UNU/ICTP PFF - Design, Signature and Dynamics

Sequence of compression in UNU/ICTP PFF at 4.0 mbar deuterium
TWELVE YEARS OF UNU/ICTP PFF- A REVIEW

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TWELVE YEARS OF UNU/ICTP PFF-A REVIEW

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PREFACE

The UNU Training Programme on Plasma and Laser Technology was conducted from October 1985 to April 1986 at the University of Malaya under the direction of Prof. Sing Lee in collaboration with Mr. Walter Shearer of UNU. Since then this programme has been followed up by the International Center for Theoretical Physics (ICTP).

A unique feature of the training program was that, upon returning, the Fellows could bring the necessary equipment to continue their research at their home institutes. Such equipment consisted of nitrogen lasers and glow discharge equipment as well as complete sets of a plasma focus facility (including diagnostics) designated as the UNU/ICTP plasma focus (fusion) facility.

From the beginning Prof. Sing Lee emphasized that the success of the programme depended on the work that would be carried out back at the home institutes of the fellows in order to achieve the multiplicative effect stressed by the UNU guidelines.

Over the years, many Ph.D. Degrees, and Master Degrees have been produced and 6 new laboratories have been built. Twelve years have passed, now, and it was considered a good time for reviewing the programme.

The review meeting was conducted, and Prof. Takaya Kawabe of UNU/IAS attended as the representative of UNU. The contents of the review have been summarized in this web site, entitled "Twelve Years of UNU/ICTP PFF – A Review". As you can see in the attachment, reports from Singapore, Islamabad, Delhi, Port Harcourt & Harare, Cairo and Kuala Lumpur have been included.

From the point of view of Prof. Kawabe, this programme has been successful for the following reasons:
● The strong leadership of Prof. Sing Lee and his colleagues.
● Proper selection of the theme.
● The unique idea of bringing back experimental equipment to the respective home institutes to continue research.
● Good financial support from the international and domestic sources.
● Good networking among the trainees after their return to their home institutes.

Outcomes from this programme are:
● Basic understanding of plasma physics, particularly experimentally.
● Training of technical know-how for construction of the experiments and with regard to the question of how to carry out experimental investigation

Suggestions for future activities may be:
● Follow-up of the results achieved thus far.
● New direction of the themes, such as plasma applications in many areas, to which many developed countries have been making efforts.

UNU/ICTP PFF made a great contribution in just twelve years. As the Rector of the UNU, I believe that this programme can serve as an excellent example of a successful international training activity in a very advanced scientific field. I look forward to the future of this activity, which may expand to new fields as well.

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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.
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 focusing 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.

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

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* 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 $\gamma$, 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

This model has also been used to predict a new type of plasma focus operating with several anodes to produce a sequence of focusing [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 PPF 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 polyaniiline film subjected to plasma ion bombardment (d) observation of p-n junction diode formation in a single polyaniiline 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$_2$Te$_3$ (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 [D21s].

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.

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)


D13P. Imtiaz Ahmed. Plasma dynamics and characteristics in gas-linear pinch and plasma focus (Experimental Stark width of Kr-III lines), PhD thesis (submitted) QAU, Islamabad, Pakistan.


M.Sc. /M.Phil. Theses (31)


M24P Muhammad Shafiq. Effect of anode material on electron temperature in Mather type plasma focus. QAU, Islamabad, Pakistan, 1995.

M25P Safdar Hussain. Effect of insulator sleeve material on electron temperature in Mather type plasma focus. QAU, Islamabad, Pakistan, 1995.


M31E M.A. Mansour Measurements of the Plasma Parameters in Plasma Focus Device. Al Azhar University, Cairo, Egypt, 1996.

Papers in Refereed Journals


Conference Papers


C43. R.S.Rawat, M.P.Srivastava and S.R.Mohanty, Laser Shadowgraphic study of Plasma sheath in Dense plasma Focus in the presence of external magnetic field,


Books/Chapters in Books/Reports


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:

<table>
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<tr>
<th>Parameter</th>
<th>Deuterium</th>
<th>Neon (for SXR)</th>
</tr>
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<tr>
<td>Minimum radius</td>
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<td>0.13a</td>
</tr>
<tr>
<td>Maximum length</td>
<td>$z$</td>
<td>0.7a</td>
</tr>
<tr>
<td>Radial shock transit</td>
<td>$t_{\text{comp}}$</td>
<td>$5 \times 10^{-6}$a</td>
</tr>
<tr>
<td>Pinch lifetime</td>
<td>$t_f$</td>
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</tr>
</tbody>
</table>

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.

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).

\[
\tau = \frac{t}{t_o}, \quad \zeta = \frac{z}{z_o}, \quad t = \frac{1}{L_o}, \quad \delta = \frac{t_o}{Z_o}
\]

\[
\kappa_e = \frac{r_e}{a}, \quad \kappa_r = \frac{r_r}{a}, \quad \zeta_e = \frac{z_e}{a}, Z_o = \frac{L_o}{\sqrt{C_o}}
\]

\[
t_a = \sqrt{L_o C_o} \quad \text{and} \quad I_o = \frac{V_o}{Z_o}
\]

Axial Phase:

Motion:

\[
\frac{d^2 \zeta}{d \tau^2} = \alpha^2 \tau^2 - \left( \frac{d \zeta}{d \tau} \right)^2 \quad (1)
\]

Current:

\[
\frac{d t_a}{d \tau} = \frac{1 - \int \mu d \tau - \beta \frac{d \zeta}{d \tau} (1 - \delta)}{1 + \beta \beta \zeta} \quad (2)
\]

to compute \( \phi \) and \( t_c \), 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:

\[
\alpha = t_o / t_s \quad \text{and} \quad t_s = \left[ \frac{4\pi^2 (c^2 - 1)}{\mu \ln c} \right] \frac{z_o \sqrt{f_s}}{f_r} \frac{\sqrt{\rho}}{(l_s / a)}
\]
giving a characteristic axial transit speed of \( v_a = z_o / t_a \) of

\[
v_a = \left[ \frac{\mu \ln c}{4\pi (c^2 - 1)} \right]^{1/2} \frac{f_c (I_o / a)}{\sqrt{f_m} \sqrt{\rho}}
\]

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 \( \varsigma \) and \( \iota \), until \( \varsigma = 1 \). Then the dynamics move to the radial phase as follows:

**Radial Phase**

Normalized radial phase equations are:

- **Inward shock:**
  \[
  \frac{d\kappa_s}{d\tau} = -\alpha s - \frac{1}{\kappa_s}
  \]

- **Elongation:**
  \[
  \frac{d\varsigma_s}{d\tau} = -\frac{2}{\gamma + 1} \frac{d\kappa_s}{d\tau}
  \]

- **Inward piston:**
  \[
  \frac{d\kappa_p}{d\tau} = \frac{2 \kappa_s}{\gamma + 1} \frac{d\kappa_s}{d\tau} \left( 1 - \frac{\kappa_s^2}{\kappa_p^2} \right) \frac{dt}{\gamma + 1 \varsigma_f} - \frac{1 \kappa_p}{\gamma + 1 \varsigma_f} \frac{d\varsigma_p}{d\tau} \left( 1 - \frac{\kappa_s^2}{\kappa_p^2} \right) \frac{dt}{\gamma + 1 \varsigma_f}
  \]

- **Current:**
  \[
  \frac{d\iota}{d\tau} = \frac{1 - \int dt + \frac{\beta_i f_c \varsigma_f \kappa_s}{F} + \frac{\beta_i c}{F} \ln(\kappa_p) \frac{d\varsigma_p}{d\tau} - \delta \iota}{1 + \frac{\beta_i c}{F} \ln(\kappa_p) \frac{k_p}{c}}
  \]

where \( \beta_i = \frac{\beta}{\ln c} F = \frac{z_o}{a} \)

and the ratio of the characteristic axial transit time to characteristic pinch time

\[
\alpha_s = \frac{t_a}{t_p} = \left[ \frac{\gamma + 1}{c^2 - 1} \right]^{1/2} \frac{F \sqrt{f_c}}{2 \sqrt{f_m}}
\]

Hence \( t_p = \frac{4\pi}{\mu (\gamma + 1)^{1/2} f_c (I_o / a) a} \)

and characteristic pinch time \( a/t_p \) is

\[
v_p = \left[ \frac{\mu (\gamma + 1)}{4\pi} \frac{f_c (I_o / a)}{\sqrt{\rho}} \right]
\]

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 \( \varsigma_f = 0 \). Eqs 7-10 are integrated step-by-step in time for \( \kappa_s, k_p, \varsigma_f \) and \( \iota \). This phase ends when the inward-going shock reaches \( r_s = 0 \) with speed \( (dr_s/dt) \) 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/dt) 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 \( r_{\text{min}} \). 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:

\[
C_0 = 3 \times 10^{-5} \text{F}, \quad L_0 = 1.1 \times 10^{-7} \text{H}, \quad a = 0.95 \times 10^{-2} \text{m}, \quad b = 3.2 \times 10^{-2} \text{m}, \quad z_0 = 0.16 \text{m}, \quad c = 3.37, \quad F = 16.84
\]

Hence \( t_z = \sqrt{L_0/C_0} = 1.82 \times 10^{-4} \text{s} \quad Z_o = \sqrt{L_o/C_o} = 0.06 \Omega \)

Typical operation is at 14 kV with ambient pressure of 3.5 torr deuterium giving:

\[
\rho = 8.2 \times 10^{-4} \text{kgm}^{-3}, \quad V_o = 1.4 \times 10^4, \quad \delta = r_o/Z_o = 0.2, \quad \text{we take } f_c = 0.7, f_m = 0.1, f_{mr} = 0.3,
\]

Hence \( t_a = 1.38 \times 10^{-6} \text{s} \quad v_a = 1.15 \times 10^5 \text{m/s}, \quad t_p = 6.0 \times 10^{-8} \text{s}, \quad v_p = 1.6 \times 10^5 \text{m/s}, \quad \text{and } \alpha = 1.31, \alpha_1 = 23.2, \beta = 0.35, \beta_1 = 0.29\)

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 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 1.6 mm from the axis and the length of the lengthening focus column is 7.1 mm. The piston speed, which had peaked at 30 cm/µs, reduces sharply as the shock approaches the axis. The speed of the shock front as it approaches the axis exceeds 50 cm/µs. This is unrealistically high and is due to the implicit assumption of instantaneous communication between the piston and the shock front i.e., 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/µs for the shock front on-axis and to about 20 cm/µs 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 \( r_{\text{min}} = 1.2 \) 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 \( r_{\text{min}} \) for a short period (some 20 ns for the UNU/ICTP PFF) before the pinch dissembles rather violently (see Fig 2).

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:

\[
\begin{align*}
  r_{\text{min}} &= 0.13 \text{ a} \\
  z_p &= 0.7 \text{ a} \\
  t_{\text{comp}} &= 5 \times 10^{-6} \text{ a}
\end{align*}
\]

We have not computed \( t_p \) but this has been measured experimentally as [8]:

\[
t_f = 2 \times 10^{-6} \text{ a}
\]

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].
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:

$$\frac{d r_p}{dt} = \left[ -r_p \frac{d I}{dt} + \frac{1}{\gamma + 1} \frac{r_p}{\mu} \frac{d Q_{\text{rad}}}{dt} \right] \left( \frac{\gamma - 1}{\gamma} \right)$$

Where $Q = Q_{\text{foul}} - Q_{\text{rad}}$ is heat absorbed by the plasma. $Q_{\text{foul}}$ is joule heating, $Q_{\text{rad}}$ is radiation loss. The radiation rate $dQ_{\text{rad}}/dt$ consists of line radiation, recombination and Bremsstrahlung:

$$P_l = 3.95 \times 10^{-35} \frac{Z_e^4}{T_{ev}} N_e N_i$$
$$P_r = 5.5 \times 10^{-37} N_e T_{ev}^{-1/2} \sum_z N_z z^4$$
$$P_b = 1.69 \times 10^{-38} N_e T_{ev}^{1/2} \sum_z N_z z^2$$

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 $\sim 30$ cm/µs and pinch length $\sim 8$ mm. By introducing a reflected shock phase a minimum compression radius of $\sim 0.4$ mm is obtained, which agrees with results from shadowgraphy and schlieren photography done on this same machine.

![Fig 7](image)

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 $\sim 10^{26}$ 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 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.

![Fig 8](image)

(a) electron temperature and density.
(b) fraction of 8th, 9th, and 10th ionised state for neon ion.
(c) $P_{\text{line}}, P_{\text{rec}}$ and $P_{\text{brem}}$ are emission rates from line radiation, recombination and Bremsstrahlung respectively; $P_{\text{joule}}$ is the joule heating rate.

Conditions: discharge at 13 kV neon at 2.5 mbar.
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:

\[
\begin{align*}
 r_{\text{min}} &= 0.04a \\
 z_p &= 0.8a \\
 t_{\text{comp}} &= 4 \times 10^{-6}a
\end{align*}
\]

These agree with experimental observations. We have also estimated from experiments:

\[
t_f = 1 \times 10^{-6}a
\]

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 \(10^{26} \text{ m}^{-3}\) 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 a multi-channel filtered pin diode spectrometer. The results, Fig 10 indicate a maximum of 5J (SXR into \(4\pi\)) from the UNU/ICTP PFF operated in neon at 1 torr.

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 mbar 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 mbar Neon

**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

**Fig 11.** SXR transferred lithographic structure with 0.2 micron linewidth

**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:

$$Y \sim n^2 \text{ (volume) (lifetime) } C$$  \hspace{1cm} (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:

\[ Y \sim n^2 a^4 C \]  \hfill (24)

**Constant S operation**

A survey of plasma focus devices [6] have shown that in deuterium the drive parameter [26] 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-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:

\[ I \sim \alpha \rho^{1/2} \]  \hfill (25)

Hence applying equation (25) to Eq (24) with \( n \sim p \) and noting that since \( T=\)constant over the range of devices, the cross section \( C \) is also constant and we have /9/:

\[ Y \sim I^8 \]  \hfill (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 ‘\( \alpha \)’ constant as the drive current is increased, we increase the drive parameter \( S \). This will give us a thermonuclear yield component better than (\( a = \) constant)

\[ Y \sim I^8 \]  \hfill (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/µs, 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 ‘\( \alpha \)’. By this means speeds up to 15cm/µs 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

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

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:

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<td>(t_{\text{comp}})</td>
<td>5x10^{-6}a</td>
</tr>
<tr>
<td>pinch lifetime</td>
<td>(t_f)</td>
<td>2x10^{-6}a</td>
</tr>
</tbody>
</table>

where, the times are in sec, when the value of anode radius, a, is in m.
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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Radiation Generation Mechanisms And Machine Parameters Optimization In A Low Energy Mather-Type Plasma Focus.

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ABSTRACT

An extensive series of experiments has been performed on a low energy (2.3 kJ) plasma focus with a view to understand radiation generation mechanisms and the dependence thereof on various parameters of the device.

1. INTRODUCTION

The plasma focus (PF) devices were developed in the early 1960s independently in the USA and the former Soviet Union [1-2]. The devices have proved an effective tool to investigate a variety of phenomena such as $J \times B$ acceleration of current sheath and pinch formation, and neutron and x-ray generation in high temperature high density plasma [3,4]. The low energy plasma focus device has also received considerable attention in the teaching of plasma dynamics and the study of nuclear fusion [5]. Various machine parameters, such as the configuration of the electrodes and the insulator, their dimensions and the material they are made of, and the initial pressure, are all interrelated in an intricate way. Similarly no general relationship has been found so far for the radiation yield. The operational simplicity and easy-to-handle changes one can execute on the machine parameters recommend these low energy plasma devices for understanding the generation mechanisms for neutron and x-ray emission and their dependence on the choice of various parameters of the device.

2. EXPERIMENTAL SETUP

The experiment is conducted on a PF system energized by a 32 $\mu$F single capacitor charged at 12 kV (2.3 kJ) giving a peak discharge current of about 190 kA. The parasitic inductance of the system is estimated to be 80 nH, whereas the current rise (quarter-period) time is about 1 $\mu$sec. The anode is a Cu rod of length 160 mm (measured from the cathode base plate) and diameter 18 mm. It is surrounded by six 10 mm diameter Cu rods forming a perforated cathode of inner diameter 50 mm. The cathode rods are screwed to a Cu plate, called the cathode base plate, which has a knife edge near the anode. A 2.2 mm thick insulator sleeve of Pyrex, with a breakdown length of 25 mm, is placed between the anode and cathode at this end. The assembly is adjusted vertically. The schematic arrangement of the Cu electrode system and diagnostics is given in figure 1. For time resolved neutron measurements, photomultiplier tubes XP 2020 optically coupled with (50x50)mm cylindrical plastic scintillator NE 102A are employed which are placed at 100±1 cm from the focus region. The detectors have a rise time of about 2 nsec. A 3 mm thick Al is employed to shield the scintillator + PMT assembly. The time-integrated neutron detectors consist of Geiger-Muller tubes along with silver foils and paraffin wax, which are calibrated against an Am-Be continuous neutron source.

The time-integrated x-ray detector is a multi-pinhole imaging camera which consists of four pinholes in linear arrangement. The time resolved detectors are three Quantrad pin-diodes. The Al(5 $\mu$m), Ti(15 $\mu$m), Cu(10 $\mu$m) and Zn(25 $\mu$m) filters mask the pinholes of the imaging camera, whereas three filters exclusive of Al(5 $\mu$m) masks the pin-diodes. The field of view of both the diodes and imaging camera include the pinch region as well as the anode end rim. The transmission characteristics of different filters, and sensitivity of the diodes masked with
corresponding filters, is given in figure 2. These curves are obtained by using the data of Henke et al. [6].

Figure 1: Schematic arrangement of plasma focus electrodes system and diagnostics.

To study the ions emitted from the focus region, solid state nuclear track detectors (SSNTDs) CR-39 of size 1.2 mm x 25 mm x 25 mm, are employed. By masking the detectors with a stack of Al foils 6, 12, 18 and 24 μm in thickness, the measurements are made simultaneously at 10°, 30°, 50°, 70° and 90° angular positions relative to the focus axis, (9.0 ± 0.2) cm from a point, 1.0 cm above the anode face, considered as the focus point. The detectors were etched in 6N NaOH solution maintained at (70±1)°C.

The time-integrated charged particle detector is the same pinhole camera used for x-ray imaging. The 0.5 mm pinhole is at a distance (8.0 ± 0.2) cm from the focus region 0.6 cm above the anode face, considered as the focus point, whereas the SSNTDs are placed inside the pinhole camera at the same distance of (8.0 ± 0.2) cm from the pinhole. Eight 25 mm x 25 mm detectors may be fixed simultaneously on the holder with the help of double-sided tape. After recording image on the detector, the holder may be rotated without disturbing the vacuum to bring the next detector in front of the focused plasma. The detectors were exposed to the plasma for a single shot and then etched in 6N NaOH solution maintained at (70±1)°C. After etching, the detectors were washed in fresh water and then cleaned in ultrasonic bath.

3. Experimental Results
We find that the proper selection of the lengths of anode [7] and the insulator sleeve [8] lowers the neutron fluence anisotropy and enhances the possibility of azimuthally symmetric and uniform current sheath. If the external plastic inductance is small enough and matches with the cumulative inductance of the focus tube and the pinch region, the deuterium pressure range as well as the neutron pulse width is broadened while the energy-to-gas ratio is greatly reduced [9]. Under such conditions, one expects that nearly 70% neutrons will be emitted within a length of 2 cm above the anode tip.

The contamination of the insulator sleeve changes the characteristics of the device [10]. However, a minimum level of contamination seems essential for prompt breakdown and good focusing action which, in turn is associated with high neutron yield. As the contamination level grows, the current partition increases which gives rise to multiple foci formation. Any further increase in sleeve contamination causes neutron yield deterioration [11]. We make another important observation that the neutron emission from the focus region records a maximum whenever the average current sheath velocity is around $6.5 \times 10^4$ m/s. Any major departure from this value lowers the neutron yield. Furthermore, the neutron generation mechanism at play also seems to depend on the said velocity during the axial run. By placing a disc downstream of the anode, the device may also be used to generate sequential neutron and x-ray pulses [12].

Proper adjustment of machine parameters and tuning of driver impedance with that of the accelerator enhances the neutron emission from the pinch filament and broadens the pressure range for high neutron emission. However, the study is far from complete. A more comprehensive and systematic study of the plasma focus system characteristics using several diagnostics in parallel seems essential to fully understand the role of different parameters and the phenomenon involved. The operational simplicity and easy-to-handle changes one can do to the machine parameters recommend the low energy devices for such investigations [13].

The x-ray and neutron emission [12] is investigated by employing time-integrated and time-resolved neutrons and x-ray detectors. The intense x-ray emission is observed within a narrow pressure range of 2.0-2.5 mbar, compared to the broader pressure range of 1.5-4.0 mbar for higher neutron yield. The width (FWHM) of the neutron emission profile is almost twice the x-ray emission profile (40-50 nsec) and is delayed for 30-40 nsec. The most intense and high energy x-rays are emitted from the anode surface. For 2.0-2.5 mbar, the pressure range of intense x-ray emission, the structure of axial shock wave becomes a bright source of x-rays.

X-ray and ion beam emission using argon as the filling gas are studied also [14]. Special attention is paid to the effects of anode shape on radiation yield. As the anode radius towards the end is reduced, the filling gas pressure has to be increased so as to time the peak current at the end of the central electrode. The data shows the tapered anode to be the best x-ray emitter. A significant part of the x-rays seems to originate from the anode end, probably via a thick bremsstrahlung mechanism by electron impacts. Furthermore, for this anode shape, the intensity of the HV probe signal, x-ray signal and ion beam signal are clearly correlated, while for the cylindrical anode there appears some correlation and for the cone shaped anode no correlation at all. The effect of electrode shape on neutron emission requires further work.

Multiple foci formation is observed in the presence of the magnetic probe placed in the vicinity of the focus region [15]. Semi-optical images of the focus tube reveal that the current sheath climbs up the probe for up to several centimeters. The climbing ability seems to deteriorate with pressure increase due to the degradation of snowplow efficiency. X-ray images
recorded in the pressure range 0.25-3.25 mbar clearly indicate enhancement of intensity as well as enlargement of the x-ray emitting source. When no probe is inserted in the system, the pressure range is restricted to 0.25-2.50 mbar only. Enhancement of intensity is also confirmed by the x-ray pin-diode signal. The electron beam is detected for the pressure range 0.25-3.25 mbar when the probe is inserted and for 0.25-2.25 mbar with no probe. Current sheath velocity after the first convergence above the anode tip is estimated to be about $10^7$ cm/sec. The formation of an intense x-ray emitting spot occurs at about 9 cm above the anode and is due to the refocusing of the fast moving current sheath at that height. The observed phenomenon strongly supports the idea suggested by Gratton et al. [16] that attention must be paid to the plasma focus research in the context of target implosion for inertial confinement. It is not so clear at this stage what causes the current sheath to climb up the probe and why the pressure range is broadened for the efficient electron and x-ray emission. Perhaps, the polarization of the magnetic probe material generates an electric field which provides an additional force to lift up the current sheath.

Neutron and x-ray emission [17] with stainless steel anode is investigated and the results are compared with previous experiments [13] employing Cu anodes. A high neutron yield of $3.5 \times 10^8$ is recorded which is almost twice as much compared to Cu anode operation in the same system. The filling pressure for high radiation yield is also extended to the higher side. The low sputtering yield of stainless steel compared to Cu by electron impact is considered to be responsible for the changes in the device characteristics. However, one needs to employ an insulator sleeve with sufficient surface contamination of some conducting material like Cu, or fire the system up to approximately 150 shots (in a 2.3 kJ device) to make it a good radiation (neutron and x-ray) source.

Charged particles and x-ray emission [18] with argon as the filling gas is investigated. At low filling pressure, the soft x-ray emission zone is broad and a significant amount of x-rays originate from the anode tip. With increasing pressure, x-ray emission zone squeezes to pinch filament at the axis. Two modes of charged particles emission are identified, the first at a low pressure of 0.25 mbar and the second at higher pressure of 1.75 mbar. The intensity of charged particle beams at lower pressure is higher. Radiation signal intensities are correlated mutually as well as with the $d/dt(IL)$ signals, except at 1.75 mbar. Probably at this pressure, some nonlinear phenomenon breaks the correlation, which need further investigation. The energy of the ion beam is high (about 4.8 MeV) for the pressure range 1.25-1.75 mbar, which may find applications for ion implantation studies.

Radiation (neutrons, x-rays and ions) emission [19] has been investigated with a view to understand its behavior vis-a-vis the filling pressures. The neutron emission profile is not a single pulse like in high energy [20] and medium energy [21] devices. Further, the intensity and fluence anisotropy of neutron emission varies with filling pressure which indicates that the neutron production mechanisms at play are functions of pressure. At low pressure (1.0-2.0 mbar), the neutron yield is low ($\sim 7 \times 10^7$) and fluence anisotropy is high ($\sim 3.5$). On the other hand, the pressure regime (2.5-3.0 mbar) of high neutron emission ($2 \times 10^8$) shows low fluence anisotropy ($\sim 1.5$) indicating enhanced contribution of fusion reactions within the focus region. An intense hard x-ray pulse is recorded at these pressures (2.5-3.0 mbar). Charged particle emission is also at its highest at the same pressures. Figure 3 describes the behaviour of neutron emission, whereas figure 4 contains the x-ray pinhole images.

The ranges of $^2$He$(0.82\text{MeV})$, $^1$T$(1.01 \text{MeV})$, $^1$H$(3.02\text{MeV})$ and $^1$D$(100\text{keV-10 MeV})$ in CR-39 are calculated by using TRIM code. The bulk etching rate of CR-39 detectors in 6N
NaOH solution maintained at 70° C is about 1.3 μm/hour [22]. It is expected that the tracks formed by impact of $^3$He$^+(0.82$ MeV) ions may be visible for etching time appreciably less than three hours. But the tracks formed by impact of $^3$T$^+(1.01$ MeV), $^1$H$^+(3.02$ MeV) and $^3$D$^+(300$ keV - 10 MeV) may grow even larger for etching time exceeding three hours. The images were examined after etching of 1.5, 2.5, 3.5 and 6 hours. The structure of the image and its distance from the anode doesn't change. However, the sharpness of the image gradually increases, as expected. Figure 5 contains the photographs of the pinhole images (with magnification 1) formed on CR-39 detectors after etching time of 6.0 hour. The images are formed for pressure range of 0.25 mbar to 3.5 mbar. In these images, the dense spots are associated with the region which contains energetic charged particles. That is, the images help to identify the energetic charged particle emission/fusion reaction zone. At 0.25 mbar, a dotted region spread over a large volume is observed. With increase in pressure to 0.50 mbar, elongated beaded structure, started just from the anode tip is observed. Probably, at this pressure, the sausage-type instabilities efficiently necks off the plasma column. At 1.0 mbar, about 8 mm long a rocket type plasma column, which looks moving away from the anode tip is observed. At 1.5 mbar, this rocket-type plasma column breaks into two whereas, at 2.0 mbar, about 12 mm long plasma column which is broken at many locations, starting 3 mm away from the anode tip is seen. At 2.5 mbar, an almost stable dense plasma region which is about 3 mm in length, 2 mm in diameter and about 5 mm away from the anode tip is seen. Its volume is estimated to be about 17 mm$^3$. With increase in pressure, dense plasma region squeezes in size and shifts away from the anode. It is 8 mm away at 3.0 mbar, 15 mm away at 3.5 mbar, and not visible at high pressure, probably it is formed out of the field of view of the imaging camera. The formation of dense plasma region away from the anode at high pressure is because the current sheath keeps on moving axially during radial compression which is now slow.

4. Discussion and conclusion

One knows [23] that the plasma focus devices may be operated either in charged particle beam optimized or neutron emission optimized mode. The former mode is observed at lower filling pressure, and the latter mode at a relatively higher pressure. The results of this experiment are in accordance with Rager [23]. At low filling pressure (<1.5 mbar), low neutron yield with high fluence anisotropy demonstrates the dominance of beam target mechanism as the mode of neutron production in this device. For filling pressure of 2.5 - 3.0 mbar, the neutron yield becomes high. At still higher pressure (3.0-4.0 mbar), the radial neutron flux is lowered and the fluence anisotropy is increased. In the light of this result as well as the result of Bostick et al. [24] in a 5.4 kJ device, which reported high neutron yield at 4.0 mbar with high ion beam intensity along the axis, it appears that the ion beam is responsible for neutron emission even in high neutron mode. One may explain the observed data by considering the notion of some anomalous magnetic field in the pinch region [20, 25-26]. Lu [25-26] suggested that some magnetic field is introduced in the pinch region from the very beginning of the discharge, and that its flux density rises to a very high value due to trapping and compression of the field lines by the plasma sheath. One speculate that the pressure range 2.5 - 3.0 mbar in this system generates favorable conditions for plasma density and pinch filament diameter to trap the energetic deuterons. These gyrating deuterons then react with the plasma column producing D-D fusion and generating high neutron emission with low fluence anisotropy, in accordance with the generalized beam-target mechanism [20]. In this way, a deuteron flux with anisotropy of about 6 may generate neutron flux with anisotropy as low as 1.5. Outside this pressure range, the axially directed deuteron beam induced neutron emission dominates, resulting in high fluence anisotropy.
The x-rays arise from the anode face either due to impact of electron beam or the electrons in the plasma sheath. In this experiment, the anode tip is engraved 25 mm deep and 10 mm wide, and the detectors are mounted in the radial direction. The x-rays emitted from the anode due to impact of electron beam cannot reach the detectors and thus the detected radiation is due to interaction of plasma sheath with the anode. The variation of electron beam intensity versus filling pressure for He, Ne and Ar [18,27] has been studied, and that the intensity is found to be the highest around 0.2-0.4 mbar pressure. Although the beam intensity goes down by a factor of three at higher pressure, it remains appreciable within the entire pressure range for good focus. The intensity exhibits another peak in the range of 1-1.75 mbar. In x-ray pinhole images, a bright core in the pinch filament is observed which probably reflects the passage of electron beam along the axis. However the bright core is seen through the Al (5 μm) filter only since the filter has pass band around (0.7-1.55) keV, implying that x-ray energy falls in the Al-filter pass-band. One may speculate that the enhanced x-ray emission around 2.5 mbar is also associated with electron beam formed and its traversal along the focus axis. Besides, the x-rays are also generated by the axially moving shock wave [12], the latter becomes a soft x-ray source for a particular narrow pressure range. Harries et al. [28] reported that low energy soft x-rays are emitted from the anode surface. In our experiment we also found that major contribution of soft x-rays is from the anode surface and that it is due to interaction of current sheath with anode. The plasma emits only soft x-rays, while the hard x-rays originate from the anode due to interaction of electron beam and the anode surface, which is in agreement with Harries et al. [28]. Wang et al. [29] reported high x-ray emission at low pressure from pinched plasma column. However, our experiment does not support their result. At low pressure, the x-ray emission is high, but the radiation is dominantly Cu Kα from the anode surface, not from the pinched plasma column.

In conclusion, we have studied the neutron, x-rays and charged particle emission vis-a-vis filling pressure in a low energy plasma focus with a view to enhance our understanding of neutron and x-ray emission mechanism from low energy plasma focus. It seems that the production mechanism at play strongly depends upon the filling pressure. The data suggests beam target mechanism at low pressure, trapped gyrating particles in some anomalous magnetic field at optimum pressure for high neutron emission, and a jet-like moving boiler at high pressure. While at low pressure the x-rays are generated by interaction of current sheath electrons with the anode surface, and at high pressure, the axially moving shock wave and interaction of energetic electron beam with plasma and the anode causes x-rays emission.
Figure 2:
(a) Transmission characteristics of different absorption foils
(b) Sensitivity curves of pin-diodes along with different absorption foils.

Figure 3:
Variation of (a) axial neutron flux (b) Radial neutron flux
(c) Total neutron emission (d) Neutron fluence anisotropy,
with filling pressure.
Fig 5. Pinhole images formed on CR-39
REFERENCES

HISTORICAL:

It may be necessary to recall the chronological historical development of experimental plasma physics research at Delhi University. It was during summer of 1983 when I was visiting International Centre for Theoretical Physics as an Associate Member coinciding my visit with Spring College on Plasma Physics, when Prof. Sing Lee in ICTP started discussing with plasma physicists from several developing countries the status of the then existing experimental plasma research in developing countries. It was felt that there was sufficient expertise and demand among developing countries to warrant the conduct of hands on plasma training programme at Regional Centres for the purpose of sharing plasma technology among developing countries. He gave his future plans of organizing a training programme under which the participants will be trained for about six months during which time they will fabricate the dense Plasma Focus chamber, electrode assembly, high voltage power supply, associated triggering electronics and some diagnostics. At the end of the training programme, the fabricated system will be supplied to the institute from where the participants had come. With the training of manpower as well as on transfer of fabricated system seemed attractive and had the potential of sharing experimental Plasma research within the developing countries. Subsequently in 1984 and in 1986 the First and the Second Tropical Colleges on Applied Physics - Laser and Plasma Technology were organized in Kuala Lumpur under the sponsorship of UNESCO and ICTP with novel features of a large element of hands on training. Thereafter, a fully hands on practical approach was adopted in a six month UNU training held in 1985/86 by Prof. Sing Lee on Plasma and Laser Technology. Prof. Sing Lee contacted me for nominating someone for the third tropical college and I decided to nominate for the UNU training Mr. MVHV Prabhakar who was doing his doctoral work under my supervision. At the end of the programme, the system was shipped to Delhi University but the main chamber got lost in the transit. Prof. Sing Lee soon shipped another chamber That chamber could demonstrate focusing action but was not suited for any work to be done. We got another chamber fabricated with suitable viewports. Nitrogen Laser used for diagnostics became operational soon after. But subsequently Dr. Prabhakar who received the UNU training left for Texas for his Post-Doctoral work. The collaboration with UNU/ICTP PFF continued and Mr. R.S.Rawat who was working under my supervision for his doctoral degree was trained on the operation of DPF system and N₂ Laser shadowgraphic diagnostics. Later Mr. Smruti Ranjan Mohanty who was working under my supervision for his doctoral degree was trained on X-ray Diode spectrometer diagnostics.

INTRODUCTION:

A Mather type [1] Dense Plasma focus having an energy of 3.3 kJ became operational at the Department of Physics, University of Delhi in 1990. Another Plasma chamber with two viewports near the top of anode was fabricated at Delhi University to carryout laser shadowgraphic work. During the period under PFF review I started a training programme to
have hands on Experiments under AAAPT and oriented my group to three types of studies viz.
(i) Basic studies on plasmas produced in Dense plasma focus in which we carried out (a)plasma
sheath structure and its dynamics in the presence of external axial magnetic field making use of
laser shadowgraphy [D8IN]; (b) quantitative study of X-ray emission from dense plasma focus
device in the presence of external axial magnetic field making use of X-ray diode spectrometer
[D9IN]; (c) measurement of argon ion velocity distribution in dense plasma focus using Faraday
cup and (d) local plasma parameters of Dense Plasma Focus from in situ Langmuir probe
signals; (ii) Plasma processing of materials of thin films on different substrates and phase
changes in which we carried out the following (a) Crystallization of an amorphous lead
zirconate titanate thin film was achieved ; (b) Amorphization of as grown crystalline thin film
was achieved for the first time; (c) n-typed doped behaviour of a polyaniline film was achieved
for the first time due to irradiation of polyaniline film by energetic high fluence argon ions of
dense plasma focus.P-N junction diode formation was also demonstrated through I-V
characteristics for the first time in a single polyaniline film ,cation doped chemically on one
side and anion doped by irradiation of ions from dense plasma focus on the other side and (d)
Magnetite phase from hematite thin film due to irradiation of energetic, high fluence argon ions
from a dense plasma focus ; the energetic high fluence ions of dense plasma focus has also been
used to raise the superconducting temperature of a thin film of high $T_c$ superconducting
material BPSCCO and for coating different films on metals; (iii) Deposition of thin films of
different substances on different substrates under which we carried out (a) deposition of thin
carbon film using energetic ions of dense plasma focus and (b) deposition of Fullerene films of
C$_{60}$ and C$_{70}$ on Si (111) substrate using energetic ions of Dense Plasma Focus .

For the basic studies on DPF system another plasma chamber with two viewports near
the top of the anode was fabricated. For the laser shadowgraphy of the plasma sheath dynamics,
the laser was shot at the plasma almost simultaneously and the timing of the two events was
adjusted by suitable delay lines. In this way laser shadowgraphic photo of the plasma was taken
at the end of second viewport with the help of a Polaroid camera at different instants. For
quantitative measurement of X-rays with the help of a X-ray diode spectrometer, the
spectrometer was attached to one of the viewports . The X-ray signals are recorded on a storage
oscilloscope. The ion velocity measurements were done by inserting a Faraday Cup from the
top of the chamber and the Langmuir probe was also inserted from the top of the chamber for
making insitu measurements.

For the plasma processing of materials and phase change studies, thin film on different
substrates for different samples have been mounted axially above the anode. The samples were
attached to the axially movable brass mount. The energetic high fluence ion beam from the
focus region was allowed to strike on the films which was attached to the axially movable brass
mount. The energetic and high fluence ions are produced when focusing is good. Good focusing
was achieved after a few shots with optimum pressure and optimum charging voltage of
capacitor. The exposure of the thin film samples to the week ion beam was avoided by using an
aluminum shutter arrangement in between the anode and the sample. For the preparation of thin
films, a perspex box housing the target and the substrate holder was inserted by means of a
brass cylindrical rod from the top plate of the plasma chamber. The material whose thin film
was to be prepared was stuck to the target holder inclined at an angle of 45° with the anode axis
The whole perspex box could be moved along the anode axis so that the target could be adjusted
at different distances from the anode. The thin films were prepared by means of multiple shots.
An aluminum shutter was provided between the anode and the box to avoid striking of ions on
the target when no proper focusing was obtained. This system has been changed completely for
deposition of thin films. Thin films with very low surface roughness average, high deposition rate and having good quality in terms of, electrical, optical, mechanical properties were deposited. More recently a good quality diamond like carbon films have also been deposited.

**BASIC STUDIES ON DENSE PLASMA FOCUS:**

The DPF device is known as a simple device which is very suitable for study of plasma dynamics, and other plasma related phenomena such as X-ray emissions, accelerated ions of mega electron volt range, source of relativistic electrons and neutrons when the chamber is filled with deuterium gas. We have done some basic studies on this device particularly shadowgraphic studies of current sheath dynamics in the presence of external axial magnetic field, measurement of argon ion current densities using biased ion collector, quantitative measurement of reduction in X-ray emission and reduction in electron temperature in the focus device due to the presence of external axial magnetic field and measurement of local plasma parameters on dense plasma focus device from insitu Langmuir probe signals.

**Nitrogen Laser Shadowgraphic Studies [D8In]:**

The Study of plasma sheath structure and its dynamics is of interest in knowing the actual behaviour and variety of plasma phenomena taking place in the DPF device. Several studies were made in the past to observe the effect of an external axial magnetic field (Bz) on various plasma phenomena. A considerable reduction in neutron yield (2,3), shift of neutron away from the top of central electrode (3), reduction in neutron produced due to instability (4) and reduction in X-ray emission as well as material erosion of the central electrode (5,6) was observed. However, no such study was made about the influence of external axial magnetic field on the plasma sheath structure. We therefore studied the plasma sheath structure and dynamics in axial acceleration and radial collapse phase of DPF device using Laser shadowgraphic technique in the presence of Bz. The shadowgraphs of the axial phase show that the current sheath gets diffused as it reaches near the end of central electrode in the presence of magnetic field. The shadowgraphs of radial collapse phase show clearly distinct hump formation above the central electrode under the influence of Bz. This hump formation has been understood to be due to the outward push of the field. Shadowgraphs of radial collapse phase also show that the portion of the sheath lying close to the anode is highly diffused and faint and is thus not able to participate effectively in pinch formation above anode. Observed shortening of focused plasma column under Bz resulted in substantial reduction in total number of particle in pinched plasma column causing thereby reduction in number of instability driven accelerated ions. Diffused bubble formation on the ionization wavefront and dominantly visible remnant of plasma sheath above the anode have also been observed during the quiescent phase under the influence of external Bz.

**X-ray Studies on DPF [D9In]:**

We have also performed the first ever quantitative study of X-ray emission from DPF device in the presence of external axial magnetic field. X-ray signals were detected with the help of multichannel diode X-ray spectrometer (DXS) attached to one of the view ports of DPF. It was observed that both the peak intensity as well as area under intensity time plot of X-ray signals got reduced by about 40%. It was also found that the average electron temperature of the plasma reduced due to application of axial magnetic field.
STUDIES OF ION CURRENT SIGNALS:

We recorded ion current signals by placing a biased ion collector at different distances from the top of the anode. The estimation of ion energies was done using time of flight method. The fine structure of ion pulse signals depicts a multispike structure indicating the appearance of successive bursts of ions from the focus.

LANGMUIR PROBE INSITU MEASUREMENT:

Langmuir probe was inserted from the top of the chamber and placed at about 1.5 cm from the top of the anode. The probe was given different voltages and the probe current converted into voltage signal was recorded. The I-V characteristics of the Langmuir probe were obtained. This was used to estimate the characteristics of the plasma.

SEQUENTIAL DENSE PLASMA FOCUS DEVICE [D9In]:

Multiple focusing have been achieved in DPF device by using a modified form of central electrode in the conventional DPF device. The DPF device with conventional anode shows one or two compression phases but by carving two rings at the top of the anode we have successfully obtained multiple (three to four) compression phases indicated by multiple spike in voltage probe and X-ray signals. Different anode design was tested at different filling gas pressure of argon for optimizing best sequential focusing. The anode with rings of decreasing radii and single support demonstrated strong sequential focusing action.

PLASMA PROCESSING OF MATERIALS AND PHASE CHANGES

The first such study was done in collaboration with the material science group of the department. I was discussing a problem with a colleague of mine, Professor Abhay Man Singh, who has been working on a piezoelectric material namely lead zirconate titanate (PZT). It is well known that the crystalline PZT thin film has a wide range of applications in thin film devices such as ferroelectric memories [7], piezoelectric transducers, electro-optic displays [8] and pyroelectric sensors [9]. The as-grown PZT thin film deposited on room temperature substrate by rf sputtering is amorphous. Various techniques such as post deposition annealing [10] and rapid thermal annealing [11] were attempted but the phase of PZT obtained in this manner was not of desired phase:

CRYSTALLIZATION OF PZT

In order to crystallize thin films of PZT, we irradiated as grown rf sputtered amorphous thin films of PZT of different thicknesses by inserting them from the top of the chamber and placing them at different distances from the top of the anode. The ion irradiated PZT films at different distances from the top of the anode and the as grown rf sputtered amorphous thin film have been analyzed for structural studies by X-ray diffractometer (PW1840) and the changes in surface morphology of the films by scanning electron microscopy (JEOL JSM1840). The PZT amorphous films were prepared by rf sputtering method. The XRD spectra of the film irradiated by ions at 4.2 cm from the top of the anode showed a sharp peak depicting the good amount of crystallization. The crystallinity decreases as we further increase the distance of the film from the top of the anode. The effect of the filling gas pressure was also examined on the degree of crystallinity and it was found that a good crystallinity is obtained at optimum pressure. SEM
studies also confirmed good crystallinity of the ion irradiated film exposed at a distance of 4.2cm.

**AMORPHIZATION OF CRYSTALLINE CdS**

Amorphization of crystalline CdS film was achieved for the first time due to ion irradiation of energetic argon ions generated in dense plasma focus. CdS has attracted attention due to a number of application including in photovoltaic. It has also been found that Cd deficient CdS films are photosensitive [12]. All earlier attempts to study ion bombarded films showed radiation damage but no amorphization was observed. Bi-ion implanted crystalline CdS was studied by Eldridge et al. [13] and the study indicated that the crystal surfaces were free from any detectable amorphous layer and no amorphization was observed. Parikh et al. [14] used Bi, Kr, Ar and Ne ions for irradiation of crystalline CdS but they concluded from their studies that ion implantation caused damage in the form of interstitial dislocation loops but it did not induce amorphization.

The as grown crystalline thin film of CdS prepared by Chemical vapour deposition technique was irradiated by energetic high fluence argon ions of dense plasma focus at different distances from the top of the anode and the amorphization was achieved for the first time at some optimized distance from the top of the anode. The ion irradiated CdS films at different distances from the top of the anode and as grown crystalline thin films of CdS have been analyzed by X-ray diffractometer (Philips-PW 1130). The thickness of the films has been measured by using Telesurf 10. Changes in the surface morphology have been studied utilizing a scanning electron microscope (JEOL JSM-840) The surface composition analysis as well as the depth composition analysis of CdS films have also been performed by using ESCA Shimadzu-750. The XRD spectra of the film irradiated at a distance of 4.2cm from the top of the anode showed complete amorphization of the film. This amorphization was also confirmed by SEM micrographs. ESCA studies showed that ion irradiation had affected the film more or less equally at all depths. Moreover, Cd deficient films have been obtained due to ion irradiation. Such films may be useful in photosensitive application.

**N-TYPE DOPED POLYANILINE FILM AND DIODE LIKE BEHAVIOR [D9IN]:**

Polyacetylene (PA) and Polyaniline (PAn) have been found to undergo significant changes in their electrical, structural and optical properties after being exposed to an ion beam [15-18]. The electrical conductivity of PAn can be varied from $10^{-9}$ S/m (emeraldine base) to more than $10^3$ S/m (emeraldine salt) by means of chemical doping. Chemical methods yield on these polymers, a behaviour similar to p-typed doped materials. On the other hand PAn films implanted by Ar$^+$ and K$^+$ from an isotope separator have shown some signature of n-type doping [18]. PAn exists in several oxidation states and has been extensively investigated due to its wide variety of applications in electrochromic displays, biosensors and molecular electronics [19,20]. We have been able to exhibit a n-type doped behavior of PAn film by irradiating it with the ions of dense plasma focus by inserting the PAn film from the top of the chamber and placing it at different distances from the top of the anode. We have also formed a p-n junction on a single PAn film which is cation doped chemically on one side and anion doped on the other side by irradiation of ions. The I-V characteristic showed the diode like behaviour for the film irradiated at a distance of 6 cm from the top of the anode. The ion irradiated films have been analysed structurally by XRD diffractometer, scanning electron microscopy (SEM) and their chemical analysis at the surface and at different depths have been performed by ESCA.
The PAN films were synthesized by chemical oxidation of aniline in aqueous acidic media using ammonium perdisulphate as an oxidant. The films were cut into smaller pieces and fixed on glass substrate for irradiation purposes. SEM micrographs showed that a dentrite type of structure showing presence of clusters breaks and there is complete smearing of clusters. The X-ray diffraction pattern of ion irradiated films showed peaks implying the formation of crystalline phase, which is absent in unirradiated films. The thermal probe analysis of the ion irradiated film showed n-type of doping which has been used to form a p-n junction on a single PAN. Diode like behaviour was found through current voltage characteristics. The ESCA spectra showed loss of nitrogen from the surface of the ion irradiated film of PAN and this reduction of nitrogen atoms results into n-type behaviour of PAN film due to crosslinking of the bonds.

**HEMATITE TO MAGNETITE PHASE CHANGE**

Thin films of iron oxide are known to exist in the form of non-magnetic FeO and α-Fe₂O₃ and ferrimagnetic γ-Fe₂O₃ and Fe₃O₄. They are particularly appealing for experimental and theoretical investigations in view of their technological application. These iron oxide films can be used as catalyst in dehydrogenation reaction [21], temperature and water sensors and optical filters [22,23] and magnetic devices [24]. Complete change of phase from hematite, which is non-magnetic, to magnetite phase, which is magnetic, has not been achieved by any other well-known methods of phase change. However, partial change of phase from hematite to magnetite has been reported recently [25] by hydrogen ion implantation. α-Fe₂O₃ films have been prepared by spin coating technique on the glass substrate. The energetic and high fluence ions generated in DPF were used to irradiate thin films of α-Fe₂O₃ at different distances from the top of the anode. XRD of both unirradiated and ion irradiated films have been carried out. SEM micrographs of these films have also been obtained. The magnetic properties of these films have been done using Vibrating Sample Magnetometer. Complete change of phase from α-Fe₂O₃ to Fe₃O₄ has been obtained for the first time for the films irradiated at a distance of 10 cm from the top of the anode. The films irradiated by ions at lesser and greater distances than 10 cm exhibited mixed phase of α-Fe₂O₃ and Fe₃O₄. The grain size of Fe₃O₄ decreases with increase in the distance of the film from the top of the anode. The SEM micrograph confirms Fe₃O₄ phase only for the film irradiated at 10 cm. At that distance one gets the columnar grains corresponding to Fe₃O₄ whereas SEM micrographs of the film at a distance greater or less than 10 cm show a mixture of granular crystalline grains corresponding to α-Fe₂O₃ and columnar grains corresponding to Fe₃O₄. Vibrating Sample Magnetometer showed maximum saturation magnetization of the order of 6.86 kG for film ion irradiated at 10 cm. This result also supports the complete change of phase from non-magnetic to magnetic phase. Coercive field is found to increase with the distance of irradiation which is in accordance with the fact that the coercive field is inversely proportional to the grain size.

**THIN FILM DEPOSITION USING DENSE PLASMA FOCUS**

A number of devices are known to exist for the deposition of thin films such as CVD, PECVD, RF sputtering, lasers etc. I therefore attempted if DPF device can be used for the deposition of thin films on different substrates. There have been several failures in the beginning but ultimately it became possible to use DPF for the deposition of graphitic,
fullerenes and diamond like carbon films on different substrates. The quality of these films in terms of mechanical, electrical and optical properties were found to be much superior as compared to the deposition of the films by others techniques.

**GRAPHITE FILM DEPOSITION**

Amorphous carbon films have been used as an overcoat to protect magnetic layers from the abrasive action of the reading head [26]. Crystalline highly conducting graphitic films have a number of technological applications [27].

In this study high fluence, highly energetic ions of DPF were allowed to hit the graphite target placed above the anode and inclined at an angle of 45 degrees to the anode axis at a distance which could be adjusted by a movable rod from outside the chamber. Films have been prepared by means of multiple shots. The deposition of films was carried out for two different orientations of the substrate with respect to the target. In the first orientation the substrate was placed parallel to the axis of the anode and at a distance of 1 cm opposite to the centre of the graphite target. In the second orientation the substrate was placed parallel to the target. The thin films of graphite on silicon, quartz and glass have been deposited by keeping the target at different distances from the substrate. The thickness of the film was found to be in the range of 1000 to 1500 Å on silicon substrate. The roughness average of the film deposited with the orientation of the substrate parallel to the graphite target was less as compared to the substrate parallel to the anode axis. For the films deposited on silicon substrate with 30 DPF shots on a target at a distance of 1.3 cm from the top of the anode, the roughness average was 5.3 nm. The X-ray diffraction spectra done on Phillips PW 1840 diffractometer showed highly textured structure of graphite on the deposited films. The symmetrical shape of the peak suggests the existence of hexagonal ABAB stacking of graphite sheets. It has also been found that quartz is a good substrate for deposition of crystalline graphite films but for many applications the deposition on silicon is of importance. The film on glass substrate was amorphous. The ESCA study of the film deposited at a target distance of 1.3 cm. above the anode showed the presence of oxygen at the surface. This was due to the oxidation of the carbon film on being exposed to atmosphere. ESCA also showed the decrease in the oxygen content as the film was analyzed for increasing depths from the surface. The Raman spectrum on Jasco-0045 confirmed the presence of sp² hybridized graphitic carbon.

**FULLERENE FILMS ON SILICON SUBSTRATE (C₆₀ AND C₇₀) [D10In]:**

The highly energetic high fluence ions emitted in a dense plasma focus have been used for the first time to get fullerene films by ablating the graphite target such that the ablated material is deposited on Si (111) substrate. Large pure carbon clusters (C₂n, n>16) known as fullerenes, made of pentagons and hexagons with covalently bonded carbon atoms have interested scientists from various disciplines. Carbon clusters have been found in flames, interstellar space, atmosphere of carbon stars and comet tails. Kroto et al. [28] who were the first to study a remarkable stable cluster consisting of 60 carbon atoms by laser vaporization of graphite. Kratschmer et al. [29] succeeded in generating large quantities of fullerenes so as to permit measurements of physical properties and to evaluate its possible applications. These carbon clusters have a wide range of potential application. In particular C₆₀ also called buckminstrefullerene which has the highest possible symmetry assuming the shape of soccer ball with 20 hexagonal and 12 pentagonal faces has found application in superconductivity [30], non linear optics [31] and solid lubrication [32] for space vehicle application. C₇₀ has the
capability to enhance diamond nucleation [33]. We have been able to deposit the crystalline fullerene films on Si (111) substrate for the first time under the appropriate conditions by ablation of graphite target with the help of highly energetic high fluence ions using multiple shots of the DPF device. The ablated material is deposited on different substrate like glass, quartz, silicon, and NaCl crystal. X-ray diffraction analysis of the film has peaks corresponding to $C_{60}$ and $C_{70}$. The internal crystalline structure has been observed with the help of transmission electron microscopy. The films have been studied for their vibrational modes using Raman spectroscopy and Fourier Transform infrared spectroscopy. The surface morphology of the films has been studied by scanning electron microscope. Systematic analysis of the films confirmed the formation of fullerenes particularly $C_{60}$ and $C_{70}$.

**DELI TRAINING PROGRAMME OF ASIAN AFRICAN ASSOCIATION OF PLASMA TRAINING:**

In view of the development of experimental research in Plasma Physics at the Department of Physics, University of Delhi and a demand from many plasma physicists from universities and institutes for getting an exposure to the experimental research activities in plasma physics at Delhi University, we started an "Attachment Programme" with Plasma Research Laboratory of Delhi University. Under this programme the visiting Scientists, could spend about a month attached to plasma laboratory and have "Hands on Experiments". The scientist participating in the Attachment programme were paid return rail fare and their local expenses in Delhi out of AAAPT allocation to Regional Centre at Delhi. The visiting scientists surveyed the literature on Dense Plasma Focus and associated diagnostics in the first week of their stay. In the second week they learnt the assembly and disassembly of the device. In the third week, visiting scientists operated the focus system and in the fourth week they wrote out the report of their visit. The visitors were also encouraged to fabricate some diagnostics or some associated electronic part of the DPF device. More than a dozen young scientists have been familiarized to work on DPF device. About of three visiting scientists who have had hands on DPF device at Delhi University have been responsible for the development of a DPF device at the Centre of Plasma Physics, Guwahati. Another participant is trying to develop some plasma experiment in his institution. The list of the participants in this programme during the period under review is at the end of this paper.

**REFERENCES:**


PARTICIPANTS TRAINED UNDER DELHI REGIONAL CENTRE TRAINING PROGRAMME OF AAAPT

1. Dr. Anandmohan Basu, Calcutta, Nov 1-29, 1991
2. Dr. Chandan Kumar Sarkar, Calcutta, Dec 8, 1991-Jan 8, 1992
3. Dr. Akash Sahu, Bhuvaneshwar, June 3-30, 1992
4. Dr. (Mrs.) Rita Paikaray, Cuttak, June 4-30, 1993
5. Mr. Heremba Bailung, Guwahati, Jan 31- Feb 27, 1994
6. Dr. Bipul Kumar Saikia, Guwahati, Jan 31- Feb 27, 1994
7. Dr. (Ms.) Manisha Gupta, Lucknow, Sept 2-28, 1994
8. Dr. (Ms.) Nuzhat Fatima, Lucknow, Sept 2-28, 1994
9. Dr. (Ms.) Joyanti Chutia, Guwahati, March 5-12, 1995
10. Dr. D. Chakraborty, Bilaspur, March 4- April 4, 1997
12. Mr. Vinit Nayar, Bilaspur, June 9- July 8, 1997
INTRODUCTION

Most of the developing countries especially in Africa are experiencing a period of reconstruction. In this period, expansion in education is inevitable. New schools in urban as well as rural areas are being opened and their number will continue to grow. The governments of Zimbabwe and Nigeria are no exceptions to this radical change in the policy of education. With this expansion comes the challenge:

(i) to develop curricula which will adopt inquiry based approach, and is appropriate to the needs of developing economy,
(ii) to develop science based education, and
(iii) to transmit technological expertise and skills.

Science education requires laboratory and demonstration facilities. In general budgetary allocation for acquiring equipment is inadequate to cater for the needs of a good ‘O’, ‘A’ or university laboratory. To improve this situation it is necessary to evolve an educational system in which university graduate can fabricate some devices for laboratories. This will generate creativity and innovation in the students. Both creativity and innovation are the basic requirements for any research work.

The National University of Science and Technology as well as R/S University of Science and Technology, Port-Harcourt strive for the advancement of knowledge with special bias towards the diffusion of science and technology. These universities have adopted curricula which differ from traditional universities in the following respects:(i) every student in the Bachelor programme has to complete a project and (ii) every student is attached to either industry or a laboratory for a period of about a year to gain practical experience, to understand the problems faced by industry and if possible to suggest solutions to these problems.

Based on this philosophy B.Tech and M.Phil programmes were developed at Port Harcourt in 1984. The M.Phil programme included course work and a research project. However, to start experimental research in any field was difficult due to limited equipment available and scarcity in skilled and trained manpower.

At this crucial point came the UNU training programme. It is difficult to believe that more than 12 years have gone by since I left Kuala Lumpur as an UNU fellow. I have many pleasant experiences to remember. As an UNU fellow in 1985-86 my job was made a lot easier as a
result of the dedicated, selfless and competent colleagues like Prof S. Lee, Prof A.C. Chew, Prof C.S. Wong, Prof K.S. Low, Drs Tou, Kwek, Saw, Miss O.H. Chin, Mr Jasbir Singh, and Mr Toh, to mention a few.

At that juncture the main objectives were to build:

(I) Plasma focus device, with its associated power supply and control electronics,
(ii) Nitrogen gas laser system with power supply and control electronics, and (iii) Some gas discharge accessories.

Each UNU fellow was trained successfully to assemble all the necessary electronic and mechanical systems of these devices. About 8 PF devices and N\textsubscript{2} laser systems were given as a donation to the fellow to take back and develop these fields in their respective countries. Needless to say that I was one of the fortunate ones to get their donation.

The donation of Plasma focus N\textsubscript{2} gas laser with associated control electronics alleviated the M.Phil research project needs. The results obtained on Plasma focus device at Port Harcourt are summarised in Section ‘A’ while those at Harare are summarised in Section ‘B’.

SECTION A

This section reports the investigations carried out on the current and magnetic field distribution profiles for 3.6 kJ UNU/ICTP Plasma Focus. The device used and the experimental setup for this section was similar to the one used in our earlier works [1].

1 Current and Voltage Signals

The current and voltage signals were displayed on 50 MHz Iwatsu Oscilloscope. The calibration constant of the Rogowoski coil was 11.6 kAV\textsuperscript{-1}. A resistive voltage divider probe with a rise time of about 15 ns was strapped across the anode collector place and the cathode plate. Magnetic probe [2] consisted of a 10 turn coil of 1 mm diameter of an enamelled copper wire. The calibration constant for magnetic probe was 6.705 TV\textsuperscript{-1}.

The azimuthal magnetic field distribution profiles were obtained by varying the axial position of the probe from $Z = 0.5$ cm to $Z = 14.5$ cm at a fixed radial distance of 2.65 cm. The typical signals are shown in Figs 1a and 1b.

![Fig 1a Voltage and Current Signals](image1) ![1b Magnetic Probe Signal z =8.5 cm](image2)
2. Results

2.1 Current Shedding Effect

Let us assume that due to current shedding effect the portion of the main current that flows into the focus tube is \( f I(t) \), where \( f \) is a factor which is always less than 1. The ratio of the actual distance travelled by the current sheet to the length of the central electrode gives the current shedding factor \( f \). The corrected inductance is given by:

\[
L_{pc}(t) = \frac{\int_{t_a}^{t_f} V \cdot dt + \int_{t_a}^{t_f} V \cdot dt}{f \cdot I(t)} \tag{1}
\]

where \( t_a \) is the time at end of axial phase, and \( t_f \) is the time of focussing.

The variation of axial inductance Fig. 2a.

\[ L_{pf} = \frac{\mu_0}{2\pi} \ln \frac{b}{r_p} \cdot z_f \tag{2} \]

where \( z_f \) is the length of the focus.

In our experiments \( L_{pf} \) was estimated to be 6.28 nH, \( b = 3.05 \text{ cm} \) and taking \( z_f = 1.00 \text{ cm} \) gave the radius of pinch \( r_p = 1.3 \text{ mm} \). The pinch ratio under various conditions are tabulated in Table 1.

For this small focus, only 67.7% to 69.4% of the total current injected flows in the focus region. This current shedding factor seems to depend on the pressure of the gas this accounts for the observed dependance of focussing action on the pressure of the filling.
gas. In the range where good focussing is observed, the leak current, i.e. the current retained by the backwall insulator is small (30.6% to 32.3%). These results are in good agreement with Eltworth [3].

2.3 Magnetic Field Distribution Profiles

The magnetic field distribution profile is shown in Fig. 2b. The profile shows that the magnetic field is almost constant at about 1.4 T in the region z = 0 to z = 8.0 cm along the tube and the constant value correspond to a current I = 186 kA. However, as the current sheet travels down further along the axis of the focus, the peak magnetic field decreases to 0.977 indicating a drop in the current. Thus, the measurement suggests that the current sheet carries 68% of the total current injected. This further confirms the observed current shedding effect.

2.4 Velocity Profiles

The times of arrival of the current sheet at different z-positions are shown in Fig. 3a. This graph is used to estimate the velocity of current sheet. The velocity as a function of time plotted in Fig. 3b. A theoretical curve is obtained from equation 3.

\[
\frac{dz}{dt} = \nu_c \left[ t - \frac{\sin 2\omega t}{2w} \left( 2\left( t^2 + \frac{\cos 2\omega t}{2w^2} - \frac{1}{2w^2} \right) \right)^{\frac{1}{2}} \right]^{\frac{1}{2}}
\]

Assuming the sinusoidal variation for the current. This curve is also shown in Fig. 3b. This graph shows that the theoretical values for velocity are more than experimental values which further confirms the current shedding effect observed in the present work.

Pinch Ratio

The pinch ratio r_p/a can be obtained from the inductance of the plasma during focussing L_pf. This is given by the relation,

\[
L_{pf} = \frac{\mu_0 z_f \ln b / r_p}{2\pi}
\]

where z_f is the length of the focus. Typically corrected inductance in the focus region was found to be 6.3 nH, b = 3.05 x 10^{-2} m and taking z_f around 1 cm [6], the radius of the focus was found to be 1.33 mm. The values of the pinch ratio under various conditions are tabulated in the table 1.

![Graph of Distance of magnetic probe from the backwall (nm)]
TABLE 1: PINCH RATIO FOR AIR PLASMA

<table>
<thead>
<tr>
<th>Press of Air in Torr</th>
<th>Axial Transit Time in μs</th>
<th>Average Velocity cm/μs</th>
<th>Current Shedding Factor</th>
<th>Pinch Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>3.45</td>
<td>3.22</td>
<td>0.694</td>
<td>0.130</td>
</tr>
<tr>
<td>0.8</td>
<td>3.50</td>
<td>3.12</td>
<td>0.683</td>
<td>0.150</td>
</tr>
<tr>
<td>1.0</td>
<td>3.60</td>
<td>3.01</td>
<td>0.677</td>
<td>0.156</td>
</tr>
</tbody>
</table>

2.4 Computer Simulation of Energy Profiles in Plasma Focus Device [J147]

To obtain the profiles of the shocked plasma gas, the following normalised equations were numerically integrated by using linear approximation method.

\[
\frac{d^2 \xi}{d\tau^2} = \frac{\alpha^2 i^2 \left( \frac{d\xi}{d\tau} \right)^2}{\xi} \quad \text{........................................(5)}
\]

\[
\frac{d\xi}{d\tau} = \frac{1 - \int_0^\tau d\tau - \beta i \frac{d\xi}{d\tau}}{1 + \beta \xi} \quad \text{........................................(6)}
\]

\[
k = \frac{\beta}{\alpha \xi} \left( \frac{d\xi}{d\tau} \right)^2 \quad \text{........................................(7)}
\]

and \[E = \int_0^\tau P_n d\tau \quad \text{........................................(8)}\]

where , \[\xi = \frac{z}{z_0}, \quad i = \frac{I}{I_0}\]

\[E = \text{Electrical input energy}\]
k = Normalised kinetic energy

\[ P_n = \text{Normalised input power} = 2 \, v_n \, t \, ; \quad V_n = \frac{V}{V_o} \]

\[ \alpha = \frac{t_a}{t_o} \, ; \quad t_a = \left[ \frac{4\pi^2 \rho \, z_o^2 \, (b^2 - a^2)}{\mu \, \ln (b/a) \, I_o^2} \right]^{1/2} \]

\[ \beta = \frac{L}{L_o} \, ; \quad \text{Plasma inductance} = L = \left( \frac{\mu}{2\pi} \right) \ln b/a \, \text{and} \, L_o \parallel \text{External inductance of the circuit.} \]

\[ \tau = \frac{t}{t_o} \]

\[ \alpha^2 = \frac{\mu I_o^2 \ln b/a}{4\pi \rho (b^2 - a^2) z_o^2} \quad (9) \]

2.5 Results

The distribution profiles of the normalised energy with time and normalised length of the central electrode were computed for \( \alpha = 0.6; 0.96 \) and 1.36 respectively. The typical results are shown in Fig 4 and Fig 5. The amplitude of the energy increase with increase in ‘\( \alpha \)’. The energy of the system is strongly influenced by the geometry of the device, the nature of the gas and the pressure of the gas. The kinetic energy profile shows the most striking outlook. It tends to have an oscillating beginning which continues until peak is reached at a plateau occurring at the point where electrical energy and the power input profiles intersect. The profiles bear a close resemblance with the results obtained by Killen et al [5]. As the \( \alpha \) is increased the kinetic energy spikes above the other energies. This may be attributed to an increase in internal energy of the current sheath due to increased magnetic field compression.

![Fig 4 Normalised Energy vs Time](Image)

![Fig 5 Normalised Energy vs Length](Image)

SECTION B

In this section we report the progress of the work done at the University of Zimbabwe, Harare. In the Department of Physics the main focus was on Geophysics and most of the manpower and ongoing research was in Geophysics till 1988. As a physicist I strongly feel that in any department of physics the main focus should be on physics which acts as a foundation for other disciplines.
It was not easy to get through the research proposals and postgraduate programmes in Physics. However, the department approved BSc (Hons) programme in physics in 1990 and MSc, MPhil and DPhil programmes in 1992. This was a major boost for developing plasma physics and laser technology.

In plasma physics we undertook a project on “Design, Fabrication and Characterization of Plasma Focus device”. The first part of this section describes the design and fabrication aspect while the second part describes some of the results on the performance of the focus.

1. Design and Fabrication

The strong focussing action is important from the point of view of increasing neutron yield [8]. Hence it is required to optimise the system parameters such as the length of internal electrode and insulator sleeve, the polarity of internal electrode, pressure, seed material, etc. The focus dynamics involves three different phases, viz:

(i) The breakdown phase, the axial or the run down phase and the radial collapse phase or pinch phase. A detailed description of the theoretical model developed can be found in reference [11].

It may be noted that the sheath run down velocity

\[ v_s = \frac{dL}{dt} = \frac{2 \ln(b/a)}{2 \ln(b/a)} \]

where L is a measure of load impedance assumed to be mainly inductive, ‘b’ is the interelectrode separation and ‘a’ is the radius of inner electrode. The random velocity determines the axial time \( t_a \) which should be equal to the quarter period of the bank for good focussing action. Thus, \( t_a \) can be optimised by choosing proper inner electrode length. Therefore it was of interest to study the focusing action at various lengths of the electrode.

2. Experimental Set Up

The schematic of Plasma Focus is shown in Fig. 6.
The inner and outer electrode system was mounted on a brass plate. The inner electrode was made of brass rod of diameter 20 mm while the outer electrode system consists of eight brass rods of diameter 8 mm fixed symmetrically around the inner electrode in the form of a squirrel cage. The inter-electrode separation was 60 mm. The length of electrodes was varied from 150 mm to 40 mm and the focussing action was investigated. Essential to the structure of the focus tube is the backwall insulator. The pyrex glass sleeve of 15 mm slides over the inner electrode and is mounted in a rubber holder (19 mm thick) which when compressed tightly and symmetrically by the brass flange grips the insulator firmly. The rubber holder absorbs the shock and prevents the glass from breaking at the onset of the discharge. The whole system is enclosed in a stainless steel chamber of length 300 mm and 163 mm diameter.

The chamber was evacuated by a two stage rotary pump, reaching an ultimate base pressure of $10^{-3}$ Torr. The pressure of the filling gas was measured by mechanical diaphragm pressure gauge.

Energy is stored in $30 \mu$F, 15 kV and 27 nH Maxwell Capacitor by charging it to 12 kV. The capacitor transfers the energy to the plasma chamber when switched through a swinging cascade spark gap which is in turn switched by a 35 kV pulse with a rise time of 1μs. The spark gap is mounted directly on the top of the capacitor using parallel plate configuration [10]. Experimental layout is shown in Fig.7.

3. Current and Voltage Signals

To display the current signals a self-integrated Rogowski coil of 400 turns of enamelled copper wire wound over the anode of the focus was connected to 100 mHz digital storage scope. To avoid reflections the coil was terminated with a 50 Ω resistance. An attenuation factor of 1:10 was necessary to scale signal. The calibration constant of the coil was 11.6 kA/V. A resistive voltage probe with a rise time of 15 ns was strapped across the anode and the cathode plate. Three different sets of electrodes, having lengths...
150 mm, 80 mm and 40 mm were investigated using argon, air and nitrogen gases. The parameters of the system are given in Table 2.

![Experimental Lay Out](image1)

**Fig. 7 Experimental Lay Out**

<table>
<thead>
<tr>
<th>TABLE 2: SYSTEM SPECIFICATION.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitance</td>
</tr>
<tr>
<td>Bank Energy</td>
</tr>
<tr>
<td>External Inductance</td>
</tr>
<tr>
<td>Quarter period of the Bank</td>
</tr>
<tr>
<td>Peak discharge Current</td>
</tr>
<tr>
<td>Radius of Internal Electrode</td>
</tr>
<tr>
<td>Insulator Sleeve Length</td>
</tr>
</tbody>
</table>

4. Results and Discussions

Typical current and voltage signals are shown in Fig. 8.

It has been observed that good focussing action was shown in the range of pressure from:
- 0.1 Torr to 2.5 Torr for argon,
- 0.1 Torr to 2.0 Torr for nitrogen,
- 0.25 Torr to 2.0 Torr for air

![Typical Signals](image2)

**Fig. 8 Typical Signals; Upper Trace: Voltage 4kV/div. Lower Trace: Current 75 kA/div. Time scale: 1μs/ div**
Focussing was observed even for 40 mm long electrodes and for 80 mm long electrodes Fig. 9a-b. Focussing with such short electrodes (given the current risetime of 3 microsec) could possibly be due to a delay in current sheath lift-off.

![Fig 9a HV Signal vs Pressure [Argon]](image)  ![Fig 9b HV Signal vs Pressure [Air]](image)

The FWHM show that good focus action is shifted towards higher pressure range as the electrode length is reduced. It may be pointed out that for argon and air the lower pressure range for focussing action is decreased from 0.3 Torr, with positive internal electrode polarity to 0.1 Torr with negative internal electrode polarity while for air it was reduced from 0.5 Torr to 0.25 Torr while the upper pressure range is increased from 2 to 2.1 Torr for argon and from 1.1 to 2 Torr for air respectively.

Our device may be different from the ‘standard’ UNU/ICTP PFF in the following factors:

(i) much longer time required for the formation of the sheath and lift off; and
(ii) more ablation of material from the electrodes.

CONCLUSIONS

1. The plasma focus device has been tested for its performance for:

   (i) current shedding effect;
   (ii) magnetic field distribution profiles; and
   (iii) pressure broadening effect in different gases for focussing action with negative internal electrode polarity.

Moreover, theoretical models for the device performance have been developed.

2. The United Nations University programme has resulted in the training of at least five scientists who can work independently on the most sophisticated and complicated devices like plasma focus and nitrogen gas laser. Research projects undertaken by these scientists have led to ten publications, in international journal, and five conference papers, four MPhil graduates and one DPhil graduate.
3. It may be concluded that the major objectives of UNU training programme viz, to spread the study of plasma dynamics and develop cost effective devices which will transfer the technology and skills to developing countries have been achieved. The South-South co-operation seems to be more successfully than North-South co-operation. Such training program should be encouraged and extended to the other areas.

ACKNOWLEDGEMENTS

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Prof. S. Lee, the prime initiator of this programme, United Nations University, International Centre for Theoretical Physics, Trieste, Italy, Third World Academy of Sciences, University of Malaya, Research Boards of both the universities and lastly but not the least, the Asian African Association for Plasma Training.

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SCIENTIFIC RESULTS AND PROGRESS
OF THE UNU/ICTP PFF

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ABSTRACT

Plasma focus is now established as a device for producing a hot, dense plasma. In the UNU/ICTP PFF device the power transmitted into plasma was enhanced. The efficiency of the system for producing high density, high temperature plasma was also enhanced. Experimental data of plasma focus parameters; focus time, magnetic piston, shock front, and minimum focus radius were compared with the theoretical predictions. This review compiles most of the results carried out on the UNU/ICTP PFF machine, including published papers.

INTRODUCTION

In 1986, El-Azhar University was donated a plasma focus machine to be used for research and educational purposes. This donation is made possible by financial assistance from the United Nations University and the International Centre of Theoretical Physics and by the design, construction and testing program undertaken by staff of the plasma Research Laboratory of the University of Malaya, and supervised by Prof. S. Lee.

Plasma focus is a device which produces high density (n >10^{19} \text{ cm}^{-3}) and high temperature (few keV) plasma with a short life time nearly about 100 nsec. PFD is one of the pinch devices operating with a capacitor bank of 1 kJ - 1 MJ, charged to 10 kV - 300kV. The PFD consists of two coaxial electrodes separated by an insulator at one end, where the breakdown of the gas discharge takes place. The discharge control uses a spark gap. The length of the electrodes is large compared with the electrode radii. The mechanisms of the discharge has three main phases, break-down phase, axial acceleration phase, and the radial compression phase (or radial collapse phase) [1]. Many studies have been carried out on the initial phase and confirm that this phase affects the efficiency of the device [2]. The Plasma focus now established as a device for producing a hot dense plasma. It is considered to be a source of intense bursts of X-ray [3]. On the other hand, the emitted x-ray can be used as a diagnostic [4] to determine the electron temperature in the focus zone. The study of plasma focus attracts scientists into several directions related to plasma fusion technology and plasma applications [5].

SET UP

Our experiment, (as shown in figure 1), has two main parts:

1- **Energy bank**: which consists of one capacitor (32 μF, 27 nH), charged by a local made power supply up to 15 kV. Connection between the bank and the focus system was made by using a swinging-cascade air spark-gap, which was supported on the upper positive plate and connected to focus apparatus via copper sheet (30 cm width, 25 cm length) instead of 16 co-
axial cable in the previous work [6,7,8] The triggering system generates a pulse (17 kV, 1.2 µsec risetime) to fire the system.

2- **Focus Chamber**: co-axial electrodes was inserted inside a steel chamber (30 cm length, 15cm diameter). The central hollow electrode (anode) made of copper, (10 cm, length, 1.95 cm diameter) was surrounded by glass sleeve (5 cm length from the end of the central electrode). Six rods (16 cm length, 0.6 cm diameter) worked as a cathode.

The chamber was evacuated by a proper vacuum system which is measured by capsule gauge in the range (0.75-16 torr) while the working gases were fed into the chamber through a needle valve (after evacuated down to 10^{-3} torr). The chamber has facilities for diagnostics, such as a pinhole camera, electric probes, magnetic probes and pin diodes. Special grounding was made for the PF experiment, all the electrical circuits were connected to the earth at one point, to avoid current loops, which act as radiated sources [7].

Measurement of the current (fig. 2) was carried out using Rogowski pick-up coil, while the discharge potential was measured using a resistive divider. The intensity of the emitted x-ray signals (fig. 3a,b) was detected using two pin-diodes (PBX) covered with two layers of aluminum foils [8].

**THEORY:**

When a capacitor bank is discharged between two co-axial electrodes, a plasma sheath is formed between the electrodes, and radial current density (Jr) flows between the cylindrical electrodes, so that an azimuthal magnetic field of discharge current I (as a function of time) is

\[
B_0 = \frac{\mu_0 I}{\pi (b - a)}
\]

(1)

where \( \mu_0 \) is the permeability of space and ‘a’, ‘b’ are the radii of the internal and external electrodes respectively. More than one current sheath may be formed depending on the applied potential, kind and pressure of the gas, electrode configuration, besides the initial rate of rise of the discharge current [9].

In the axial phase the JxB force drives plasma along the axis, forcing it across lines of Bo, hence azimuthal pairs of vortices arise. Ignoring viscous force and pressure gradient, the electromagnetic force acting on the current sheath equals to the change of rate of momentum of the plasma sheath. The circuit equation is given by [7].

\[
\frac{dV_o}{dt} = \frac{\int Idt}{C_o} - \frac{\mu_0 I}{2\pi} \ln \left( \frac{b}{a} \right) \frac{dz}{dt}
\]

\[
L_o + \frac{\mu_0}{2\pi} \ln \left( \frac{b}{a} \right) z
\]

(2)

where \( C_o, L_o \) are the capacitance and inductance of the circuit, while \( V_o \) is the discharge voltage.

When the current sheath is at position \( Z \), the mass of the rest gas \( \rho_o [\pi (b^2 - a^2)Z] \) is swept up by the sheath, (\( \rho_o \) is the gas density). The force exerted by the self magnetic field
\[ \frac{\mu_0 I^2}{4\pi} \ln \left( \frac{b}{a} \right) \]

may be equated to the rate of change of momentum of the mass trapped by the current sheath. This rate of change of momentum is given by:

\[ \{ \rho_o [\pi(b^2 - a^2)Z] \} \frac{dz}{dt} \]  

At the end of the axial phase, the current sheath reaches \( Z = Z_o \) and the component of the current density will be in the Z direction \((J_z)\). The \((J_xB_0)r\), pinch force will be in the radial direction. If \( J \times B = (J_0 B_z - J_z B_0) r = 0 \); at sheath radial collapse, hence it is force free in the plasma focus has \( J_0 B_z = J_z B_0 \) implies helical lines. If \( J_z B_0 > J_0 B_z \), the filament pinches occur. The plasma sheath will be compressed inward - (radial phase) - and a hot dense column of plasma is formed [10]. The mechanism of the radial compression phase was discussed by using a combination of 4 equations of motion and solution of them by slug model [7,11]. The normalization and computation of these equations of motion show the mechanisms of the radial collapse phase. The end point of the radial compression may be obtained by considering a set of equations. [12,13].

**RESULTS AND DISCUSSION:**

The plasma inductance \((L_t)\) and the maximum axial speed \((Z)\) are calculated [6], indicating that the plasma inductance was reduced while the axial speed of the plasmoid (current sheath) was increased in the present device when compared with an earlier device[14,15]. It is found that the power is enhanced and therefore the power dissipated was minimized. The pinch time can be estimated [16]. The calculation of pinch time shows that the occurrence of focus was delayed in the previous device when compared with the present device.

X-ray is emitted from the discharge of the plasma. Its production occurs at a time characterized by a dip of the discharge current as shown in Fig.(3). Ratio of the intensities of two signals of x-ray are calculated, at different conditions of gas pressure, applied potential, and gas type. The maximum wavelength of the emitted x-ray was approximately calculated at different charging voltages as a function of pressure. For Helium gas, the range of x-ray wavelength is between 8 and 10A while it is between 2 and 9A for Argon discharges (18).

Electron temperature can be estimated from the intensity ratio of the emitted x-ray [17] in the focus region. The calculation of electron temperature in hydrogen discharge, gives a value of 4 keV when using the last device, while it was 6 keV, when using the present device. Figures 6, 7 indicate the values of electron temperature as a function of gas pressure and discharge potential for Ar & He gases respectively.

The electron density in the radial compression phase was estimated using the values of the measured electron temperature and the computed x-ray intensity [19]. Fig.(8) represents the electron density, in arbitrary units, as a function of the gas pressure at different charging voltages.

The current sheath as shown in Fig. (2) is seen to undergo two successive compressions at 4 and 4.5 µsec. respectively, which are indicated by the two dips. Fig. (9) shows a
comparison between the theoretical predictions and the experimental data of the normalized discharge current. The theoretical curve shows a dip which coincides with the first dip of the experimental observation. The difference between theoretical and experimental results may be related to the fact that the gas is not completely snow plowed by the sheath. Besides the energy losses from the current sheath due to radiation is not taken into account as well as the effect of the instabilities [9].

The trajectories of magnetic piston radius ratio, \((K_p)\) and the shock front radius ratio, \((K_s)\), versus normalized time \((\tau)\) are shown in Fig. (10). It was found that the quasi-equilibrium radius ratio of plasma is 0.18 (i.e. focus radius is 0.18 cm at time 4 µsec.). Fig. (10) confirms also that the shock front is separated from the piston, thus the piston is decelerated as the shock front reaches the axis.

Fig. (11) shows the computed plasma focus radius ratio \((K_m)\) versus the charging voltage \((U_{ch})\) at three different pressures. It is seen that \((K_m)\) decreases for increasing \((U_{ch})\). This is quite easily understood since increasing the applied energy must increase the collapse force and hence will reduce focus radius values. Also Fig. (11) indicates that \((K_m)\) increases when the gas pressure is increased. This is related to the fact that at high pressures, more particles are affected by the collapse force and thus larger radius is expected.

Fig. (12) shows the variation of the time at which focus takes place, \(t_p\), versus gas pressure at different charging voltages. A reasonable agreement is shown in Fig. (12) between the measured and the predicted values.

CONCLUSION

In this work, a Mather type plasma focus device was operated, and systematic study of the electrical parameters is investigated. The electric circuit was modified to reduce the inductance in order to match the focus time. The power transmitted into the plasma was enhanced by replacing the co-axial cables with a one sheet of copper [6]. X-ray emitted was studied and the electron temperature determined. The electron density was estimated using the values of the measured electron temperature and the computed x-ray intensity. The volume of the plasma column was estimated [20].

Plasma dynamics in the PF device was studied using the snow-plow model, slug model, and electric circuit equation, which were solved numerically in a normalized form using a linear approximation method. Experimental data, (such as focus time, magnetic piston, shock front and minimum focus radius), were compared with the theoretical predications.
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In the following figures, Figs (4) and (5) have been deleted.
Fig. (1): Schematic diagram of the plasma focus device.

Fig. (2): Typical signals of the current and voltage of hydrogen gas :D (when discharged by 14 kV).
Fig. (3.a): Typical signals of current and X-ray transmitted front helium and Argon discharge using single and double Aluminum sheaths, which are indicated by $I_1$ and $I_2$ respectively.

Fig. (3.b): Discharge Hydrogen gas in last and developed devices (charging, voltage 14 KV), where $I_1$ single sheath of Al= 10 μm and $I_2$ double sheaths of Al=20 μm.
Fig. (6): Electron temperature as a function of pressure of Argon at different discharge potentials.

Fig. (7): Electron temperature as a function of pressure of Helium at different discharge potentials.
Electron density \( n_e \) versus gas pressure \( P_e \) (mbar).

**Fig. (8)**
Fig. (9): Experimental and theoretical normalized discharge current.

Fig. (10): Trajectories of the magnetic piston (Kp) and the shock front (K_c) (normalized) versus time.
Fig. (11): Minimum radius ratio of plasma focus $K_m$ versus the charging potential $U$ at different Ar pressures.

Fig. (12): Theoretical predictions and experimental focus time ($t_f$) versus pressure at different charging voltage, $U$
ABSTRACT

A brief historical account is first given to put in perspective the important stages that finally led to the realization of the UNU/ICTP PFF in 1986. In the twelve years that followed, this plasma focus facility has been put to good use at the University of Malaya. In this paper, training and research using this plasma focus facility is reviewed under the following headings: Training, attachments and visits; Neutron and ion beam studies; Shadowgraphy and sequential plasma focus; Hard X-ray emission; Soft X-ray studies; and The plasma focus opening switch.

INTRODUCTION

Plasma Focus Research at the University of Malaya started in the early seventies [1-3] following the successful installation of a 40 kV, 48 kJ, 2 MA capacitor bank [4]. Using this capacitor bank, various electric, geometric and material parameters for the plasma focus have been investigated. One device, the UMPF1 was operated at 20 kV, 12 kJ, and 550 kA. At 10 torr deuterium the neutron yield was $1.5 \times 10^9$. Another arrangement, the UMPF2 was operated at 33 kV, 12 kJ, and 760 kA. At 16 torr deuterium the neutron production was $6.3 \times 10^9$. Much experience was gained using these devices, the results of which have been reported in the literature [5, 6]. A total of eight M.Sc candidates and three Ph.D. candidates successfully completed their studies using these devices.

With the experience and expertise gained from the early years of plasma physics research, the Plasma Physics Group together with the Laser Physics Group, conducted a series of four Tropical Colleges on Applied Physics: Laser and Plasma Technology [7-10]. These colleges were held biannually from 1984 to 1990. Prior to the start of the Second College in 1986, a six-month Training Programme on Plasma and Laser Technology was conducted at the University of Malaya for the United Nations University. It was during this UNU Training Programme that a low cost 15 kV, 3 kJ plasma focus device was designed, built and tested. It was fortuitous that during this Training Programme Professor Abdus Salam visited the Laboratory. As a result of

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this visit, funding was made available from ICTP to allow several sets or parts of the small, low cost plasma focus to be duplicated for transfer. Subsequently, at the initiative of the Asian African Association for Plasma Training, several more sets of the small plasma focus device, designated as the UNU/ICTP PFF (United Nations University/ International Centre for Theoretical Physics Plasma Fusion Facility), were built for transfer. Today a network of about 15 identical machines exist in eleven countries, and the research carried out using this device is very varied indeed [C6, C26].

Early work at the University of Malaya on the UNU/ICTP PFF has been presented at the Second Tropical College on Applied Physics. Complete details on the machine have also been published [J2, J23]. And some research and training experience on the machine have been presented in international meetings [C6, C26].

In this paper, the work carried out at the University of Malaya with the UNU/ICTP PFF after the Second Tropical College in 1986 will be reviewed. Because of its low cost, and versatility, three independent sets now exists at the University of Malaya. One set is entirely dedicated to undergraduate teaching, a second set for research (Fig. 1), and another set has been modified as a plasma focus opening switch.

![UNU/ICTP PFF at the University of Malaya](image)

**Fig. 1.** A photograph of a UNU/ICTP PFF at the University of Malaya.

**TRAINING, ATTACHMENTS AND VISITS**

Because of its simplicity of operation and maintenance, the UNU/ICTP PFF has been incorporated as a teaching device for the final year undergraduate physics programme for the past 12 years. The small plasma focus has been found to be an excellent teaching device. At the preliminary level, students are introduced to work with high voltages and high currents and their measurements. They are taught the basics of the vacuum system and pressure measurement, and they learned how to use a fast CRO. The small plasma focus has been used to teach plasma dynamics through anode voltage and current measurements, and magnetic field measurements. Together with a coupled circuit-dynamic analysis these measurements enable parameters such as axial speeds and shock plasma temperatures and densities to be obtained [B8]. The small plasma focus has also been used regularly for one semester project work. The rich variety of phenomena taking place in the plasma focus has made it an excellent tool. Projects that have been carried out include soft X-ray measurements using pin diodes and a pinhole camera,
simple lithography, neutron measurements, shadowgraphy studies and ion beam measurements using CR39. At the graduate level, a total of five M.Sc. projects have been successfully completed [M1M-M5M] using this machine. Two of the projects were on neutron and ion beam studies, two on soft X-ray emission, and one on the plasma focus opening switch.

In addition to the series of Tropical Colleges, the Plasma Research Group also played host to a number of visits and attachments from member institutions of AAAPT. These include the following: M.A. Alababa from Rivers State University of Science and Technology, Port-Harcourt; Mohammad Nisar from Quaid-i-Azam University, Islamabad; R.S. Rawat and S.R. Mohanty from the University of Delhi, Delhi; A.V. Gholap and Mathuthu Manny from University of Zimbabwe, Harare: C. Silawatshananai from Prince of Songkla University, Songkla; H. Min and C..M. Luo from Tsinghua University, Beijing; X.P. Feng and Z. M. Jiang from Shanghai Institute of Optics and Fine Mechanics, Shanghai; Yin-an Li from Institute of Physics, Beijing. During this period we had also the pleasure of hosting P. Choi and C. Dumitrescu-Zoita from Ecole Polytechnique, Paris, and Mario Favre from Pontificia Universidad Catolica, Santiago. We were pleased to learn from Mario that his visit to Kuala Lumpur had played a significant role in starting plasma focus research in Chile.

**NEUTRON AND ION BEAM STUDIES**

The UNU/ICTP PFF is capable of producing about $10^8$ neutrons per shot with 3 torr deuterium. Following the initial measurement of the neutron yield [J2], the question that emerges is whether such a device is useful as a source of neutrons for research or application or teaching. We have looked specifically at pulsed neutron activation [J26]. Using relatively simple detector systems we are able to determine fairly accurately the half-lives of $^{116}$In, $^{104}$Rh and $^{24}$Na. With more sensitive detectors, the number of nuclides that could be identified would certainly increase.

In an effort to understand the neutron production mechanism in the plasma focus, and at the same time to ascertain whether the neutron yield could be increased, we have used a simple technique which involves the bombardment of a solid target with the ion beam from the plasma focus [J6]. A metal (copper) obstacle and a deuterated target are used. They are placed, in turn, at various axial positions from the end of the anode. From this study it is found that in the normal operation of the focus, less than 15% of the neutrons are produced within the pinch column, and that more than 85% of the neutrons are arose from the deuterium ion-beam bombardment of the deuterium gas in the region 20-60 mm from the end of the anode. The neutron production is highest between 30-40 mm from the anode. Fig. 2 shows the variation with position of the neutron counts due to the deuterated target alone, and due to per centimeter of the deuterium gas in the chamber.

In recent years there is growing interest in using neutrons for the interrogation of materials, especially of drugs and explosives. Now that repetitive plasma focus devices are becoming available, plasma focus neutrons could possibly be used for this purpose. We have started some work to ascertain how single shot devices such as the UNU/ICTP PFF could assist in this work. With this purpose in mind we are presently looking, in greater detail, at the neutron pulse profile and at the same time to investigate whether doping of deuterium with a heavier gas such as argon could change its pulse width as has been observed in a medium energy plasma focus [11]. Fig. 3 shows the neutron pulse profiles recorded with scintillator detectors at several angular positions with respect to the pinch for deuterium doped with 30% argon [M5M].
Fig. 2. Variation with position of the neutron counts (single shot) due to the deuterated target alone ($Y_{bt}$) and due to per centimeter of the deuterium gas in the chamber ($Y_{bg}$).

Fig. 3. Neutron pulse profiles recorded with scintillator detectors at several angular positions for a 40% argon doped deuterium discharge.

SHADOWGRAPHY AND SEQUENTIAL PLASMA FOCUS

In the studies with targets, the question arises as to whether the presence of a target placed 20 mm downstream from the end of the anode would influence the focusing dynamics. This is investigated by means of shadowgraphy using a nitrogen laser. Shadowgraphs taken show that a flat disc placed at a distance further than the anode radius (10 mm) does not affect the dynamics of the focusing event [J6]. Fig. 4 shows the shadowgraphs of the current sheet configuration before and after peak compression for a target placed 15 mm from the anode. Further investigations show that after the focus proper the current sheet moves axially downstream until it reaches the disc target. The current sheet then propagates around the target and pinches or focuses again beyond it. It would seem that the target has become a new “anode.” The question then arises whether each of a series of separated discs placed downstream of the main anode...
could become sequentially a new anode to the advancing plasma current sheet, resulting in a series of sequential or cascading plasma focus. This suggests the possibility of designing a sequential focus device. A model for such a device has been presented [J7].

![Shadowgraphs of current sheet configuration before and after peak compression with a flat target at a distance of 1.5 cm from the anode surface.](image)

**Fig. 4.** Shadowgraphs of current sheet configuration before and after peak compression with a flat target at a distance of 1.5 cm from the anode surface.

### HARD X-RAY EMISSION

Hard X-ray emission from a plasma focus has been studied for many years. It is now generally agreed that the hard X-rays are produced when nonthermal energetic electrons produced in the plasma hit the metal anode. The time resolved hard X-ray emission from UNU/ICTP PFF has been studied using a plastic scintillator – photomultiplier detector and correlated to the anode voltage [J75]. The time profiles of the X-rays detected end-on and side-on are shown in the lower traces of Fig. 5 (a) and Fig. 5 (b) respectively. The hard X-rays are emitted about 15 ns before the peak anode voltage, and they reach a maximum about 10 ns after the peak of the anode voltage. The duration of the X-ray emission is about 100 ns. The shapes of the X-ray signals suggest the possibility of two peaks corresponding to two periods of X-ray emission, the second period appearing some 40 ns after the first period. The energy (monoenergy equivalent) of the X-rays in the first period is estimated to be between 50 to 80 keV.

In view of the hardness of the X-rays, and in view of the increasing number of small plasma focus devices being operated in many small laboratories, an assessment of the occupational exposure to X-rays from the UNU/ICTP PFF becomes necessary and has been made [J82].
Fig. 5. The upper traces of (a) and (b) are voltage Spikes. The lower traces are hard X-ray signals observed through 5 mm Al. (a) end-on (vertical scale 2.4 V/div), (b) side-on (vertical scale 2.0 V/div). The time base is 50 ns/div. The delays in the X-ray signals are indicated with arrow.

Table 1. Estimated X-ray dose rates (assuming 2 shot h\(^{-1}\) for the average dose, and 15 shot h\(^{-1}\) for the maximum dose).

<table>
<thead>
<tr>
<th>Absorption</th>
<th>6 mm pyrex Window</th>
<th>4.8 mm steel chamber wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>2 m 3 m</td>
<td>2 m 3 m</td>
</tr>
<tr>
<td>Average dose rate ((\mu)Sv h(^{-1}))</td>
<td>1.0 0.4</td>
<td>0.03 0.012</td>
</tr>
<tr>
<td>Maximum dose rate ((\mu)Sv h(^{-1}))</td>
<td>7.7 3.0</td>
<td>0.2 0.09</td>
</tr>
</tbody>
</table>

The dose received by a person who operates the plasma focus will depend on where he is positioned and on the firing rate. Because of the high voltage and large current involved, the person who operates the plasma focus always stands at a considerable distance from it (greater than 2 m). Further, it is our normal practice to purge and refill the focus chamber after a few shots. This limits the firing rate to a ‘maximum’ of about 15 shots per hour. In practice, the average firing rate over a 3-month period is closer to 2 shots per hour.

Table 1 summarises the estimated average dose and the ‘maximum’ dose received by an operator standing at 2 m and 3 m from the PFF. These data may be compared with the
regulatory limits of 0.5 $\mu$Sv h$^{-1}$ and 25 $\mu$Sv h$^{-1}$ for the whole body exposure of a member of the public and a radiation worker, respectively. It is seen that the intensity of the X-rays emitted is high, even for a small focus. However, absorption in the 4.8 mm thick steel chamber is sufficient to reduce the exposure to an operator to a level below the regulatory limit applicable to a member of the public if he stands at a distance greater than 2 m from the focus device.

SOFT X-RAY STUDIES

Soft X-ray emission from the UNU/ICTP PFF using pure argon or argon-hydrogen admixtures has been studied in fairly great detail [J8, J73-J76, J83] using PIN diodes with differential filtering, single-pinhole and multi-pinhole cameras, and a time-resolved X-ray pinhole imaging system. The characteristics of the X-ray emission varies considerably from shot to shot and depends crucially on the gas pressure. In general, there are two sources of soft X-rays. One source is the cylindrical pinch column located above the anode. The length of the column is about 10 mm and the diameter about 1 mm. The X-ray emitting column shows fine structures such as filaments and hot spots. For argon, the temperatures of the hot spots are in the region of 1.5 – 5 keV. The second source of soft X-rays arises from electron beam activity on the copper anode and the vaporised anode material above the anode surface. These X-rays are mainly copper K$_\alpha$ radiation. The time profile of the X-ray emission exhibits two periods. The first period lasts for about 60 ns and is characterized by one or more sharp spikes of about 5 ns duration. These sharp spikes correspond to the hot spots in the pinch column. The second period occurs some 200-300 ns later and is characterized by a broad pulse of about 200 ns duration. The X-rays in this second period are copper K$_\alpha$ lines. The relative contribution from the two sources of X-rays depend crucially on the gas pressure as shown in Fig. 6 for argon at 0.7 mbar and Fig. 7 for argon at 3 mbar.

![Image](image.png)

**Fig. 6.** Soft X-ray emission at 0.7 mbar argon: (a) pinhole image through 48 $\mu$m mylar (b) time profile measured with a PIN diode with 24 $\mu$m aluminized mylar filter.
Fig. 7. Soft x-ray emission 3 mbar argon: (a) pinhole image through 48 um mylar, time profile using a PIN diode with 24 um aluminized mylar filter.

Fig. 8. A picture of the modified plasma focus opening switch.
THE PLASMA FOCUS OPENING SWITCH

One of the three sets of the UNU/ICTP PFF has been modified to assess the operation of a plasma focused based long conduction opening switch, with a plasma filled diode as a load [M4M, C71, C73]. A picture of the modified plasma focus opening switch (MPFOS) is shown in Fig. 8. The electrode geometry of the UNU/ICTP PFF has been modified to redirect the plasma motion to avoid the normal plasma focus action. To enhance plasma opening action the operating pressure regime is shifted to below 0.01 mbar. Initiation of discharge at such a low pressure is achieved by means of a set of twelve injection cable guns. For the present study, a diode element is arranged to sit directly on top of the switch to act as the load. The diode is plasma filled by allowing a small portion of the switch plasma to pass from the switch section into the diode section through a ring of apertures. Fig. 9 shows the voltage, current, magnetic and ion beam signals for a discharge in nitrogen at 0.018 mbar. The initial breakdown is under the control of the plasma guns, delayed from the start of the voltage by 80 ns. After a conduction period of 1.9 μs, the voltage rises sharply within a time < 50 ns, and is maintained for over 100 ns. The MPFOS has exhibited reproducible opening action in various gases at optimum operating pressures of between 0.01 mbar to 0.035 mbar. Ion beams of 85 keV for hydrogen, 225 keV for nitrogen and 285 keV for argon have been obtained [M4M].

![Figure 9](image.png)

**Fig. 9.** A typical MPFOS discharge in nitrogen at $1.8 \times 10^{-2}$ mbar. (a) Voltage signal, (b) current signal, (c) outer magnetic signal, (d) first ion beam signal, and (e) second ion beam signal.

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