(f) $z=10.7\text{cm}$

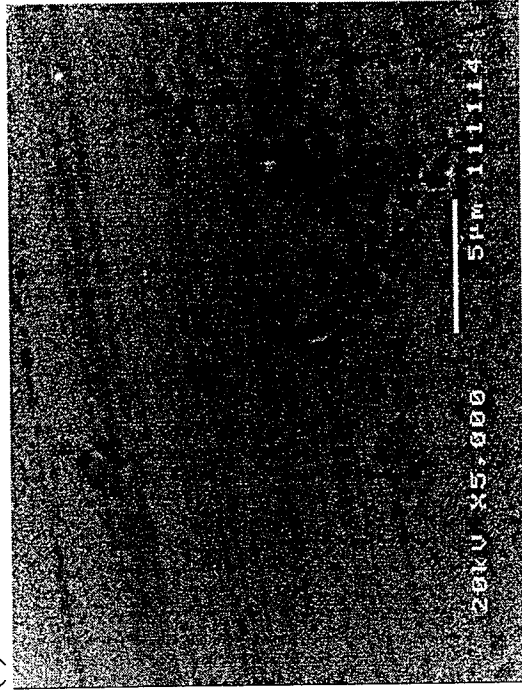
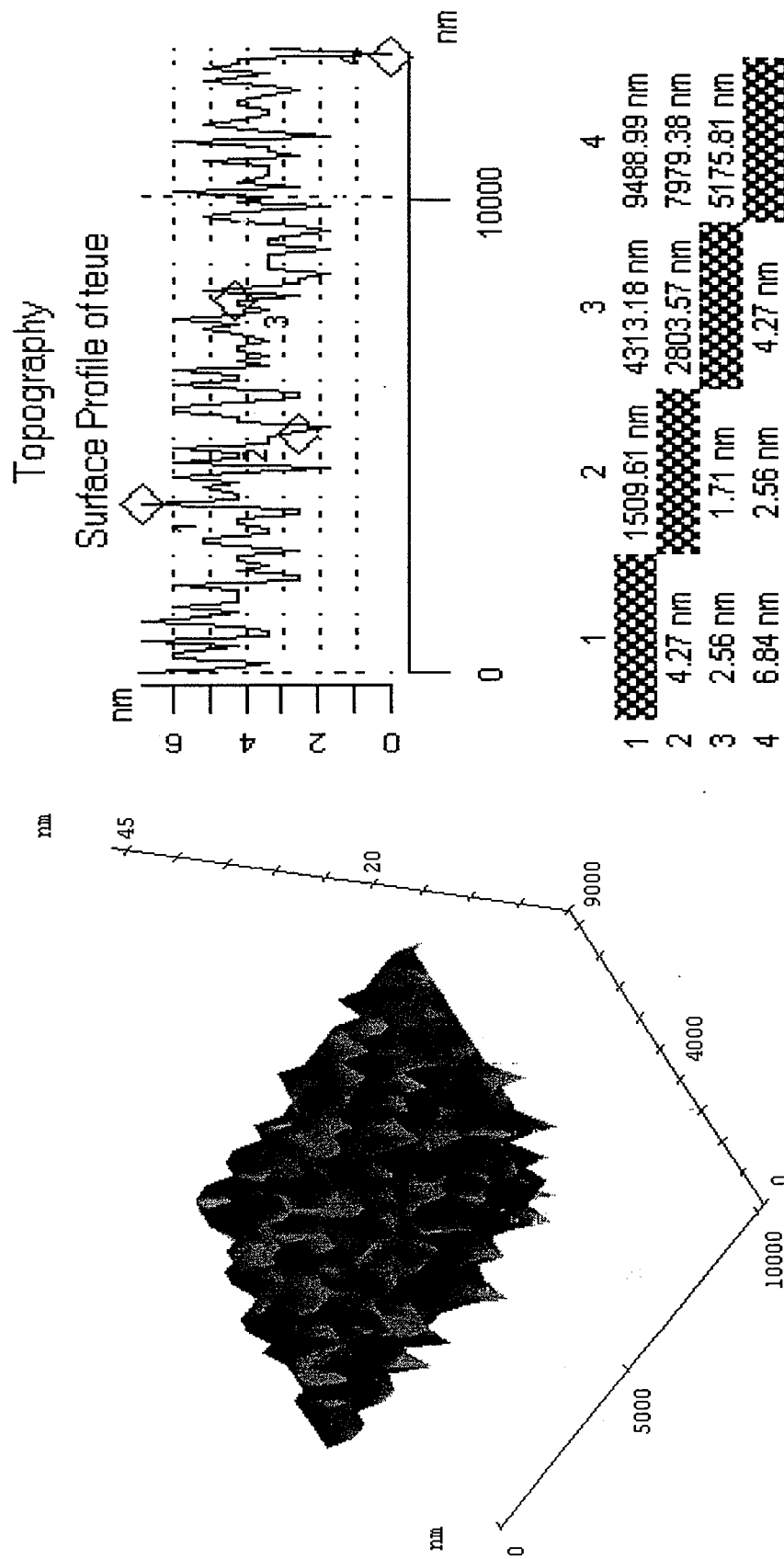


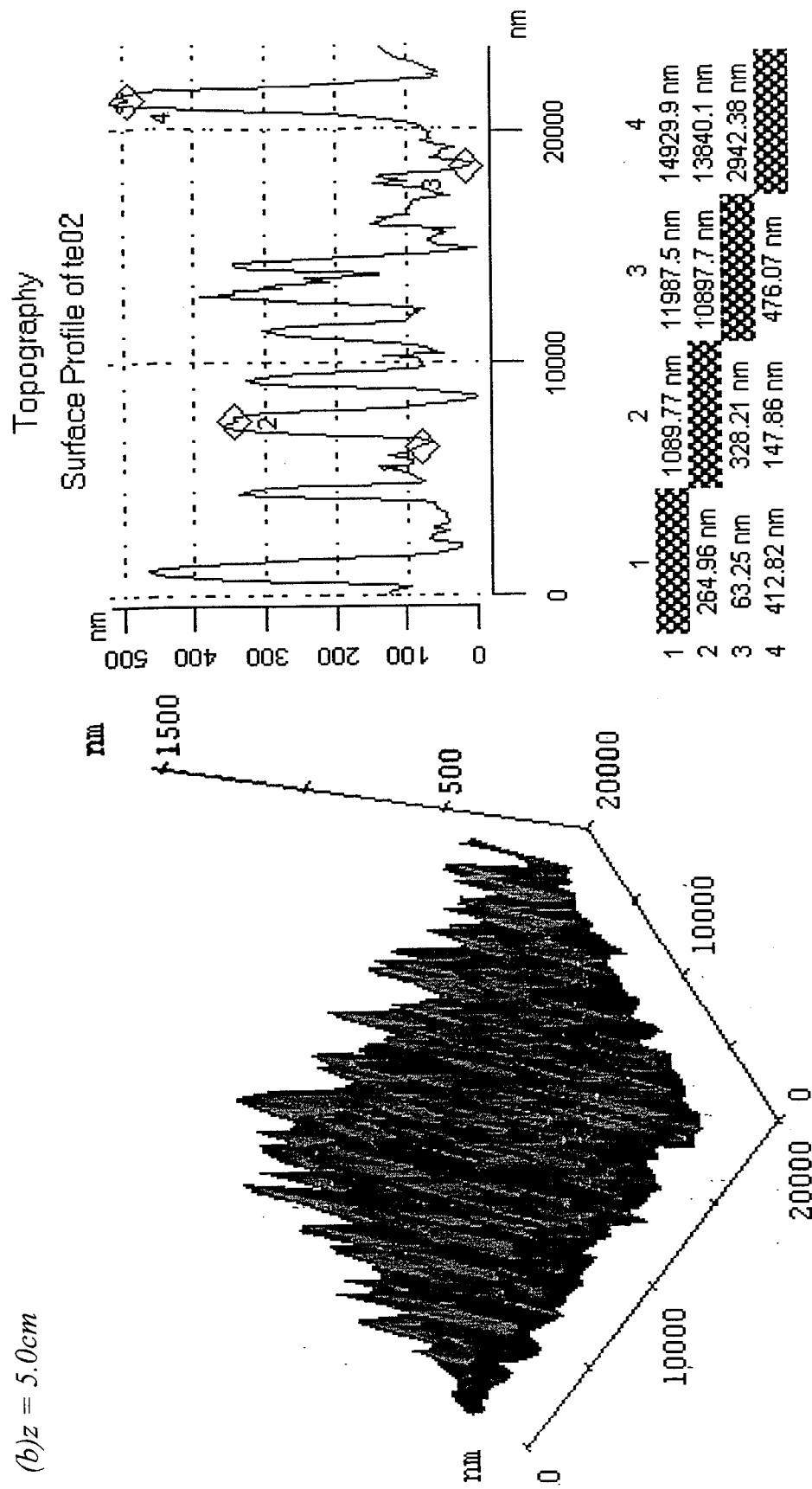
Fig. 3 (a) to (f)
SEM micrographs of Sb_2Te_3 films on glass substrate

Plots of Surface Profile (To determine the smoothness of the films)

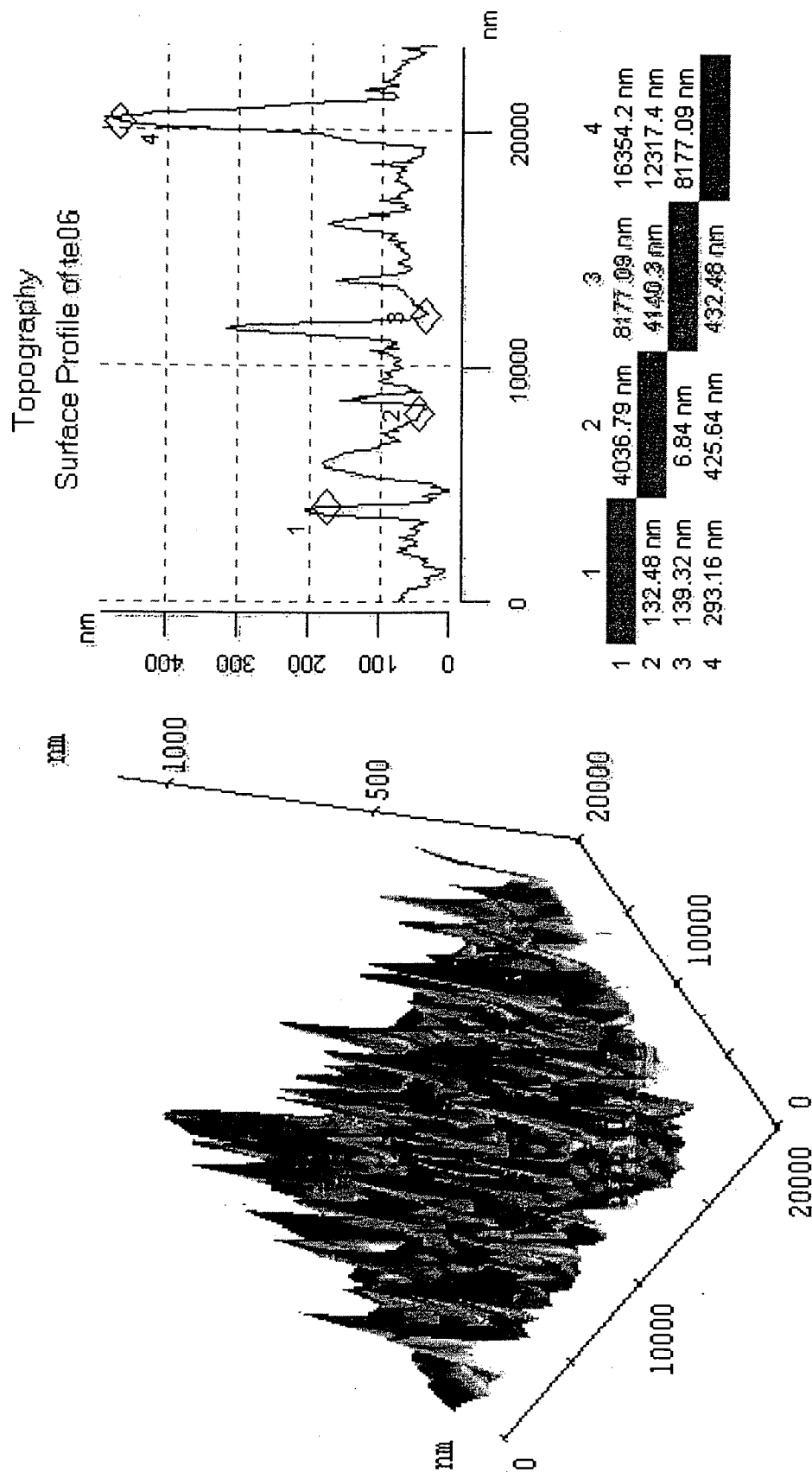
(a) unexposed film



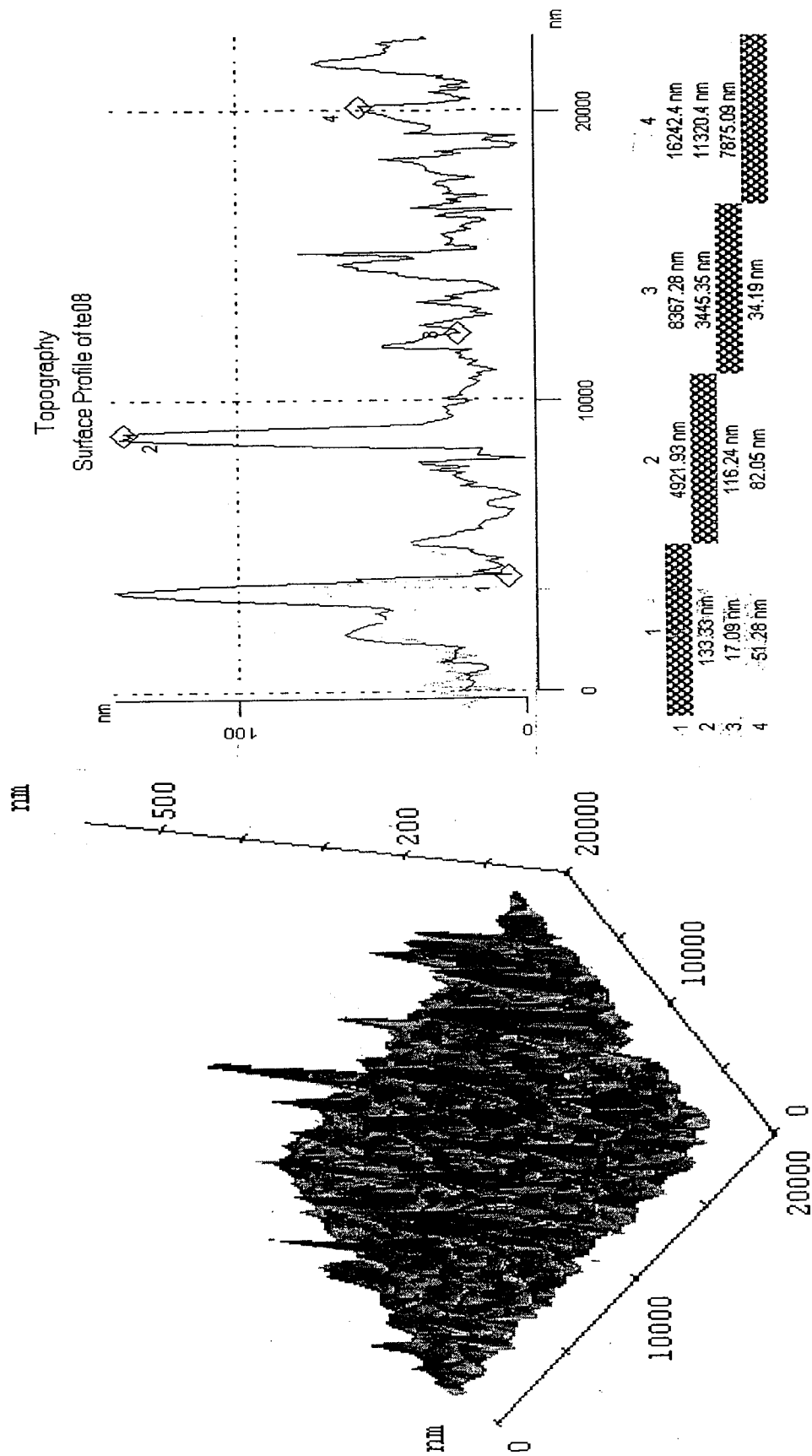
(b) $z = 5.0\text{cm}$



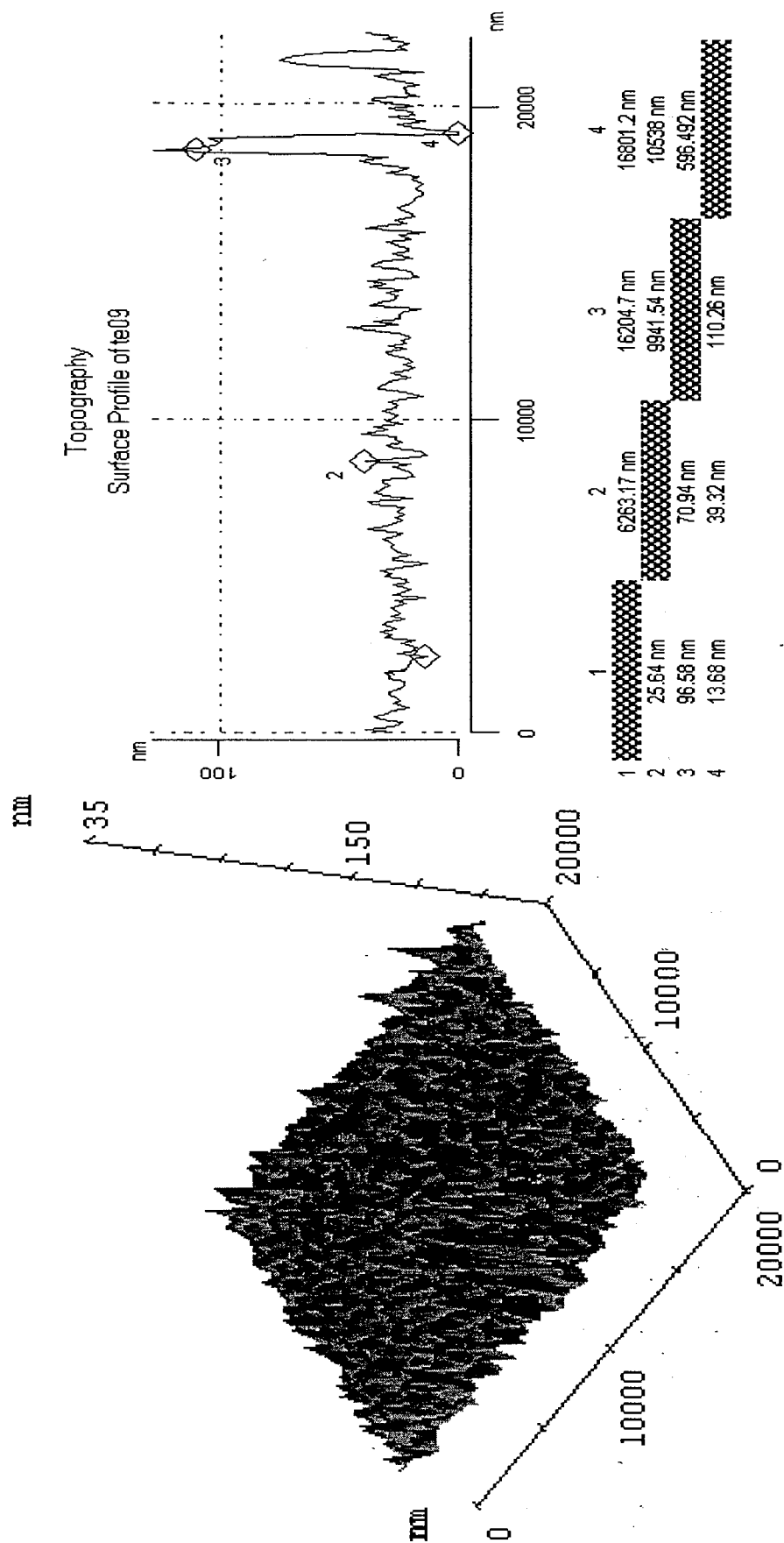
(c) $z = 7.0 \text{ cm}$



(d) $z = 8.0\text{cm}$



(e) $z = 8.5\text{cm}$



(f) $z = 10.7\text{cm}$

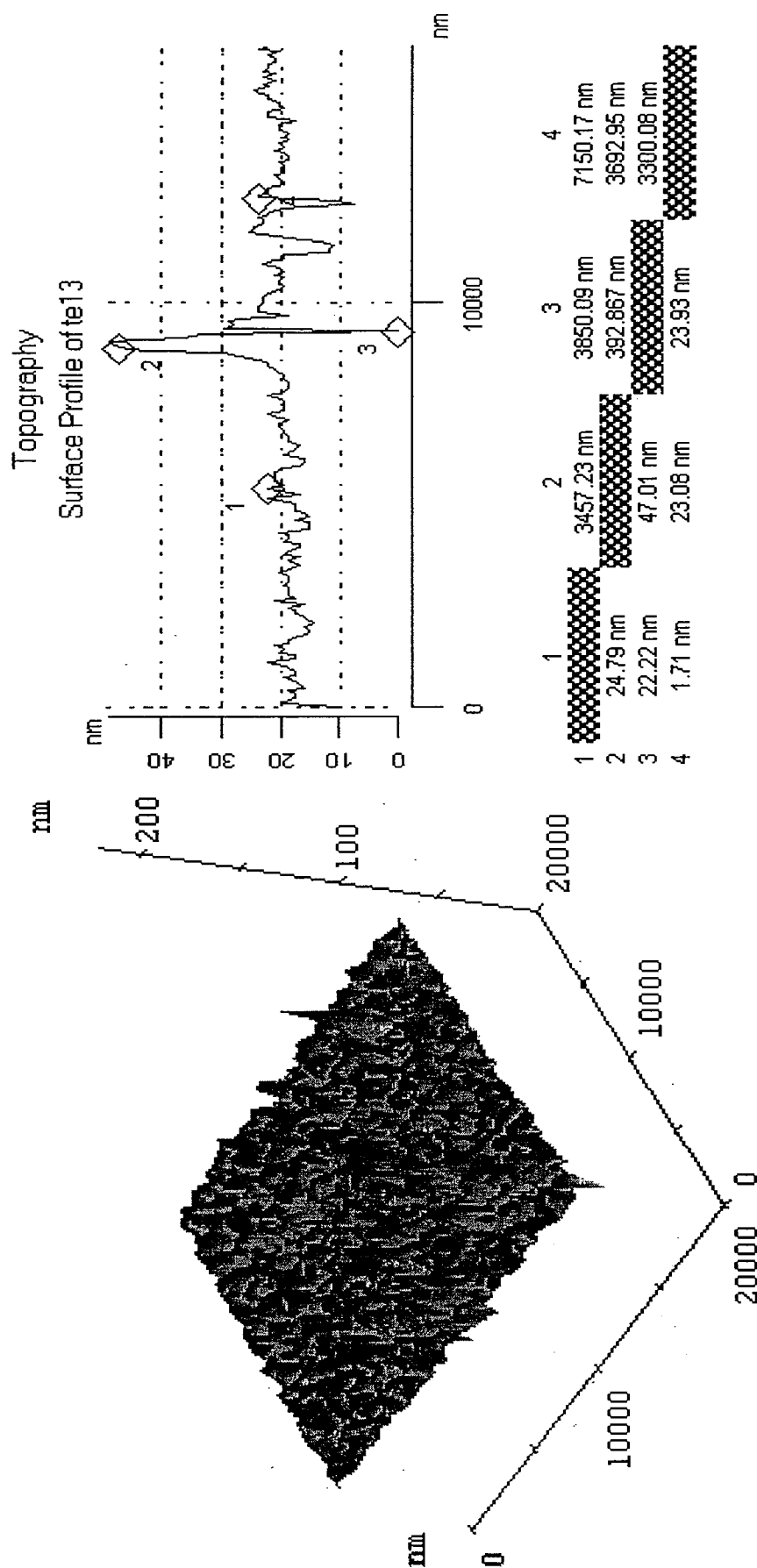
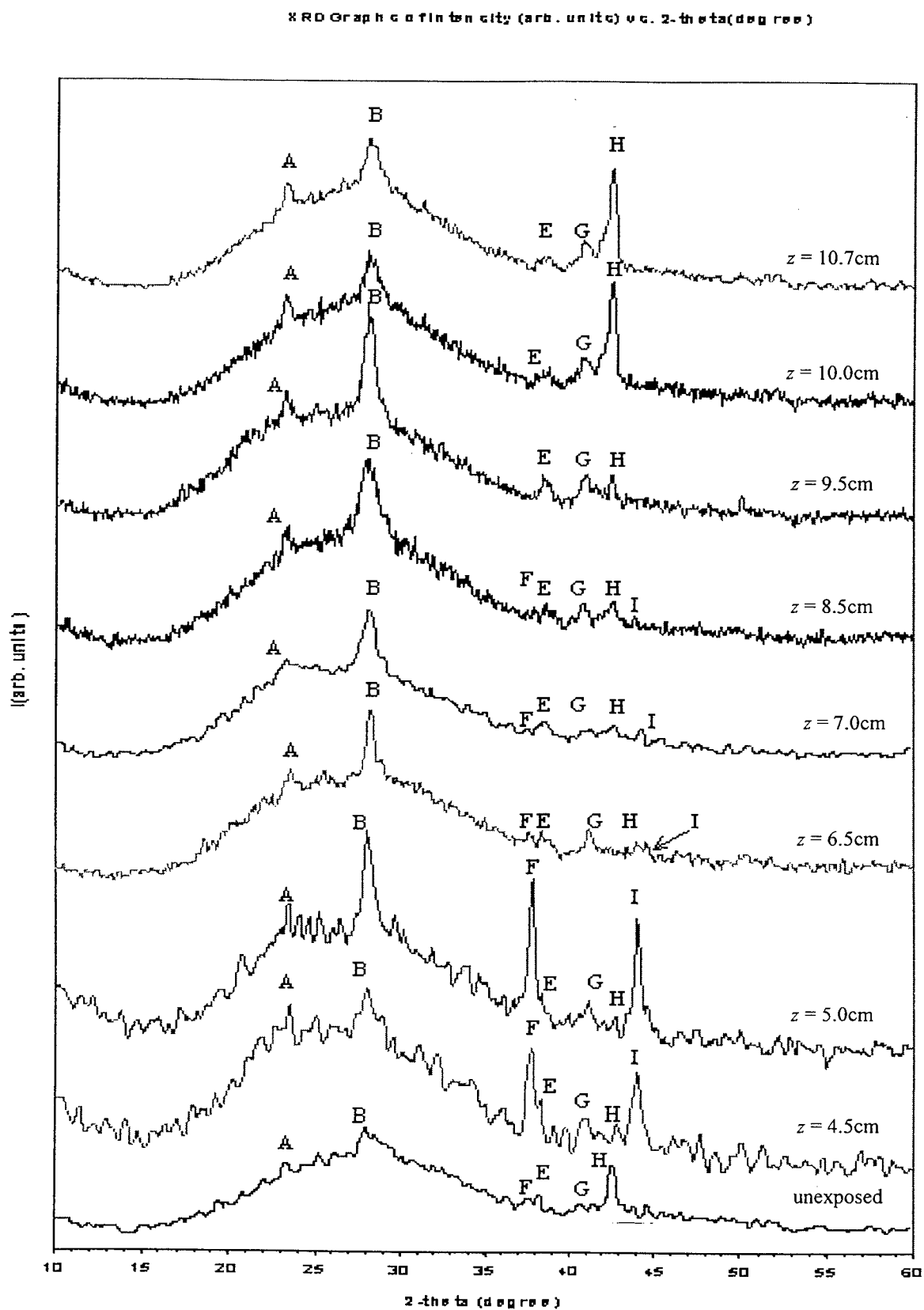


Fig. 4
AFM Surface profile plots of the various films

Fig 5:XRD Spectra





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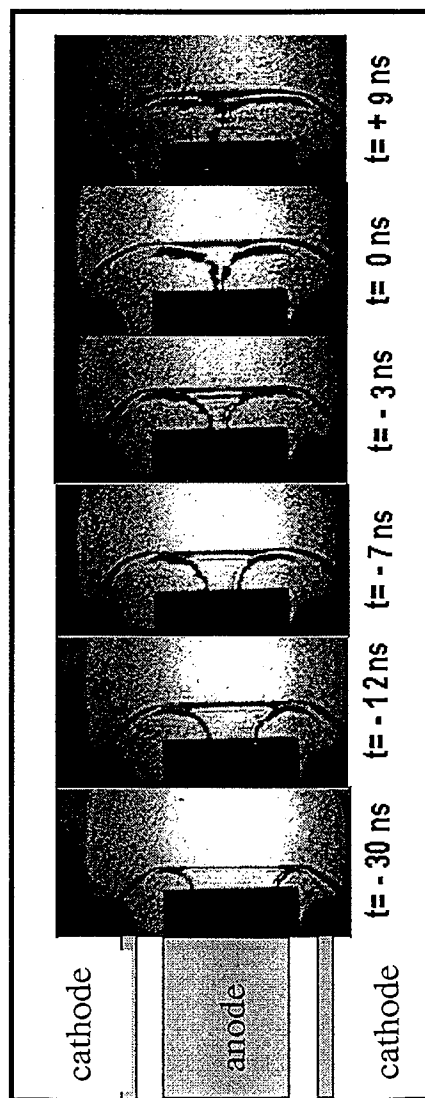
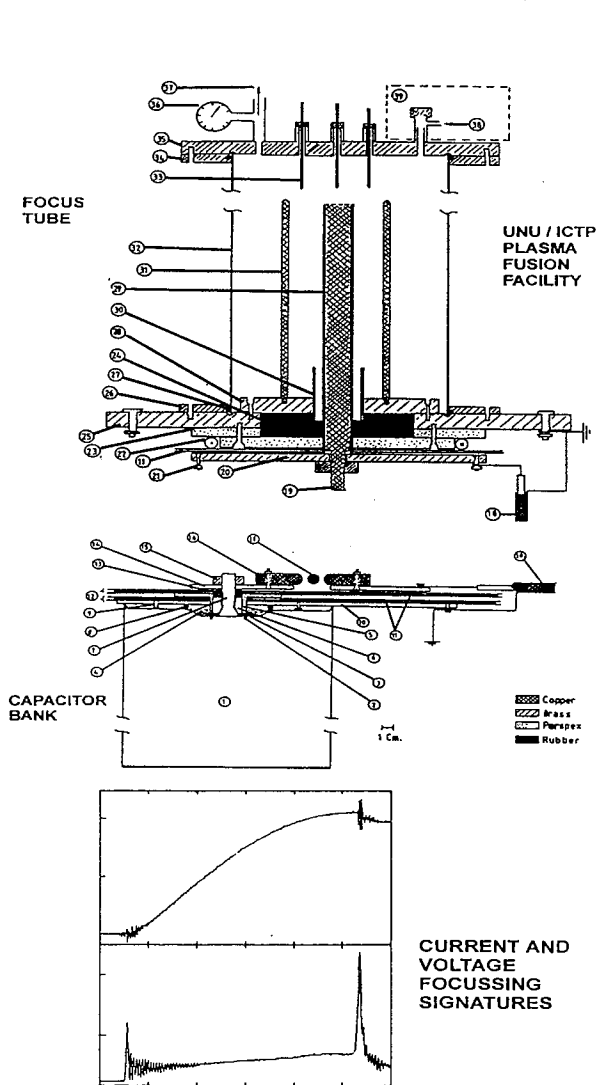
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TWELVE YEARS OF UNU/ICTP PFF - A REVIEW



Sequence of compression in
UNU/ICTP PFF at 4.0 mbar deuterium

UNU/ICTP PFF - Design, Signature and Dynamics



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TWELVE YEARS OF UNU/ICTP PFF- A REVIEW

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*More information on the UNU/ICTP PFF and AAAPT may be viewed at
<http://155.69.49.35:8001/UNUICTPPFF.htm>

TWELVE YEARS OF UNU/ICTP PFF – A REVIEW

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Abstract

The UNU/ICTP PFF is a research network based on a 3kJ Plasma Focus. Designed in 1985/86 during an United Nations University Training Programme, it is now established in 10 institutions in 8 countries. Research activities on the facilities have built up 7 research laboratories and research groups and has produced 16 PhD's, 31 Masters and 160 research papers. It was instrumental in the formation of the Asian African Association for Plasma Training. It has assisted in producing the first sandwich PhD's of the AAAPT Research & Training Center in Beijing. This work has produced innovative concepts of radiation enhancement and a wide range of studies encompassing plasma dynamics, radiation, scaling and optimization, modification of advanced materials, neutron activation and analysis, radiation safety, plasma space propulsion, astrophysics and non-linear deterministic mechanics and new types of high power devices and switches.

1. Introduction

The United Nations University/International Centre for Theoretical Physics Plasma Fusion Facility (UNU/ICTP PFF) is a research system based on a 3 kJ plasma focus. A network of 12 UNU/ICTP PFF's is actively operated in 10 institutions in 8 countries. The research has produced a total of 16 PhD's, 31 Masters, some 82 papers in refereed research journals and 83 conference papers. The research has contributed significantly to an understanding of pulsed dense plasmas. It has developed innovative concepts of enhancement of radiation yield and a wide range of applications. The research continues to grow. This review gives an account of how it started, summarises the main scientific results of the network and compiles a list of the research output.

2. How It Started

It started in 1983. At the Spring College on Plasma Physics held at the International Centre for Theoretical Physics (ICTP) in Trieste, a group of scientists from developing countries met in the evenings to discuss about the difficulties faced in trying to start experimental research. **What was needed** were small plasma devices that could be built, on which fruitful and sustained research could be carried out in their home institutes. Various ideas were discussed and the ideas were boiled down to the glow discharge, the linear pinch, the electromagnetic shock tube and the plasma focus.

In 1984 [C1] a proposal was made to various international agencies. **The proposal** was to use the facilities and resources of an existing group in a developing country to prepare a program to transfer its total research technology in a specific topic to another group in the region having an interest and commitment in the specific subject area offered.

The proposal covered the **identification of the host centre** which needed to have the experience, technical infrastructure and willingness. **Identification of participants** was also

important. The proposed participants needed to have a strong Physics and technical background and have the backing of the home institute to build up the project for several years AFTER the training programme.

The **role of the Centre** was also carefully defined. The Centre would **identify** a useful facility modelled on its own experience and expertise, It would **plan** a breakdown of the facility into its **basic technical sub-systems**, (e.g. see Fig 1) and **plan a detailed programme** for the participants to acquire the expertise and technology and the components of each of these sub-systems. The Centre would **run an intensive training programme, provide the follow-up equipment including shipping, and then follow-up help** or the facilities to be set up in the home institute.

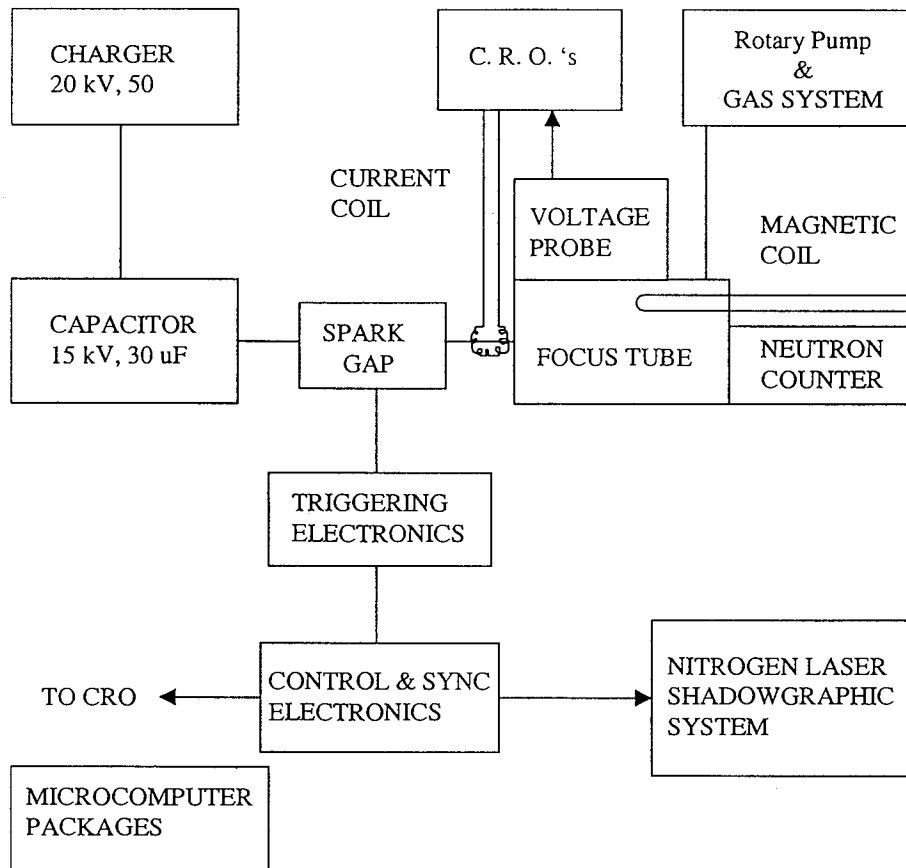


Fig1 Sub-systems of the UNU/ICTP PFF

The United Nations University (UNU) agreed to fund a training programme. Rector Dr. Soedjatmoko added a further dimension when he stated in a communication: "We..... have strong reasons to believe that plasma physics will be one of the major technologies of the future in developing as well as industrialised countries. We find great merit in the argument that developing countries should begin now to experiment with and develop modest plasma systems in order to acquire practical knowledge and skills to better employ technologies based on plasma physics once major breakthroughs permit the utilization for the production of energy as well as for other applications."

3. The Intensive Training Programme

Eight UNU Fellows were identified during site visits in early 1985 and in October a six month UNU Training Programme in Plasma and Laser Technology started at the University of Malaya.

For the first three months an intensive and comprehensive programme of lectures and experiments on existing facilities and devices was carried out. These included pulsed electronic modules, power supplies, glow discharge, electromagnetic shock tube, plasma focus, computation packages on circuit and plasma dynamics; and various laser systems. During this period the Fellow also carried out system planning, design and construction and development of all the sub-systems that he needed for the device that he has chosen to install back at his home institute. Most of the Fellows chose the plasma Focus.

4. Why the plasma focus?

From the very beginning of the discussions at the ICTP in 1983 it was decided that low cost, cost effectiveness, simplicity and good educational value, combined with a large variety of plasma phenomena, amenable to study by simple diagnostics should be among the factors to be considered in relation to devices for developing countries. Thus, the glow discharge had often been suggested as a suitable plasma for study in a developing country. The glow discharge has several applications, for example deposition and sputtering of thin films, and can also be used as a medium for the experimental study of plasma waves. It serves as a good starting point to develop plasma jets and arcs. These may be used as plasma torches or heaters for industrial and metallurgical applications or for MHD power generation.

To move upwards in temperature so that one may aspire to study intense and fusion aspects of plasma physics one may consider building an electromagnetic shock tube to study shock heating; or a linear Z-pinch for the study of imploding shocks and magnetic compressions. These are 'classical' devices with well-known technology. The Z-pinch, even in the low cost form for this educational exercise could produce a plasma of sufficient density and temperature to be of interest even though no measurable nuclear fusion may be expected.

The plasma focus goes one stage better [C2-C4]. It is an excellent device for teaching plasma dynamics and thermodynamics besides being a rich source for a variety of plasma phenomena including soft x-rays and plasma nuclear fusion. The plasma focus is superior to both the electromagnetic shock tube and the linear Z-pinch in its range of plasma parameters. It combines the essential mechanisms of both devices in such a properly sequenced manner that all the features of both devices, and others including fusion, may be demonstrated in one single simple low cost device.

5. Cost effective physics

Further, in order to implement a project whereby a developing country may produce a suitable package for sharing technology with other developing countries with the aim of initiating experimental plasma research it was necessary to consider the cost effectiveness of the device to be chosen. Does it produce a rich variety of plasma phenomena? Does it require an expensive vacuum system? Can its power supplies, control electronics and basic diagnostics be packaged at reasonable cost? What physical mechanisms operate to make the chosen device perform better at lower packaging cost than other devices? Can we understand and model the design and

performance of the device so that we may effectively do research on it? What are the areas of research and potential applications of the device?

For the production, at a low cost, of a pulsed plasma of fusion interest, there is little doubt that the class of fast magnetic compression devices known generally as the pinch, including the linear Z - pinch, the superfast pinch, the gas-puff pinch and the plasma focus offers the best potential. During our planning phase we had considered this class of device and found that the plasma focus is the most cost-effective. The plasma focus needs only the same power supply, control electronics and basic diagnostic requirements as required by the simple Z-pinch. It needs a much cheaper vacuum system with only rotary pump requirement. Yet it produces more intense plasma phenomena including copious x-rays, relativistic electron beam (REB) and fusion neutrons, all in one small easily packaged facility. What is the physics behind this cost effectiveness?

Ultra high power superfast pinches have been operated with pulse forming lines to reduce current risetimes so that the pinch may be operated at smaller radius, hence higher density. This high power approach requires the use of complex and expensive technology.

On the other hand the plasma focus uses a very simple principle. Essentially it allows a conventional (slow risetime of 3 usec or more) capacitor bank to drive a very fast pinch (typically 1 cm radius in 50 ns) at a high density.

The plasma focus has two sections:- the first section is a coaxial electromagnetic shock tube whose length is adjusted so that the transit duration matches the capacitor risetime. During this axial phase the rising capacitor current drives a shock wave axially down the shock tube at a suitable speed until the shock wave reaches the end of the tube at peak current. Then by the geometry of the device the axial phase moves to a radial compression or pinch phase.

The pinch phase is very intense because it starts at a very large current (typically hundreds of kA) and at a relatively small radius (typically 1 cm). Thus the operating pressure may be relatively high (5 torr in D, for a plasma focus against 0.1 torr or less for a pinch). The increased density and temperature more than compensates for the reduced volume in terms of radiation and neutron yield.

6. Developing a Package

During the first three months of intense training, experiments with various devices and discussions most of the Fellows were convinced that the plasma focus is capable of high levels of performance without special technological development. We had at the same time developed an educational package starting from the modelling and design of a practical compact device based on a single capacitor as the pulsed power source (see Fig 2)

In the next month, the development, assembly and testing of the first version of the UNU/ICTP PFF was carried out. It was during this phase that the programme was visited by Professor Abdus Salam, Director of the ICTP, on 20 Jan 1986. After seeing the activities Abdus Salam on the spot offered to provide the missing brick in the structure-funds which eventually proved enough for the bulk of the follow-up equipment.



Professor Abdus Salam visiting the UNU/ICTP PFF at the University of Malaya-January 20 1986

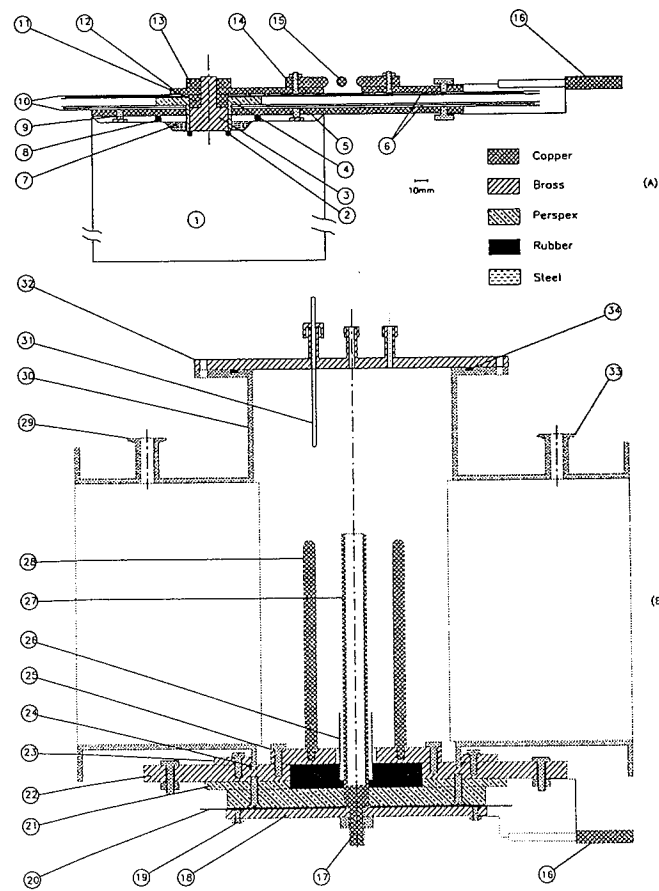
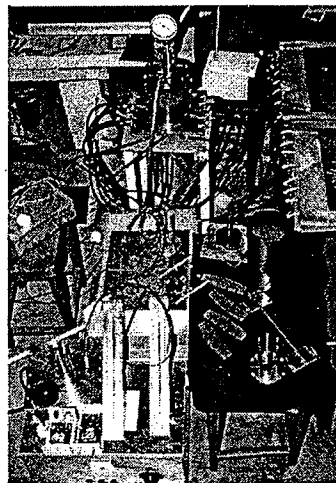
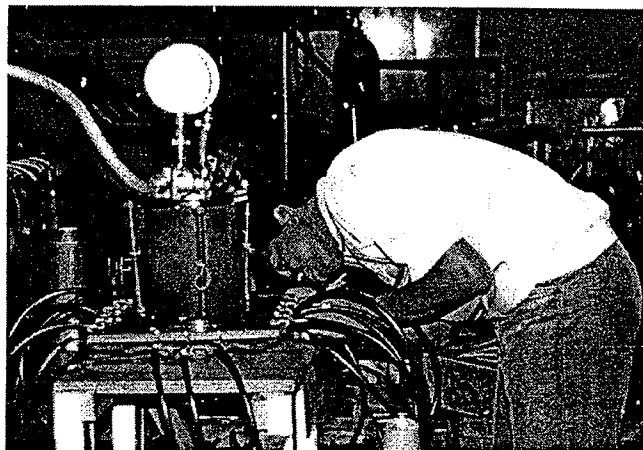


Fig 2: Design of the UNU/ICTP PFF

7. Assembling and Testing 6 sets of UNU/ICTP PFF's

In the following six weeks there was a battle against time, a period of intense activity, a time when the machine workshop at the Physics Department operated day and night, manufacturing the parts needed for six sets of UNU/ICTP PFF; followed by the assembly and testing of each

set. Each set was assembled by its 'owner', tested for vacuum tightness, tested for voltage holding and current conduction and then for full operation. Full operational tests include focussing characteristics in various gases, and finally in deuterium with fusion neutrons detected by a paraffin-wax moderated silver activation counter. Six sets were thus assembled and tested, one after another.



UNU Fellow Widdi Usada assembling his UNU/ICTP PFF Parts of several UNU/ICTP PFF's



Dr Walter Shearer of UNU with UNU
Fellows Zakaullah and Dr Eissa



UNU Fellows Warmate and Dr Smith with
1 set (in crates) of UNU/ICTP PFF

8. Research Phase and Shipping of Follow-up Equipment

By end of March 1986, reports and preparation for shipment of equipment were completed and some research papers were presented at the Second Tropical College on Applied Physics. Six research papers were written and eventually published, including 2 in international (US) journals. Dr Walter Shearer represented the UNU in a ceremony in early April 1986 at which the equipment, in 7 consignments weighing over 1000kg, was handed over to the Fellows and then to the company arranging the air-freight.

9. Not the Programme but the Follow-on Work

A key message during this handing over ceremony was that the **success of the programme will depend on the work achieved by the Fellows back at the home institutes in the years to come.**

10. Twelve Years on

Twelve years on, it is time to review the work. In the intervening years more programmes, funded by the ICTP, were run. In 1988 a second (UNU)/ICTP Training Programme (6 month) was conducted during which a Sequenced Nitrogen Laser was invented. The start of this Training Programme was timed to coincide with the Third Tropical College on Applied Physics and the Formation of the AAAPT. The Third ICTP-UM Training Programme on Plasma and Pulse Technology was held from Dec 1989 to June 1990 with an associated Nitrogen Laser Training Programme from Oct-Nov 1990. A total of 24 Fellows funded by UNU, ICTP, TWAS, AAAPT and UM were trained up to November 1990.

In the meantime regional centres to assist in the propagation of the technology had been set up in Delhi and Islamabad, run by former UNU Fellows, to assist in the propagation of the UNU/ICTP PFF technology.

Several attachment/training programmes were run by these Centres as well as by the Kuala Lumpur, Cairo and Beijing Centres from 1992. These have resulted in the training of another 20 scientists in UNU/ICTP PFF technology and the collaborative research of several other scientists already working in the area of plasma focus. With the help of Prof Gallieno Denardo, Head of the Office of External Activities at ICTP, an UNU/ICTP PFF was placed at the ICTP. In 1991 and 1993 training experiments were conducted at the ICTP during the Spring College of Plasma Physics. These sessions were attended by some 35 scientists.

The following table (not comprehensive) shows the facilities transferred to the various recipient institutes after the first 3 Training Programmes.

Table 1

	UNU/ICTP PFF	EMST Flow Simulator	Nitrogen Laser System	Laser Shadowgraph System	Glow Discharge
Cairo, Al Azhar U.	X*		x	x	
Jaipur, Rajasthan U.	X		x		
Delhi, Delhi U.	x.*		x*	x*	
Srinaga,SP College Jakarta, LAPAN (Space research)		x*	x		
Yogyakarta, PPNY (Nuclear research)	x.*		x*	x*	x
Islamabad, QAU	x.*		x*	x*	
PortHarcourt, US&T	x.*		x*	x*	
Sierra Leone, NUC	x.*				
Songkla, PSU	x.		x		
Liberia			x	x.*	
Harare, Uni of Zimbabwe	x*+				

* Have produced PhD/MSc theses from these facilities

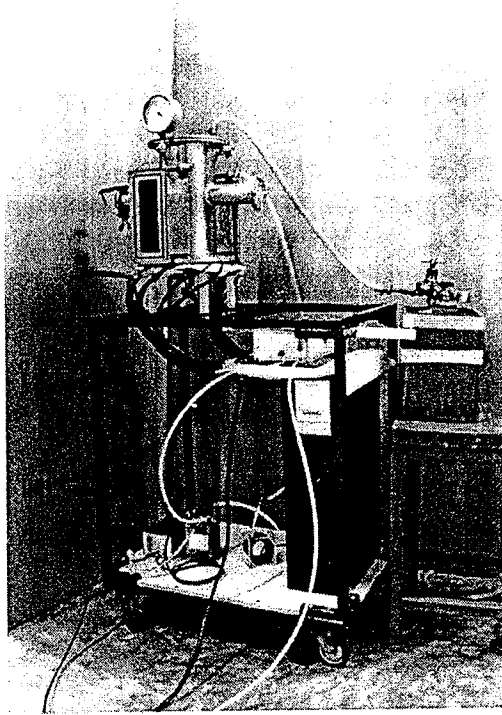
+ Developed the UNU/ICTP PFF locally

11. Progress at home Institutions

Good progress has been achieved back at the home institutions [C9-C11, C13-C14, C26] as a result of the training programmes and the follow-up equipment and assistance. Plasma Focus facilities are now fully operational at Quaid-I-Azam University, University of Delhi, Rivers State University of Science and Technology, Al Azhar University, Prince of Songkla University and Yogyakarta Nuclear Research Centre. Other facilities have been established at Njala University College, University of Rajasthan, Shanghai Institute of Optics and Fine Mechanics, National Space and Aeronautics Board of Indonesia, University of Zimbabwe, Harare. and a training facility at the ICTP. Strong postgraduate programmes have been established at Quaid-I-Azam University, University of New Delhi and Yogyakarta.

12. Theses and Research Output

At last count research work on the UNU/ICTP PFF have produced 16 PhD's, 31 Masters and 160 research papers. These are listed at the end of this paper.



The UNU/ICTP PFF placed at the ICTP in Trieste.

It just fitted into the narrow elevator and was wheeled into Room A, Terrace Level for experiments during the Spring College on Plasma Physics in 1991 and 1993 when some 35 scientists carried out training/research experiments on this device in Trieste

13. What of the scientific results?

A brief summary of the main scientific results achieved by the network of UNU/ICTP PFF's is collated as follows. Detailed results are discussed in the reviews given by the institutions.

13.1 Plasma Dynamics:

Central to the study of dynamics in the UNU/ICTP PFF is the development of theoretical understanding based on computational models [B1,B4,B5,C6].

A model was developed using a current sheath snowplow for the axial phase, followed by a slug model applied to an elongating pinch in the radial phase [J2]. This is followed by a reflected shock phase and large plasma column phase. The model incorporates current shedding and mass loss effects, and is used as the basis of many UNU/ICTP PFF experiments to model current, voltage, axial and radial speeds and size of the gross plasma pinch column. In deuterium the non-dimensionalization of the model has identified a drive parameter $S = (I/a)/\sqrt{\rho}$ which has a constant value of 90 kA/cm per torr for all machines ranging from small plasma focus of 3kJ to big plasma focus of 200kJ [J13]. This study has suggested the concept of speed enhancement of neutron yield, enhancing from the observed $Y \sim I^4$ to $Y \sim I^8$ [C3,C28]. Inclusion of thermodynamics into the model shows that the thickness of the radially collapsing current layer and the radius of the gross pinch at maximum compression depend on γ , the specific heat ratio of the gas [C27,C30]. A detailed study shows that the minimum radius, maximum length, radial shock transit time and pinch lifetime of the gross plasma focus pinch are functions of radius 'a' for both deuterium and neon [C15,J13]. Inclusion of radiative terms

into an additional radiative phase [C27,C42,D4S] enables optimization of the neon focus for SXR yield in the range of 0.8 - 1.4 nm, this being the range suitable for microelectronics lithography.

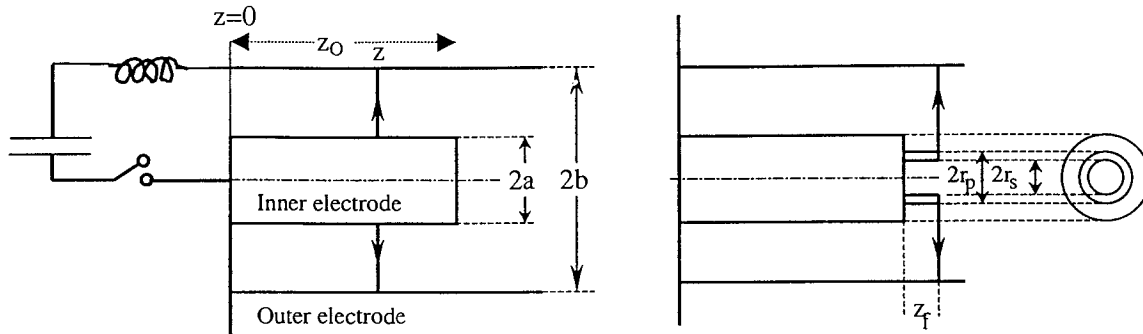


Fig3 Axial (left) and radial (right) phases of the Plasma Focus Model

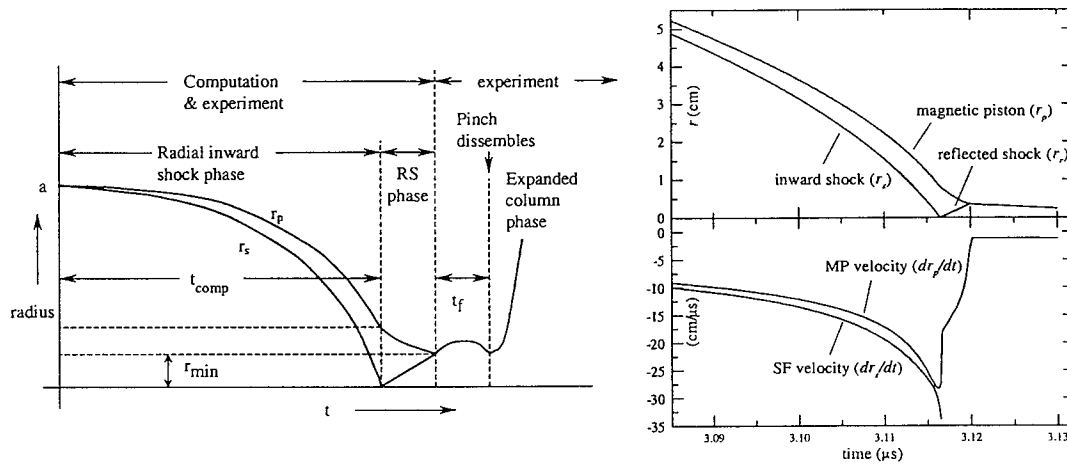


Fig 4. Schematic of radial sub-phases of the PF

Fig 5 Radial Dynamics-neon PF

This model has also been used to predict a new type of plasma focus operating with several anodes to produce a sequence of focussing [J7], hence a sequence of neutron and SXR bursts. The 1-D axial phase has been modified in Zimbabwe[J50] by incorporation of current sheath curvature to improve the model in its design capability. The Islamabad group had developed a 2-D model covering both axial and radial phases which sought to optimise the Lawson parameter $n\tau$ for plasma focus [C54].

13.2 Machine Optimization / Scaling

This has been a major concern right from the beginning of the design of the UNU/ICTP PFF [J2] in Kuala Lumpur. Going further the Islamabad group [D11P,J55-J58,J61-62] using a modified UNU/ICTP PFF has studied in detail the effect on performance of configuration of the electrodes and backwall insulator sleeve, their dimensions and the materials they are made of, besides the obvious parameter of operational pressure. It was found that proper selection of the lengths of the anode and the insulator sleeve improves current sheath uniformity and

axisymmetry and moreover lowers neutron fluence anisotropy. Lowering the external parasitic inductance towards the load inductance represented by the focus tube including the pinch, widens both the neutron pulse and the optimum pressure range of operation. Contamination of the insulator sleeve was found to be an important factor in device operation. The sleeve needed a minimum level of contamination for prompt breakdown and good focussing action and high neutron yield. However too high a contamination level promotes too much current loss, giving rise to multiple focus formation.

The UNU/ICTP PFF has been bench-marked for optimum performance under standardized conditions [J2,J9]. This is important so that performance can be compared across all the UNU/ICTP PFF's installed worldwide in order to ensure that we are talking about the same regimes of operation. One key bench-mark is the average axial speed, which in deuterium is 5.5 cm/usec, which translates into 5.5 cm of anode length for each microsecond of current risetime. The UNU/ICTP PFF was modified in Al-Azhar University in Cairo, whilst in Harare, a new device was constructed locally. Experimental results in these devices are reported in detail in individual review papers in this volume (p84, p89, p74). The results indicate that regimes different from those reported by other UNU/ICTP PFF's may have been studied in these two devices.

An optimum axial speed for neutron yield in deuterium and for SXR (0.8 - 1.4 nm) yield in neon are observed in the UNU/ICTP PFF as also in other machines world-wide [C15,J13]. This has given rise to the concept that all conventional plasma focus of Mathers type operate, in deuterium, at the same magnetic pressure, hence at the same energy density or temperature.

This begs the question, why do we not operate at higher speeds and higher temperature so as to make use of the increased fusion cross-section? The answer may be that at higher speeds, mass-field, flow-field separation tends to occur because of the high Magnetic Reynolds Number (which depends on the fourth power of velocity). An experiment has been carried out using the UNU/ICTP PFF with a two-stage anode [C31,J31,J33,D3S]. The first stage is a normal radius designed to give the normal universally observed correct drive parameter. The second stage has reduced radius, thus a larger than 'normal' drive parameter. This stage is adjusted to be long enough to give a significant increased in speed, yet short enough to limit the mass-field, flow-field separation.

The results of the experiments indicate that yield enhancement occurs. However these experiments need to be repeated using a range of currents, at a fixed radius; rather than with a fixed current (as in the UNU/ICTP PFF) and reducing the radius. Reducing the radius also reduces the pinch volume which reduces the neutron yield thus bringing in a reduction factor which tends to partially mask the speed enhancement effect.

13.3 Radiation Studies and Radiation Enhancement

Comprehensive studies of plasma focus radiation (neutrons, ion beams, relativistic electron beams, SXR, hard XR) have been made in all the UNU/ICTP PFF's. The 'standard' neutron yield for the 3 kJ UNU/ICTP PFF has been found to be 10^8 n per shot. In a series of experiments using deuterided and plain targets placed at different distances from the end of the anode, it was found that 15% of the neutrons are thermonuclear whilst the remaining 85% is due to beam-gas interaction [J6,M1M]. The effect of different anode material and configuration and different operating pressures on neutron yield was also studied.

Ion beams were studied using Faraday cups, Thomson spectrometer and Solid State Nuclear Track Detectors (SSNTD) such as CR-39. Pin-hole images of the charged particle (deuterons) emission zone [J72] were obtained at different pressures showing the deuteron source to vary in shape from a spot to a column to a number of spots located generally between one to two radii from the end of the anode. A magnetic field deflecting the ions has also been used with SSNTD to obtain the ion energies. The ion energies have also been estimated using Faraday cups.

Soft x-rays (SXR) have also been increasingly studied from deuterium, argon and neon plasmas. The time history of the SXR pulses is used to correlate the plasma dynamics e.g. defining the moment of maximum compression, and later of the copper jetted from the anode [J8]. In deuterium the SXR are from Bremsstrahlung and there are indications that there may be a speed enhancement effect [J14]. For neon operation to obtain a SXR source suitable for microelectronics lithography, calculations and experiments show that a neon plasma temperature of 300-400 eV is required [D4S, C42] to generate the desired 0.8-1.4 nm spectrum mainly from H-like and He-like neon lines. Using calorimeter, crystal spectrometer and 5-channel pindiode spectrometer, an optimised yield of 5J in wavelength range 0.8 - 1.4 nm is obtained from the UNU/ICTP PFF [D4S, J18, J32].

13.4 Applications: Materials modification using Plasma Focus Ion Beam

Studies on the ion beams produced by the UNU/ICTP PFF at Delhi led to the use of the ion beams for plasma processing [D8In-D10In, J37-J42, J44] of thin film materials on different substrates with different phase changes. The following were achieved: (a) Crystallization of an amorphous lead zirconate titanate (PZT) thin film (b) amorphization of crystalline thin film of PZT (c) observation of n-type doped behaviour of a polyaniline film subjected to plasma ion bombardment (d) observation of p-n junction diode formation in a single polyaniline film, cation doped chemically on one side and anion doped by plasma focus ions on the other side (e) observation of magnetite phase from hematite thin film irradiated by plasma focus ions (f) observation of a rise in superconducting temperature of a thin film of high T_c superconducting material BPSCCO (g) deposition of thin carbon film (h) deposition of Fullerene films of C_{60} and C_{70} on Si. In cooperation with Delhi, experiments were also carried out in Singapore [J36] in which plasma focus ions were used to improve the crystallinity of Sb_2Te_3 (antimony telluride) thin films and to encourage a preferred direction of crystal orientation.

13.5 Other applications

Experiments on neon SXR emitted from the UNU/ICTP PFF have provided the database that contributed to development in Singapore of one of the most powerful SXR point sources (300W) in the world [D5S, J84], leading to demonstration of sub-0.2 μm lines [J85, D5S] transferred from a mask to a substrate. There is potential for applications in **microelectronics lithography**.

Speed enhancement of neutron yield could lead to the development of a neutron source of **fusion interest**. In the meantime **pulsed neutron activation** [J25, J26] was used to determine the half-lives of ^{116}In , ^{104}Rh and $^{24}Na^m$. An investigation is also being carried out to change neutron pulse profile by doping deuterium with argon in order to obtain suitable neutron pulse profiles for **interrogation of materials** such as explosives and illicit drugs.

The level of radiation, neutrons and x-rays from the UNU/ICTP PFF have been studied in Kuala Lumpur [J82] from the safety point of view. Such studies are useful beyond the UNU/ICTP PFF, since they contribute to an understanding of **radiation safety** from intense pulsed sources in general, including from nuclear explosions.

In Jakarta a study was made using the UNU/ICTP PFF as a source of high pressure to look into the possibility of developing a system to study **plasma space propulsion [D2Is]**.

In Port Harcourt, Nigeria, studies [D15N,D16N] were also carried out on the UNU/ICTP PFF including applications to a situation of **astrophysical interest [D15N]** has been studied.

At the ICTP a statistical study of the plasma focus in its good-focus, bad-focus modes has enabled some conclusions to be made in terms of a model based on **non-linear deterministic mechanics [J81]**.

New devices have been suggested by experiments carried out during the UNU/ICTP Training Programmes. A **sequential plasma focus [J5]** device and a **sequential nitrogen laser system [J4]** were both invented during training programmes. The sequential plasma focus was later modelled [J7] and subsequently confirmed in operation by both the Delhi [D9In] and the Quaid-I-Azam [J59] groups. This device is capable of generating bursts of neutrons and SXR at programmable times.

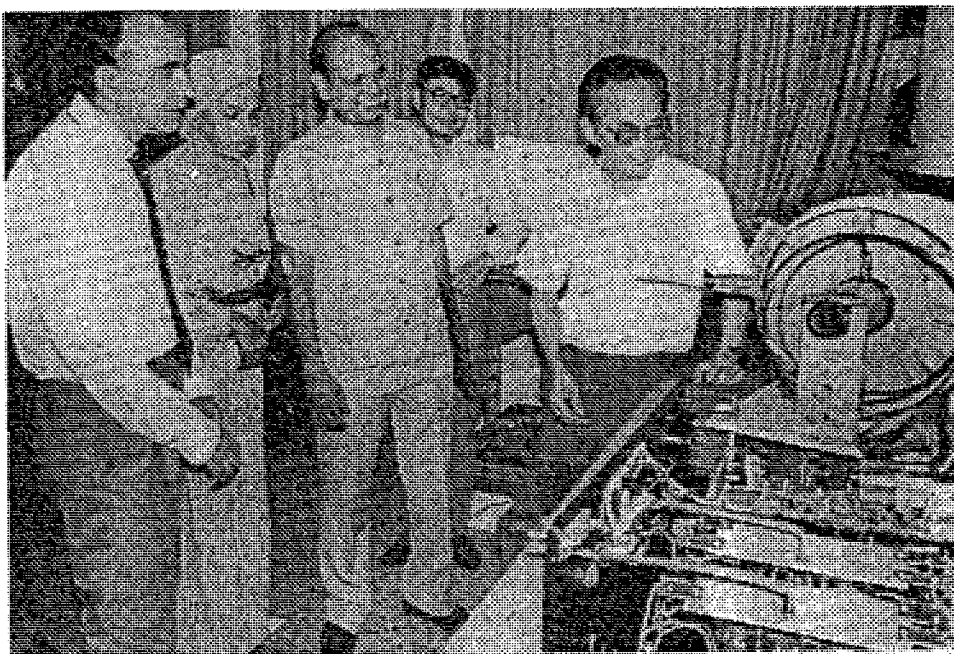
An UNU/ICTP PFF has been modified to assess the operation of a plasma focus based **long conduction opening switch M4M,C71,C73]**. The electrode geometry of the UNU/ICTP PFF has been modified to redirect the plasma motion. This device is operated at below 0.01 mb and requires a set of injection cable guns to initiate the discharge. Reproducible opening action has been achieved in various gases at optimum operating pressures between 0.01 mb to 0.035 mb. **Ion beams** of 85 keV for hydrogen, 225 keV for nitrogen and 285 keV for argon have been obtained [M4M].

14. Conclusion

The UNU/ICTP PFF programme started as an exercise to initiate/strengthen experimental research as an educational process in developing countries. The model that was adopted had 3 components: A training centre, a trainee institution and an international funding agency. The training Centre worked out a procedure to transfer totally its expertise in a selected facility. The transfer involved 3 components: intensive and comprehensive training, follow-up equipment and follow-up assistance. The training was individually tailored and was most intensively concentrated into the workings of each sub-system of the device and facility to be transferred. The sub-systems approach proved critical to the success. The Fellow had to assemble and maintain his system back home; and he had to understand how each sub-system, each component worked.

Over the twelve years the training, transfer and follow-up activities cost an estimated total of USD500,000 in international funds and contributions from training institutions, not counting the contributions of the home institutions. The programme had contributed significantly to the establishment of 7 active experimental research groups, was instrumental in the formation of the Asian African Association for Plasma Training (AAAPT) with membership of 34 Institutions from 21 countries and had assisted in the formation of the International Centre for Dense

Magnetised Plasmas (ICDMP) now sited in Poland. The network of ICTP PFF's has produced 16 PhD's, 31 Masters and more than 160 research papers and has a significant impact on the knowledge and practice of pulsed dense plasmas. It is an example of what can be achieved from the initiative and cooperation of scientists with the support of international agencies like the UNU and the ICTP.



TOUR OF THE LAB: Physicists at UM's plasma lab

**Several Key Personnel of AAAPT convening before the
Inaugural Meeting on 7.6.1988**

15. Theses & Publications Resulting from research using the UNU/ICTP PFFs in Egypt, India, Indonesia, Italy, Malaysia, Nigeria, Pakistan, Singapore and Zimbabwe.

PhD theses (16)

- D1M. Jalil bin Ali. Development and Studies of a Small Plasma Focus. PhD thesis. Universiti Teknologi Malaysia, Malaysia, 1990.
- D2Is Susetyo Mulyodrono. Parameter Rancangan Tabung Kejut Elektromagnetik Koaksial Bubu Berkemampuan Memfokus Plasma (Kemungkinan Penerapannya Dalam Sistem Propulsi Plasma). The Electromagnetic Shock Tube with Plasma Focussing Ability: Possibility for use in a Plasma Propulsion System. PhD thesis. Institut Teknologi Bandung, Indonesia, 1993
- D3S. A.Serban. Anode Geometry and Focus Characteristics. PhD thesis. Nanyang Technological University, Singapore, 1995.

- D4S. M.H.Liu. Soft X-Rays from Compact Plasma Focus. PhD thesis. NTU, Singapore, 1997.
- D5S G.X.Zhang. Plasma Soft x-ray source for Microelectronics lithography. PhD thesis (in preparation) NTU, Singapore 1998.
- D6S Muhammad Shahid Rafique. PhD thesis (in preparation) NTU, Singapore.
- D7Z. M. Mathuthu. Design, fabrication and characterization of Plasma Focus Device. Ph D thesis. University of Zimbabwe, Harare submitted May 1998.
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RADIATION ENHANCEMENT AND APPLICATIONS SCALING FROM THE UNU/ICTP PFF

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ABSTRACT

Computational and experimental studies made on the UNU/ICTP PFF have resulted in a concept of speed enhancement for neutron yield and an application of SXR for microelectronics lithography. In this review the computational model is first discussed. Following the snowplow axial phase, the radial phase is treated as an elongating slug. A reflected shock phase gives the maximum compression configuration of the plasma focus pinch in the case of operation in deuterium. An expanded column phase is used to complete the post-focus electric current computation. For operation in neon a radiative phase is included in order to study soft x-ray (SXR) yield for the purpose of microelectronics lithography. Parameters of the gross focus pinch obtained from the computation, supplemented by experiments are summarised as follows:

		Deuterium	Neon (for SXR)
minimum radius	$r_{\min}$	0.13a	0.04a
maximum length	z	0.7a	0.8a
radial shock transit	t_{comp}	$5 \times 10^{-6} \text{a}$	$4 \times 10^{-6} \text{a}$
pinch lifetime	t_f	$2 \times 10^{-6} \text{a}$	$1 \times 10^{-6} \text{a}$

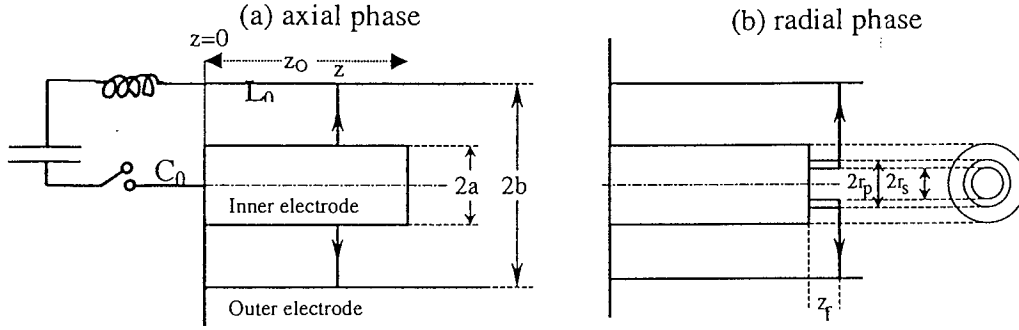
where, for the times in sec, the value of anode radius, a, is in m. The scaling suggests a speed enhancement effect on neutron yield, enhancing from the conventional I^4 to a superior I^8 scaling law. Speed enhanced experiments using stepped anodes in the UNU/ICTP PFF suggest evidence for such neutron yield enhancement and also SXR speed-enhanced yield. For SXR yield for microelectronics lithography a wavelength range of 0.8-1.4nm is deemed to be desirable, requiring a neon focus pinch temperature limited to 300-400eV. Thus there is no speed enhancement for the neon SXR yield. Computation and experiments on the UNU/ICTP PFF provide a data base for the successful development of a 300W SXR source, which has demonstrated transfer of 0.2 micron structures in a lithographic process.

INTRODUCTION

The axial trajectory (Fig 1a) of a Mathers type plasma focus /1/ is computed using a snowplow model. This is followed by a radial phase (Fig 1b) when the magnetic piston separates from the inward going shock, forming an elongating slug /2-4,10/. A reflected shock (RS) phase (Fig 2) /5/ follows which ends when the out-going RS hits the in-going piston, defining a gross compressed configuration with minimum radius and maximum length, which are dependent on anode radius 'a'. Moreover for a given gas there appears to be mechanisms that require the drive magnetic energy density to be constant over a range of the devices from small (kJ) to big (hundreds of kJ). It follows that the lifetime of the plasma focus pinch is also dependent on 'a'. Thus the bigger the anode radius, the bigger are the radius, length and lifetime of the compressed pinch. This dependence on 'a' is alone sufficient to derive the general rule that radiation yield is proportional to I^4 . It also suggests a speed enhancement effect on neutron yield, which however does not appear to apply to soft x-ray (SXR) yield for microelectronics lithography.

MODEL

Fig 1: Schematic of (a) axial phase and (b) radial phase /2/



The equations for the axial and radial phases are written and normalised in the following manner /2-4,7/: (geometrical quantities are shown in the Figs 1 & 2, L_o , C_o , r_o are the circuit inductance, capacitance and resistance, V_o is the voltage C_o is charged to).

$$\tau = \frac{t}{t_o}, \quad \zeta = \frac{z}{z_o}, \quad \iota = \frac{I}{I_o}, \quad \delta = \frac{r_o}{Z_o}$$

$$\kappa_i = \frac{r_i}{a}, \quad \kappa_p = \frac{r_p}{a}, \quad \zeta_r = \frac{z_r}{a}, \quad Z_o = \sqrt{\frac{L_o}{C_o}}$$

$$t_o = \sqrt{L_o C_o} \text{ and } I_o = V_o / Z_o$$

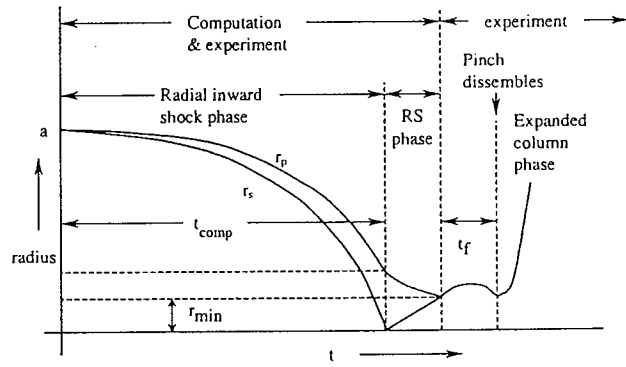


Fig 2. Schematic of radial phases

Axial Phase:

$$\text{Motion: } \frac{d^2 \zeta}{d\tau^2} = \frac{\alpha^2 \iota^2 - \left(\frac{d\zeta}{d\tau} \right)^2}{\zeta} \quad (1)$$

$$\text{Current: } \frac{d\iota}{d\tau} = \frac{1 - \int \iota d\tau - f_c \beta \frac{d\zeta}{d\tau} \iota - \delta \iota}{1 + f_c \beta \zeta} \quad (2)$$

to compute ζ and ι ; with two scaling parameters:

$$\beta = \left[\frac{\mu}{2\pi} z_o \ln c \right] / L_o \quad (3)$$

which is the ratio of the full axial phase tube inductance to the external fixed inductance. Ratio of characteristic electrical discharge time to characteristic axial transit times is:

$$\alpha = t_o / t_a \quad (4)$$

$$\text{where } t_a = \left[\frac{4\pi^2 (c^2 - 1)}{\mu \ln c} \right]^{1/2} \frac{z_o \sqrt{f_m}}{f_c} \frac{\sqrt{\rho}}{(I_o / a)} \quad (5)$$

giving a characteristic axial transit speed of $v_a = z_o / t_a$ of

$$v_a = \left[\frac{\mu \ln c}{4\pi^2(c^2-1)} \right]^{1/2} \frac{f_c}{\sqrt{f_m}} \frac{(I_o/a)}{\sqrt{\rho}} \quad (6)$$

The parameters f_c , f_m are current factor and mass swept-up factor /9/. We note the dependence of v_a on $(I_o/a)/\sqrt{\rho}$ which is designated as the drive parameter S . Equations (1) & (2) are integrated step-by-step in time for ζ and ι , until $\zeta = 1$. Then the dynamics move to the radial phase as follows:

Radial Phase

Normalised radial phase equations are:

$$\text{Inward shock: } \frac{d\kappa_s}{d\tau} = -\alpha\alpha_1 \frac{\iota}{\kappa_p} \quad (7)$$

$$\text{Elongation: } \frac{d\zeta_r}{d\tau} = -\frac{2}{\gamma+1} \frac{d\kappa_s}{d\tau} \quad (8)$$

Inward piston:

$$\frac{d\kappa_p}{d\tau} = \frac{\frac{2}{\gamma+1} \frac{\kappa_s}{\kappa_p} \frac{d\kappa_s}{d\tau} - \frac{\kappa_p}{\gamma\iota} \left(1 - \frac{\kappa_s^2}{\kappa_p^2}\right) \frac{d\iota}{d\tau} - \frac{1}{\gamma+1} \frac{\kappa_p}{\zeta_r} \left(1 - \frac{\kappa_s^2}{\kappa_p^2}\right) \frac{d\zeta_r}{d\tau}}{\frac{\gamma-1}{\gamma} + \frac{1}{\gamma} \frac{\kappa_s^2}{\kappa_p^2}} \quad (9)$$

$$\text{Current: } \frac{d\iota}{d\tau} = \frac{1 - \int \iota d\tau + \frac{\beta_1}{F} f_c \frac{\zeta_r}{\kappa_p} \frac{d\kappa_p}{d\tau} \iota + \frac{\beta_1}{F} f_c \ln\left(\frac{\kappa_p}{c}\right) \frac{d\zeta_r}{d\tau} \iota - \delta\iota}{1 + f_c \beta - f_c \frac{\beta_1}{F} \zeta_r \ln\left(\frac{\kappa_p}{c}\right)} \quad (10)$$

$$\text{where } \beta_1 = \frac{\beta}{\ln c}, F = \frac{z_o}{a} \quad (11)$$

and the ratio of the characteristic axial transit time to characteristic pinch time

$$\alpha_1 = \frac{t_a}{t_p} = \frac{[(\gamma+1)(c^2-1)]^{1/2}}{\sqrt{\ln c}} \frac{F\sqrt{f_m}}{2\sqrt{f_{mr}}} \quad (12)$$

$$\text{Hence } t_p = \frac{4\pi}{[\mu(\gamma+1)]^{1/2}} \frac{\sqrt{f_{mr}}}{f_c} \frac{\sqrt{\rho}}{(I_o/a)} a \quad (13)$$

and characteristic pinch time a/t_p is

$$v_p = \frac{[\mu(\gamma+1)]}{4\pi} f_c \frac{I_o/a}{\sqrt{\rho}} \quad (14)$$

We note that v_p has the same dependence on drive parameter S as v_a . At the start of this phase $r_s = r_p = a$ and $z_f = 0$. Eqs 7-10 are integrated step-by-step in time for κ_s , κ_p , ζ_r and ι . This phase ends when the inward-going shock reaches $r_s = 0$ with speed $(dr_s/dt)_{\text{on-axis}}$. We define the length of the column at this point as z_p .

Following the radial inward shock phase, a reflected shock (RS) /5/ develops and moves radially outwards with a speed of $0.3 (dr_s/dt)_{\text{on-axis}}$ /35/. The piston continues moving in-wards. When the out-going reflected shock hits the in-going piston the compression enters a radiative phase /6/ in which for gases such as neon e.g. radiation cooling may actually enhance the compression. For deuterium we assume the radiative phase is not significant to the dynamics. We treat this point as the point of maximum compression with minimum gross radius r_{min} . If we just want the gross parameters of the plasma focus pinch the calculations may end here. To simulate the current trace beyond this point we allow the column to suddenly attain the radius of the anode, and use the expanded column inductance for further integration /7,8/.

PARAMETERS AND RESULTS

The UNU/ICTP PFF is a 3 kJ plasma focus /8,11/ designated as the United National University/International Centre for Theoretical Physics Plasma Focus Facility. This device was developed during UNU/ICTP training programmes /11-18/ and is now established in 6 countries for postgraduate training and research. To compute the above model for the UNU/ICTP PFF we note its operational parameters:

$$C_o = 3 \times 10^{-5} \text{F}, L_o = 1.1 \times 10^{-7} \text{H}, a = 0.95 \times 10^{-2} \text{m}, b = 3.2 \times 10^{-2} \text{m}, z_o = 0.16 \text{m}, c = 3.37, F = 16.84$$

$$\text{Hence } t_o = \sqrt{L_o C_o} = 1.82 \times 10^{-6} \text{s} \quad Z_o = \sqrt{L_o / C_o} = 0.06 \Omega$$

Typical operation is at 14 kV with ambient pressure of 3.5 torr deuterium giving:

$$\rho = 8.2 \times 10^{-4} \text{kgm}^{-3}, V_o = 1.4 \times 10^4, \text{ Also } r_o = 0.012 \Omega, \text{ Hence } I_o = V_o / Z_o = 2.33 \times 10^5 \text{A},$$

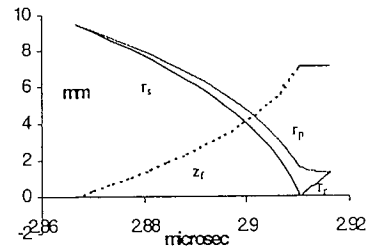
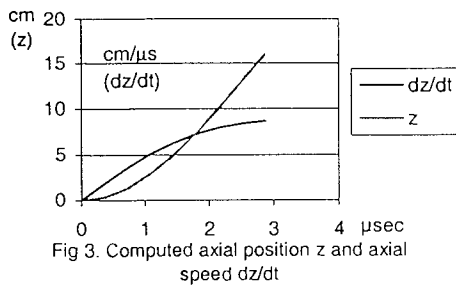
$$\delta = r_o / Z_o = 0.2, \text{ we take } f_c = 0.7, f_m = 0.1, f_{mr} = 0.3, \text{ Hence } t_a = 1.38 \times 10^{-6} \text{s} \quad v_a = 1.15 \times 10^5 \text{m/s}, t_p =$$

$$6.0 \times 10^{-8} \text{s}, v_p = 1.6 \times 10^5 \text{m/s}, \text{ and } \alpha = 1.31, \alpha_1 = 23.2, \beta = 0.35, \beta_1 = 0.29$$

We also use $\gamma = 5/3$ (specific heat ratio for fully ionized deuterium)

The axial and radial phases are computed followed by the RS phase. Fig 3 shows the axial phase dynamics in terms of axial position and speed presented in real quantities. It shows that the current sheath reaches the end of the axial phase at $2.87 \mu\text{s}$ with a peak speed of $8.6 \text{ cm}/\mu\text{s}$.

Figure 4 shows the radial phase dynamics. The shock front and the piston start together at $r=a$;



the length of the focus pinch is zero at this time. The shock front accelerates onto the axis, hitting the axis 40 ns from the start of the radial phase. At this time the piston position is 1.6mm from the axis and the length of the lengthening focus column is 7.1 mm. The piston speed, which had peaked at $30 \text{ cm}/\mu\text{s}$, reduces sharply as the shock approaches the axis. The speed of the shock front as it approaches the axis exceeds $50 \text{ cm}/\mu\text{s}$. This is unrealistically high and is due to the implicit assumption of instantaneous communication between the piston and the shock front ie an assumption of infinite signal speed /7,10/. We have considered the actual communication delay due to the finite small disturbance speed between the piston and shock front (of the order of ns, dependent on plasma slug temperature) and incorporate into the model.

This slows down both the shock front and piston, as they near the axis, to peak values of 25-30 cm/ μ s for the shock front on-axis and to about 20 cm/ μ s a short time before the shock front hits the axis.

When the shock front hits the axis, a reflected shock develops (Fig 4) and moves radially outwards. The piston continues to compress inwards until it hits the out-going reflected shock front. We define this point where the piston meets the reflected shock as the point of maximum gross compression, obtaining $r_{\min} = 1.2$ mm. Experimental observations using shadowgraphs and streak photographs complemented by electrical and x-ray measurements [19-26,30,32], indicate that beyond this point of time the plasma radius remains at about the value of $r_{\min}$ for a short period (some 20ns for the UNU/ICTP PFF) before the pinch disassembles rather violently (see Fig 2).

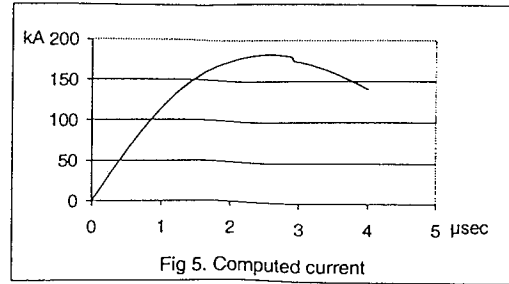


Fig 5. Computed current

Figure 5 shows the computation of the electric current [8], extending to the post-focus phase by using a simple expanded column approximation. The current agrees well with Rogowskii coil measurements [11,30,32].

The key computed pinch parameters for the deuterium focus are as follows:

$$r_{\min} = 0.13 \text{ a} \quad (15)$$

$$z_p = 0.7 \text{ a} \quad (16)$$

$$t_{\text{comp}} = 5 \times 10^{-6} \text{ a} \quad (17)$$

We have not computed t_p but this has been measured experimentally as [8]:

$$t_f = 2 \times 10^{-6} \text{ a} \quad (18)$$

The above results have been verified experimentally [26,30,32] with shadowgraphs and measurements of current, voltage, neutron and SXR of the UNU/ICTP PFF operated in deuterium. A sequence of shadowgraphs, taken recently using an improved arrangement consisting of a N-laser, CCD-computerised frame grabber [37] is shown in Fig.6/39/.

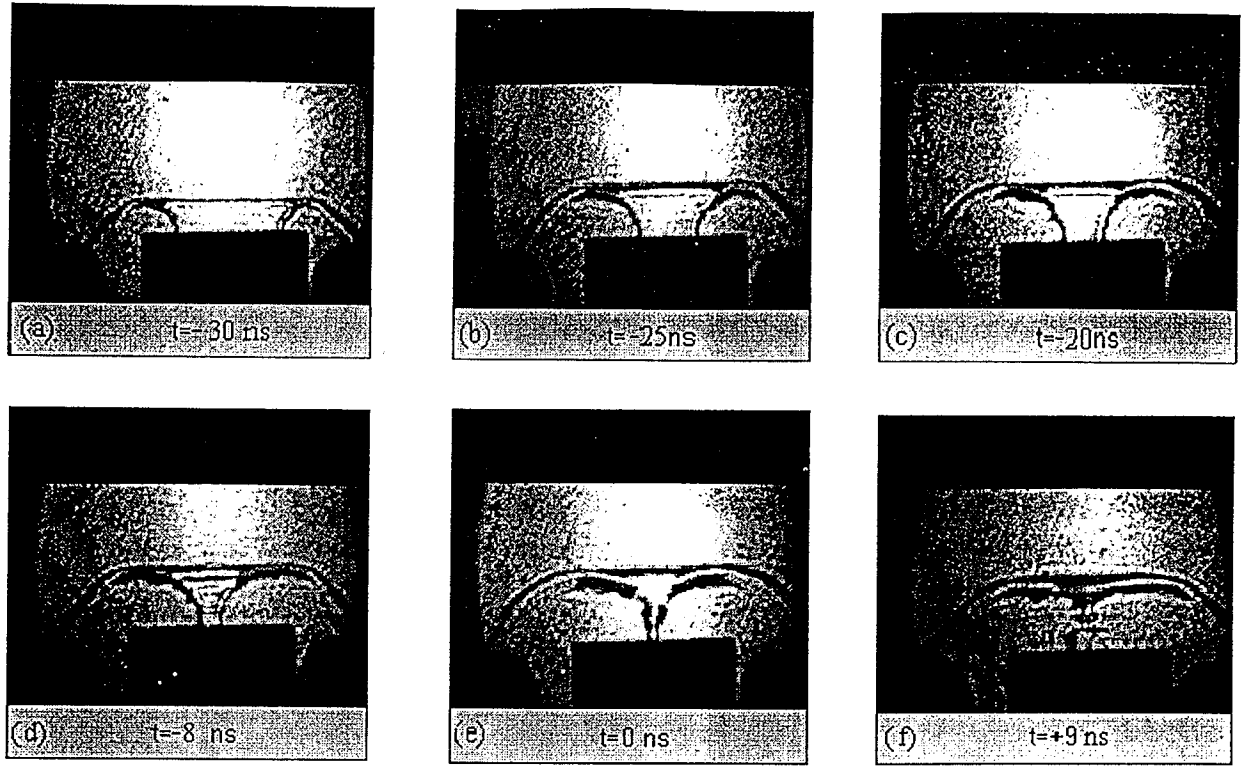


Fig 6 Sequence of compression in UNU/ICTP PFF at 4.0 mbar deuterium/39/

RADIATIVE PHASE FOR NEON

The plasma focus is operated in neon to generate SXR for microelectronic lithography /31-34,38/ in the wavelength range /32,34/ of 0.8 – 1.4 nm. We have performed calculations /32,33/ using the axial-radial model described above but including radiation terms (free-free, free-bound and bound-bound) into the dynamical equations as well as SXR yield equations. For a more realistic trajectory we have also included a delay in communication between the piston and shock front, the delay being computed from the finite small disturbance speed in the shocked plasma. This delay causes the shock front to feel the pressure of the magnetic piston some moments ago, likewise the piston to feel the position of shock front some moments ago. Including radiation loss and Joule heating, the piston radial motion is as follows:

$$\frac{dr_p}{dt} = \left[\frac{-r_p}{\gamma I} \frac{dI}{dt} - \frac{1}{\gamma + 1} \frac{r_p}{z_f} + \frac{4\pi(\gamma - 1)}{\mu\gamma z_f} \frac{r_p}{I^2} \frac{dQ}{dt} \right] \left(\frac{\gamma - 1}{\gamma} \right)$$

Where $Q = Q_{joul} - Q_{rad}$ is heat absorbed by the plasma. Q_{joul} is joule heating, Q_{rad} is radiation loss. The radiation rate dQ_{rad}/dt consists of line radiation, recombination and Bremsstrahlung:

$$P_l = 3.95 \times 10^{-35} \frac{Z_n^4}{T_{ev}} N_e N_i$$

$$P_r = 5.5 \times 10^{-37} N_e T_{ev}^{-1/2} \sum_z N_z z^4$$

$$P_b = 1.69 \times 10^{-38} N_e T_{ev}^{1/2} \sum_z N_z z^2$$

where N_z is the concentration of ions in z th ionised state, z is the charge number of the ions, T_{eV} the electron temperature in eV and Z_n the atomic number. The equations of motion are integrated together with circuit equation and the work done (W), the kinetic energy (E), the heat energy (Q) are computed for each time step; from which the internal energy (U) and hence the plasma temperature is computed using: $U = W + Q - E$

The radiation phase is computed for 10 ns, as observed experimentally for our UNU/ICTP PFF.

RESULTS FOR NEON

The trajectory of the plasma sheath in radial phase and its velocity are shown in Fig.7. The model gives the final radial velocity of the imploding plasma sheath ~ 30 cm/ μ s and pinch length ~ 8 mm. By introducing a reflected shock phase a minimum compression radius of ~ 0.4 mm is obtained, which agrees with results from shadowgraphy and schlieren photography done on this same machine.

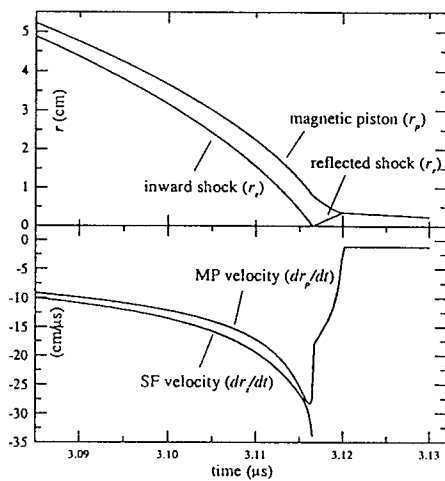


Fig 7

Upper plot: trajectories of radial inward shock (r_s), reflected shock (r_r) and magnetic piston (r_p).

Lower plot: inward shock speed (dr_s/dt) and magnetic piston speed (dr_p/dt)

(SF: shock front,

MP: magnetic piston)

The temperature of 360 eV and electron density of $\sim 10^{26} \text{ m}^{-3}$ are computed, as shown in Fig.8. The neon plasma is highly ionised, as can be seen in Fig.8(b). Fig.8(c) shows the comparison among the line radiation rate, recombination emission rate and the Bremsstrahlung rate. The

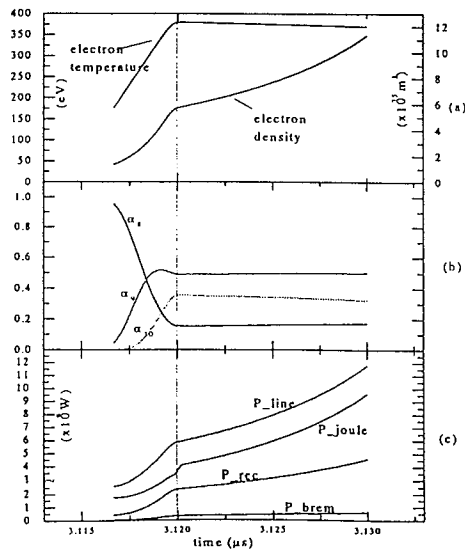


Fig 8

(a) electron temperature and density.

(b) fraction of 8th, 9th, and 10th ionised state for neon ion.

(c) P_{line} , P_{rec} and P_{brem} are emission rates from line radiation, recombination and Bremsstrahlung respectively; P_{joule} is the joule heating rate.

Conditions: discharge at 13 kV neon at 2.5 mbar.

joule heating rate is also shown. We see that the line radiation dominates the total radiation yield which in this particular case is 10 J.

Detailed ionization calculations indicate that the focus pinch temperature needs to be adjusted to 300 – 400 eV for optimum yield in the correct wavelength range (0.8-1.4nm for microelectronics lithography). We obtain this wavelength range from the radiation of He-like and H-like Neon ions. For the UNU/ICTP PFF we found that optimum yield is obtained at 14 kV operation at 1 torr. Because the neon is still ionising (rather than fully ionised) its effective specific heat ratio is computed as 1.4. This gives it a thinner slug layer and a smaller compressed radius. Some of the parameters of the neon focus pinch are calculated as:

$$r_{\min} = 0.04a \quad (19)$$

$$z_p = 0.8a$$

$$t_{\text{comp}} = 4 \times 10^{-6}a \quad (21)$$

These agree with experimental observations. We have also estimated from experiments:

$$t_f = 1 \times 10^{-6}a \quad (22)$$

The radiative plasma focus model gives the dynamics in the radial phase as well as quantitative results of the SXR emission from neon plasma focus. With the finite speed of small disturbance and reflected shock included into the model we obtained realistic physical picture of the radial inward compression and minimum compression radius. An electron density of 10^{26} m^{-3} and an electron temperature of 360 eV are computed using the model. For neon plasma at this temperature the line radiation is found to be the strongest feature, whereas the Bremsstrahlung is relatively weak. As the joule heating rate is small compared to the radiation loss, the radiative loss increases the compression of the plasma.

These results show good agreement with experimental measurements. For example the spectrum of the SXR is measured using a Flat Crystal Spectrograph /32-34/ and shown in Fig 9. SXR yield is measured by a calorimeter and by multi-channel filtered pin diodes and shown in Fig 10. These SXR computation and experiments on the UNU/ICTP PFF have produced part of the data base for the development of a high performance, high repetition rate SXR source, the NX2, for lithography applications, which is now in operation in the plasma SXR source laboratory of Nanyang Technological University /31,38/. The NX2 has 3.9 cm diameter anode of 5 cm length powered by a fast capacitor bank with 30 uF and exceedingly low inductance of 12 nH up to the focus head. It is operated typically at 2 kJ in 4 mb neon, produces 20 J per shot of SXR /31,38/ at the point source with peak currents of 400kA. Both the anode and cathode and the plasma chamber are cooled with chilled water and at 16 shots per second the NX2 produces 300W of SXR during burst duration of minutes. SXR lithography has been carried out with feature transfer effected at the 0.2 micron level /41,42/ (see Fig 11).

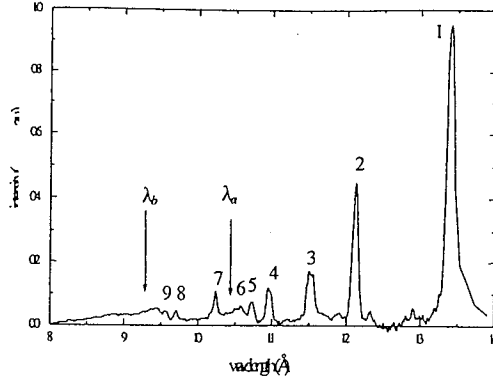


Fig 9. Spectrum of UNU/ICTP PFF, 3.5 mb Neon

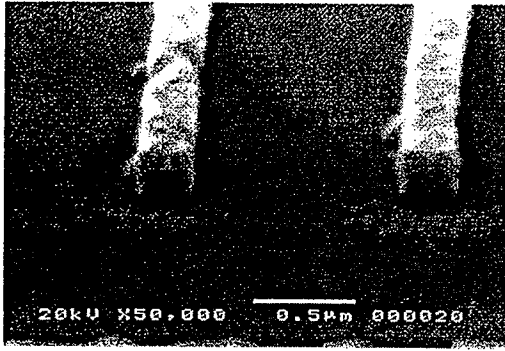


Fig 11. SXR transferred lithographic structure with 0.2 micron linewidth

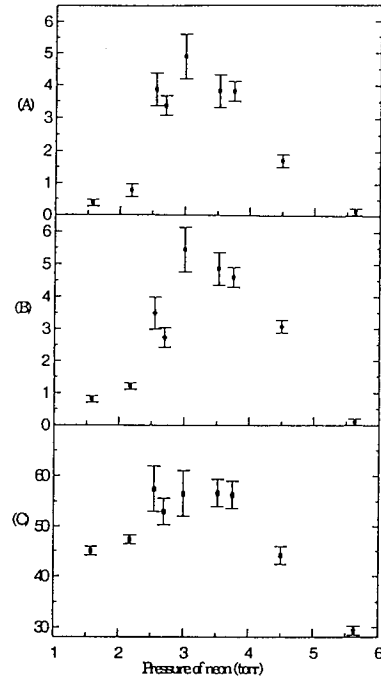


Fig. 10. (A) X-ray yield (Joules) measured by channel 5 of the 5-channel detector incorporating spectral information obtained from spectrograph (B) X-ray yield measured by calorimeter (C) Input energy (Joules) into the focus plasma of UNU/ICTP PFF

SCALING OF YIELD

For a thermalised plasma we can generally assign density n and temperature T . If the particles of density n interact among themselves with a cross section $C(T)$, generally depended on T , we may write down a general radiation yield, Y , relationship as follows:

$$Y \sim n^2 (\text{volume}) (\text{lifetime}) C \quad (23)$$

For the plasma focus, given the dimensional and temporal dependence as shown in equations (15), (16) and (18) or (19), (20) and (22) we have:

$$Y \sim n^2 a^4 C \quad (24)$$

Constant S operation

A survey of plasma focus devices /6/ have shown that in deuterium the drive parameter /26/ is $S = 90 \text{ kA per cm per (torr)}^{1/2}$ of deuterium over a range large range of energy from 3kJ – 200kJ. This corresponds to the well-known phenomenon that similar speeds are observed in small devices as well as in large devices. The quantity S is the magnetic energy density driving the system. Hence since the driving magnet energy is constant over the range of devices, it is consistent that the temperatures generated is also constant over the range of devices.

Given this observed constancy we have: $I \sim ap^{1/2}$ (25)

Hence applying equation (25) to Eq (24) with $n \sim p$ and noting that since $T=\text{constant}$ over the range of devices, the cross section C is also constant and we have /9/:

$$Y \sim I^4 \quad (26)$$

This yield law really applies to the thermonuclear neutron yield. Experimentally for a small neutron-optimised plasma focus it has been shown /27/ that the thermonuclear component of the neutron yield is only 15%, the other 85% being ascribed to beam-target mechanisms. Nevertheless we note that these yield proportions are occurring at a plasma ion temperature of about 1 keV and a beam energy of about 50 keV.

SPEED-ENHANCEMENT OF NEUTRON YIELD

This leads to the concept of speed enhancement /14,29/. If the driver parameter S is increased, the drive energy density increases, the speed increases and we may expect the focus pinch ion temperature also to increase. This leads to a dramatic increase in neutron yield since in the range of 1 – 10 keV, the neutron fusion cross-section is a rapid function of T with $C \sim T^n$, n being greater than 4. We note $T \sim v^2$. If we keep 'a' constant as the drive current is increased, we increase the drive parameter S . This will give us a thermonuclear yield component better than ($a = \text{constant}$) $Y \sim I^8$ (27)

Increase in speed will also increase the energy of the beam component. The beam component will however not have a significant increase since above 50 keV the cross section C barely increases with T . This means that as operational speed is increased, the plasma focus neutron yield becomes more thermonuclear.

However it is not a simple matter to increase the drive speed. Experiments have shown that if the peak axial speed is pushed above 10 cm/ μ s, plasma focus quality simply deteriorates. A force-field flow-field decoupling mechanism /4,14,28/ has been proposed to account for the deterioration of the focus quality. An experiment /29,30/ was carried out to achieve this speed increase yet overcome the decoupling by keeping the 'speed-enhanced' region short. A stepped-anode, Fig 12, was used consisting of a 'normal' radius section designed with the normal S value, followed by a short 'speed-enhanced' section for which the S value was increased by a reduction of 'a'. By this means speeds up to 15cm/ μ s was achieved with focussing. Neutron-yield enhancement /29,30,36/ was indicated (see Fig 13). SXR yield IN DEUTERIUM was also speed-enhanced /25,30/

However this experiment was severely limited in its scope since 'speed-enhancement' was achieved not by an increase of I at fixed 'a', rather by effectively fixing I and reducing 'a'. This was due to the limitations imposed by the UNU/ICTP PFF in its electrical range of operation. It is proposed that speed-enhancement experiments should be carried out in a machine with fixed 'normal' 'a'; and to increase I above 'normal' values. In neon operated for SXR for microelectronics lithography no such enhancement is expected.

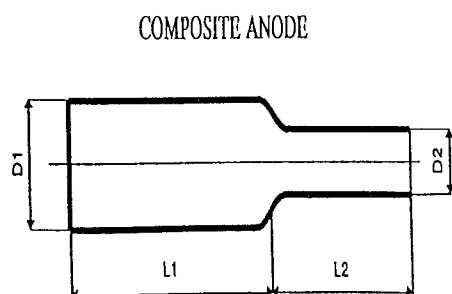


Fig 12. 2-stage anode for Speed enhancement

7. CONCLUSION

We conclude from computation, supplemented by experimental observations that the plasma focus pinch has gross parameters that scale according to anode radius 'a' in the following manner:

		Deuterion	Neon (for SXR)
minimum radius	$r_{\min}$	$0.13a$	$0.04a$
maximum length	z_p	$0.7a$	$0.8a$
radial shock transit	t_{comp}	$5 \times 10^{-6}a$	$4 \times 10^{-6}a$
pinch lifetime	t_r	$2 \times 10^{-6}a$	$1 \times 10^{-6}a$

where, the times are in sec, when the value of anode radius, a, is in m.

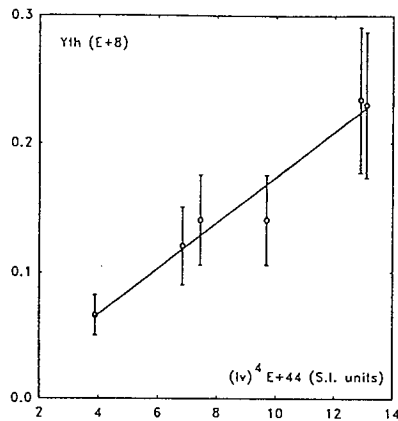


Fig 13. Non-beam component of neutron yield as function of $(Iv)^4$, speed-enhanced UNU/ICTP PFF, operated at 14 kV, 4.5 mb deuterium

The experiments confirm the validity of our axial-radial-reflected shock model which was developed for the UNU/ICTP PFF. Consideration of the model led to the concept of speed-enhancement of neutron and SXR yield for operation in deuterium. It has also given the basis for SXR yield computation. These experiments and computation on the UNU/ICTP PFF have resulted in a data base for the development of SXR lithography source /41.42/ which may have critical importance for the future of microelectronics industry. Work on the UNU/ICTP PFF was also responsible for inventing a cascading focus /7/ and a sequenced nitrogen laser /40/.

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