PLASMA FOCUS-DEVELOPMENT AND APPLICATIONS FOR INDUSTRIAL SECTOR

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We discuss the development & applications of the PF from the work of our network

- Historical aspects - Malaysian region
- The role of training programmes
- Neutron applications
- Multi-radiation applications
- Materials- fabrication, enhanced properties
- The DuPF
Historical notes:
Development of PF in Malaysia

• Professor S P Thong started plasma research in Malaysia in 1960, when he joined the Physics Department, Universiti Malaya as Head of Department.

• Experimental work started on:
  - Glow discharge – S P Thong
  - Electric shock waves – H H Teh
Example of UM Plasma publications – pre 1970

**INT. J. ELECTRONICS, 1967, VOL. 22, NO. 2, 193-196**

**RESEARCH NOTE**

Transition from Electromagnetic to Hot-gas Driver in an Electric Shock Experiment

By H. H. Teh and S. Lee

Fig. 1

Electric shock tube with ring electrodes; EE, electrodes, X, expansion chamber, S, sink.

Fig. 2

Graph of $\log_{10} U$ plotted against $\log_{10} P$ for argon at a constant voltage of 10 kV. $P$ is in cm. $U$ in 10$^{-4}$ mm Hg.
HISTORICAL NOTE

HRH Prince Philip of Great Britain visits UM Physics Department, 1965, in conjunction with gift of large capacitor bank to start Plasma Physics Laboratory under Colombo Plan

(R-L: Dr A Husain, Dr Lee Kuen On, Dr Teh Hock Heng, Lee Sing and Dr Lim Chuan Poh)
A simplified method of switching a 2-mega-ampere capacitor bank using a voltage division technique

S. P. THONG\textsuperscript{1,2} AND S. LEE\textsuperscript{1,3}

Fig. 11

Photograph of experimental set-up. In the centre is shown the pyrex return focus tube. The inner electrode can be seen through the glass tube. The high voltage collector plates of the two modules, each with 25 cable connections, are also shown with the coaxial transmission cables leading downwards to the condensers, which are on a lower platform, not shown.
40 kV bank switched by 20 kV ignitrons with voltage dividing gaps — 100 capacitors in 4 modules
UM Bank recorded 1.92 MA in 1972
UM PF in Fusioning Self Light
Time of Flight Measurement, D-D neutrons: UM PF- Oct 1973-

Claim: First electric plasma fusion neutron measurement in Asia

485 ns over 10.19 m, backwards direction
Conclusion:
2.3 MeV n from D-D fusion
Beam ions at ~150 keV

Neutron yield $10^8$
1971 Published streak and framing pictures of PF with dynamics and inductance measurements
HE Ambassador Dr Ritter of West Germany on the platform of the Juelich I (2 MegaAmp facility) in 1977 on the occasion of Presentation of the Juelich PF II as follow-up grant of AVH Fellowship
Nuclear fusion observed in laser-initiated Vacuum Spark-1977

Soft X-ray pinhole photograph taken with a photographic sensitivity of 1–2.5 Å. The anode, in this case, has a central channel filled with LiD. The circular spot at the top of the intense image has a diameter corresponding to the pinhole size of 0.4 mm.
First Physics PhD Thesis produced by a Malaysian University in 1978 was in the field of Plasma Focus


university needs to produce its first PhD before it comes of age- Abdus Salam
D vs Ar focus pinches - insights into plasma thermodynamics - 1982

PINCH DYNAMICS OF THE PLASMA FOCUS
T.Y. Tou and S. Lee
Plasma Research Laboratory
Physics Department, University of Malaya

\[ \kappa_p = 0.18 \]
\[ \kappa_p = 0.12 \]

Figure 2b Side-on streak image of a deuterium focus pinch at 5.5 torr, 14 kV.

\[ \kappa_p = 0.12 \]
\[ \kappa_p = 0.08 \]

200ns

WAYNE T. ROYER
University of Missouri
Columbia, Missouri

DYNAMICS OF REB–SPUTTERED COPPER PLASMA JETS
S. LEE, HARITH AHMAD, T. Y. TOU, K. H. KWEK and C. S. WONG

Preliminary observations of sputtered deposits on a flat glass plate indicate the possibility of depositing areas of very clean film of copper by this method. These observations also raise the possibility of producing plasma jets of other materials by simply placing an insert of the desired material in the anode cavity so that this insert may then be bombarded by the relativistic electron beam. This technique may have useful applications.
DEVELOPMENT OF PLASMA TRAINING PROGRAMMES
UM Plasma started to organise international training programmes in 1984:
(Concept: South-south technology creation, sharing and transfer)
Distinguished scientists from India, China, Pakistan, UK, US, Australia Visiting UM Plasma Research Lab during First Tropical College on Applied Physics In 1984
Nobel Laureate Abdus Salam visiting the UNU Training Programme on Plasma and Laser Technology at UM in January 1986

L-r: Widdi, Gholap, Sapru, Smith, Tou, Abdus Salam, K Eissa (almost hidden), Suryadi, Zakaullah, Kwek, Lee, Chatar Singh, Susetyo, Tan
UNU Training Programme on Plasma and Laser Technology in 1985 to 1986

Parts of several UNU/ICTP PFF’s
Warmate & Dr Smith with 1 set (in crates) of UNU/ICTP PFF-at Foyer Of UM Physics

Dr Walter Shearer (UNU), Zakaullah, Dr Eissa, Lee
We provided hands-on experiments to some 80 participants in:

- Em shock tube, plasma focus, glow discharge, tokamak, control electronics, plasma computations and laser experiments.
- The intensive training programmes trained 24 Fellows.
- 18 papers were written during the programmes; 5 published in ISI journals, the others in journals and conference proceedings.
- The following equipment was transferred.
Equipment transferred up to 1991 (not comprehensive)

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<td>Harare, Uni of Zimbabwe</td>
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* Have produced PhD/MSc theses from these facilities
+ Developed the UNU/ICTP PFF locally
Research results of training programmes
Research results of training programmes

A simple facility for the teaching of plasma dynamics and plasma nuclear fusion

S. Lee, T. Y. Tou, S. P. Moo, M. A. Eissa,4 A. V. Ghopal,5 K. H. Kwok, S. Mulyodomo,6 A. J. Smith,7 Suryadi,8 W. Usada9 and M. Zakariah3
United Nations University Training Programme on Plasma and Laser Technology, Physics Department, University of Malaysia, 91900 Kuala Lumpur, Malaysia
(Received 11 July 1986; accepted for publication 23 February 1987)
Sequenced nitrogen lasers

S. Lee and K. H. Kwek
Plasma Research Laboratory, University of A.
J. Appl. Phys. 65 (11), 1 June 1989

Jalil Ali, a) M. V. H. V. Prabhakar, b) Y. c)
(United Nations University) International Centre for Theoretical Physics. Training Programme on Plasma and Laser Technology, Physics Department, University of Malaya, 50100 Kuala Lumpur, Malaysia

(Received 26 September 1988; accepted for publication 3 January 1989)

FIG. 1. Circuit diagram of the three-channel sequenced nitrogen laser.

FIG. 2. Computed voltages across the laser channel, laser current, and laser current squared as functions of time. All variables are normalized. Parameters used are those for a “prolonged sequencing” mode.

FIG. 3. Shadograph of current configuration before and after peak compression with a flat target at a distance of 1.5 cm from the mode face.

FIG. 4. Schematic of a three-channel sequenced nitrogen laser. The high-voltage plates of the capacitors $C_1$, $C_2$, $C_3$, and $C_4$ are made of aluminum foils.
Review of 1998

• The UNU/ICTP PFF - research network based on a 3kJ PF. Designed in 1985/86 - during an UNU Training Programme.

• Established in 10 institutions in 8 countries; built up 7 research laboratories and research groups

• Produced 16 PhD’s, 31 Masters, 160 research papers (as of 1998)

• It was instrumental in the formation of the AAAPT.

• 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
PhD thesis completed on the UNU/ICTP PFF

- **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.
Papers in Refereed Journals
(from results obtained during training programmes)


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Other Papers in refereed journals— from Network research (up to 1998)

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Other Papers in refereed journals - from Network research (up to 1998)

Other Papers in refereed journals- from Network research (up to 1998)


Other Papers in refereed journals- from Network research (up to 1998)


• J72. Zakaullah M., Ijaz Akhtar, G. Murtaza and A. Waheed, Imaging of fusion reaction zone in plasma focus,


85 papers published using the UNU ICTP PFF in International journals as of 1998

DEVELOPMENT OF PLASMA FOCUS MACHINES
UNU ICTP PFF: 3 kJ Plasma Focus
The Parts for the Plasma Focus
Diagnostics

KSU-DPF Machine (Diagnostics)

- Voltage Probe
- Plastic Scintillator
- DC Voltage Probe
- BPX65 PIN Diode
- LiI Detector
- Bubble Detector
- Rogowski Coil
- He³ Detector
- He³ Detector

Organizers:

Sponsors:

INTERNATIONAL WORKSHOP on Plasma Physics for the next century and beyond...
28-30 August 2018, Johor Bahru, Malaysia
Development of a range of Plasma Focus Machines

Critical scaling properties
Scaling Properties

3 kJ machine
Small Plasma Focus

1000 kJ chamber only
Big Plasma Focus

Organizers:

Sponsors:

INTERNATIONAL WORKSHOP on Plasma Physics
for the next century and beyond...
28-30 August 2018, Johor Bahru, Malaysia
Comparing large & small PF’s: Dimensions & lifetimes - putting shadowgraphs of pinch side-by-side, same scale

Anode radius 1 cm 11.6 cm
Pinch Radius: 1 mm 12 mm
Pinch length: 8 mm 90 mm

Lifetime ~10 ns order of ~200 ns

SAME ENERGY DENSITY in all optimised PF’s
A range of PF’s in Singapore – Paul Lee

DPF Devices @ Plasma Radiation Sources Lab (PRSL)

0.2 kJ

3.0 kJ

2.0 kJ

10.0 kJ

Organizers:

Sponsors:

INTERNATIONAL WORKSHOP on Plasma Physics for the next century and beyond...
28-30 August 2018, Johor Bahru, Malaysia
NX2-Plasma SXR Source-Hi Rep

- 11.5kV, 2 kJ
- 16 shots/sec; 400 kA
- 20J SXR/shot (neon)
- $10^9$ neutrons/shot
Current-Stepped Pinch – PhD S H Saw 1991

Fig. 2.3 Schematic diagram of the arrangement of a current-stepped Z-pinch.

Fig. 3.1 The capacitor, C, and the spark-gap connections.

Fig. 3.16 Block diagram of the NCZPPEP set-up.

Fig. 3 Current and voltage signals and time-resolved radial profile of the single compressional Z-pinch.

Fig. 4 Current and voltage signals and time resolved radial profile of the current-stepped Z-pinch.

\[ V_1 = 9 \text{ kV} \quad C_2 = 60 \text{ µF} \quad L_2 = 70 \text{ mH} \]
\[ t_{r1} = 1.4 \text{ ms} \quad I_{Q1} = 251 \text{ kA} \quad dI_{Q1}/dt = 1.3 \times 10^{11} \text{ A/s} \]

and

\[ V_2 = 18 \text{ kV} \quad C_2 = 22 \text{ µF} \quad L_2 = 25 \text{ mH} \]
\[ t_{r2} = 1.3 \text{ ms} \quad I_{Q2} = 463 \text{ kA} \quad dI_{Q2}/dt = 5.5 \times 10^{11} \text{ A/s} \]

[1] First bank – A Marx-photographed water-line:

Water-line:
\[ V_0 = 100 \text{ kV} \quad L_0 = 90 \text{ mH} \quad C_0 = 30 \text{ nF} \]
\[ L_1 = 150 \text{ cm} \quad L_2 = 20 \text{ cm} \quad d_x = 15 \text{ cm} \]
\[ t_1 = 52 \text{ ns} \quad L_2 = 1.7 \text{ Q} \quad I_0 = 88 \text{ kA} \]
\[ dI/dt = 2 \times 10^{12} \text{ A/s} \]

[2] Second bank – A Marx-photographed water-line:

Water-line:
\[ V_0 = 100 \text{ kV} \quad L_0 = 90 \text{ mH} \quad C_0 = 30 \text{ nF} \]
\[ L_1 = 150 \text{ cm} \quad L_2 = 20 \text{ cm} \quad d_x = 15 \text{ cm} \]
\[ t_1 = 52 \text{ ns} \quad L_2 = 1.7 \text{ Q} \quad I_0 = 88 \text{ kA} \]
\[ dI/dt = 2 \times 10^{12} \text{ A/s} \]
Current-Stepped PF

Fig 15 Plasma Focus with an additional circuit to provide a current step.

Fig 16 Comparing the current waveforms of main bank ($I_1$ with CS), current-step bank ($I_2$) and the combined current ($I$). Also shown for comparison is the current when the current-step is not switched on ($I_1$).

Fig 17 Comparing radial trajectories with and without current step.
Development of Applications
Code-correlated templates (CCT):
1. SXR spectrometer (5-ch) with CCT
2 channels each selectively filtered to give a narrow transmission window.
Template- Correlating current, neon SXR with modelled dynamics and anomalous resistance
Expanded for ns resolution
3-channel Magnetic probe with CCT
CCT- Information obtained

- Magnetic field and current sheet structures
- Current sheet speeds
- Axial phase dynamics
- Magnetic Reynolds Number inferred
- Correlation with Lee Model code
Integration of numerical experiments with laboratory experiments

• Using our code we have integrated the results of world-wide experiments with our own to obtain scaling laws and insights into plasma focus experiments
Applications using neutrons
1. 300J portable (25 kg); $10^6$ neutrons per shot neutron source
Pulsed portable neutron source

 NX2
 1.4 x 1.6m x 1.6m
 V ~ 3.6m³

 2kJ ↑ 0.2kJ
 10⁸ n/s ↑ 10⁶ n/s

 FMPF-1
 0.2m x 0.2m x 0.5m
 V ~ 0.02m³

Advantages of small PF
• Short time scale
• Small source size
• => high brightness

Advantages of large PF
• High efficiency
• => low power input
• => low heat load

At 2kW input power,
200J PF 10⁶ x 10Hz ~ 10⁷ n/s
2kJ PF 10⁸ x 1Hz ~ 10⁸ n/s
10kJ PF 2 x 10⁹ x 0.2Hz ~ 4x10⁸ n/s
Summary of neutron sources - Singapore

<table>
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<tr>
<th>Machine</th>
<th>Current kA</th>
<th>Yield neutrons/shot</th>
<th>Yield rate neutrons/s</th>
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<td>FMPF3, 200J</td>
<td>100</td>
<td>$10^6$</td>
<td>$10^7$</td>
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<tr>
<td>UNU-ICTP, 3kJ</td>
<td>170</td>
<td>$10^8$</td>
<td>$10^7$</td>
</tr>
<tr>
<td>NX2, 2kJ</td>
<td>340</td>
<td>$10^8$</td>
<td>$10^9$</td>
</tr>
<tr>
<td>NX3, 10kJ</td>
<td>500</td>
<td>$10^9$</td>
<td>$10^8$</td>
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</table>

Order of magnitude comparison based on machines as designed and constructed
Neutrons: Application R&D yttrium detectors

- The yttrium detector relies on the detection of 909 keV gamma-rays from the de-excitation of $^{89m}$Y detected by a scintillation detector.

- For efficient operation of this detector the scintillator crystal BGO was used which as its high bismuth (Z=83) content and density of 7.13 g/cm$^3$, is very suitable for detection of the 909 keV gamma-rays from $^{89m}$Y.

- The mono-energetic nature of the secondary radiation enables the detector to measure absolute neutron flux without reference to an external standard.

- This detector does not need periodic re-calibration due to the mono-energetic secondary radiation and the absence of an electronic threshold.

- The yttrium fast absolute neutron detector has been calibrated numerically using the well-known Monte Carlo radiation transport code MCNP.


Neutrons: Application R&D beryllium detectors

REVIEW OF SCIENTIFIC INSTRUMENTS 77, 10E713 (2006)

Novel fast-neutron activation counter for high repetition rate measurements

S. Mahmood
Natural Science and Science Education, NIE, Nanyang Technological University, Singapore 637616, Singapore and Department of Physics, University of Karachi, Karachi 75270, Pakistan

S. V. Springham, T. Zhang, R. S. Rawat, and T. L. Tan
Natural Science and Science Education, NIE, Nanyang Technological University, Singapore 637616, Singapore

M. Krishnan
Alamosa Applied Sciences Corporation, California 94

F. N. Beg
Department of Mechanical and Aerospace Engineering, San Diego, California 92931-0411

S. Lee
Natural Science and Science Education, NIE, Nanyang Singapore 637616, Singapore

H. Schmidt
International Centre for Dense Magneto-plasma, B and Laser Microfusion, 00-908 Warsaw, Poland

P. Lee
Natural Science and Science Education, NIE, Nanyang Singapore 637616, Singapore

![Graph showing the uncertainty of the novel fast-neutron activation counter for high repetition rate measurements.](image-url)
High energy deuterons from NX2 plasma focus device have been used for short-lived positron emitting radioisotopes $^{13}$C, $^{13}$N and $^{15}$O production. For the $^{12}$C(d,n)$^{13}$N reaction, 13 kBq of $^{13}$N was obtained by bombarding the graphite target at 1 Hz shot repetition rate for 30s.

This could be increased to 3 MBq at 16 Hz repetition rate and longer exposure time.
Applications as a multi-radiation source

For the purpose of using the plasma focus as a radiation source, there are a number of advantages listed below:

- Elegance and Simplicity
- High efficiency
  - When radiation produced by plasma mechanism
- Short pulse, high brightness
- Possibility of more than 1 type of radiation at the same time.
  - E.g. simultaneous neutron and hard x-ray radiography
SXR application: microlithography using NX2 in neon
PF SXR Schematic for Microlithography

- 1 - anode
- 2 - cathode
- 3 - SXR point source
- 4 - x-rays
- 5 - electron beam deflection magnets
- 6 - shock wave shield
- 7 - Be window
- 8 - x-ray mask
- 9 - x-ray resist
- 10 - substrate
Lines transferred using NX2 SXR

X-ray masks in Ni & Au
Our results showed that an X-ray exposure dose of 2500 mJ/cm² from a neon-filled DPF device is sufficient for complete cross-linking of the 25 μm SU8 resist.


Soft x-ray applications: soft biological imaging

- Soft X-ray images

Insect, UNU-ICTP

Medium energy x-ray applications

Medium X-ray video

Medium X-ray Images of soft/small biological samples obtained on NX2
RAPID MATERIAL INTERROGATION USING X RAYS FROM A DENSE PLASMA FOCUS (KSU- DPF)

• MOHAMED ISMAIL ABDELAZIZ MOHAMED ISMAIL

• Used signature-based radiation-scanning (SBRS) technique.

• The SBRS technique uses template matching to differentiate targets that contain certain types of materials, such as chemical explosives or drugs, from those that do not.

• Experiments were performed with different materials in cans o1 quart to 5 gallons

• Nitrogen-rich fertilizers and ammonium nitrate were used as explosive surrogates.

• 100% sensitivity for all sizes of samples while; 50% specificity for 5 and 1- gallon and 29% for quart samples.

• Simulations using MCNP-5 gave results in agreement with experimental results. In the simulations, a larger number of materials, including real explosives were tested.

• Results were encouraging. Experimental and simulation results indicate that use of DPF devices with simple, room-temperature detectors may provide a way to perform rapid screening for threat materials, especially for places where large number of packages need to be investigated.
Experimental set-up for SBRS of explosive materials

Figure 6-2 Schematic diagram of the experiment.

- D1: Bare Plastic scintillator.
- D2: NaI(Tl) scintillator filtered with 0.5 mm cadmium sheet.
- D3: Bare NaI(Tl) scintillator.
- D4: Bare NaI(Tl) scintillator.

Figure 7-2. X-ray signals for signature and direct detectors.

- BC-418 plastic scintillator, 2 x 1 in, coupled with a Hamamatsu PMT, model H7195.
Radiatively collapsed Intense Point Light source

- This thesis was the start of our work on DPF radiative collapse with development of the radiation coupled PF pinch motion equation

\[
\frac{dr_p}{dt} = \frac{-r_p \frac{dI}{dt}}{\gamma I} - \frac{1}{\gamma + 1} \frac{r_p}{z_f} \frac{dz_f}{dt} + \frac{4\pi(\gamma - 1)}{\mu \gamma z_f} \frac{r_p}{f_c^2 I^2} \frac{dQ}{dt} \frac{\gamma - 1}{\gamma}
\]

- \( Q = \) Joule heat (+ve) + radiation (-ve)
- When radiative power is large, it gives a large negative component to \( \frac{dr_p}{dt} \) leading to radiative collapse of the plasma pinch
Radiative collapse in Kr, measured in the INTI PF on the basis of a current measurement (2 kJ operation)

- 250 J in PF plasma energy
- 40 J radiated away in 50 ps
- 0.8 TW, 40 kJ per mm$^3$
Intense pulse light

- Suggests design of following light source
  - 10 kJ fast discharge in Kr DPF,
  - 3 kJ in plasma energy
  - Kr light pulse: 1 kJ in 50 ps,
  - 20 TW (peak power) light source
- Viewed end-on, it is a point source
Developing EUV source
Visualising fusion ions

Imaging of Plasma Focus Fusion by Proton Coded Aperture Technique

Ali reza Talebihaer · Stuart Victor Springham · Paul Maurice Edmund Shutler · Paul Lee · Rajdeep Singh Rawat
Electron beam applications: materials ablation


Applications to thin film deposition, fabrication

Materials modification using Plasma Focus Ion Beam

For plasma processing of thin film materials on different substrates with different phase changes.
Applications: depositing Chromium and TiN - M Ghoranneviss
Applications: Nanoparticles synthesis

R S Rawat et al

- Synthesize nano-phase (nano-particles, nano-clusters and nano-composites) magnetic materials
- Mechanism of nano-phase material synthesis
- Effect of various deposition parameters on the morphology and size distribution of deposited nano-phase material
- To reduce the phase transition temperatures
100nm FeCo agglomerates deposited

NX2 set-up for depositing thin films; deposited thin films with consisting of 20nm particles
Textured Tool for dry machining of aluminum—project of T.O.Teh –INTI IU

PF provides hardening and suitable texturing

Tool is tested successfully in dry-cutting of aluminum.
160 kJ DuPF – Fast mode: high intensity radiation; Slow mode: nano materials fabrication

Fig. 1. Computed radial trajectories of INTI PF based on Lee Model Code for 3 Torr D(left) and 14 Torr D(right); FFM (left), SFM (right)

Fig. 1. The radius of pinch exit in INTI PF for D, Ne, and Ar.
160 kJ DuPF – Fast mode: high intensity radiation; Slow mode: nano materials fabrication

Fig. 4. FIB energy (per ion) versus D, Ne, and Ar pressure in INTI PF based on Lee Model Code

Fig. 6. Number of ions per shot in INTI PF versus D, Ne, and Ar pressure based on Lee Model Code

Fig. 5. FIB damage factor for D, Ne, and Ar in INTI PF

Fig. 7. FPS energy per ion in INTI PF for D, Ne, and Ar
The plasma focus apparatus is for producing plasma radiation in two pinch modes. The pinch modes are a slow pinch mode (SFM) and a fast pinch mode (FFM). The speed factor for the FFM is in a range from \((60 \text{ kA/cm})\text{Torr}^{0.5}\) to \((100 \text{ kA/cm})\text{Torr}^{0.5}\) and the speed factor for the SFM is substantially in a range less than \((50 \text{ kA/cm})\text{Torr}^{0.5}\).
The **DUPF** – A collaborative project of INTI IU, UTM and NIE/NTU

Biggest DPF dedicated to material fabrication: the concept is proven; it has been designed and almost completely installed at INTI IU
Summary
In this presentation we have discussed the development & applications of the Plasma Focus from the work of our network with emphasis on the following:

- Historical - Malaysian region
- The role of training programmes
- Neutron applications
- Multi-radiation applications
- Materials- fabrication, enhanced properties
- The DuPF
THANK YOU &
Thanks to all collaborators