RESULTS OF THE UNU/ICTP PFF- 3 kJ PLASMA FOCUS NETWORK

S Lee
Plasma Radiation Laboratory
Nanyang Technological University
National Institute of Education
Singapore

Paper Presented at the International Meeting on Frontiers of Physics, Kuala Lumpur, Malaysia; updated for IAEA/ICTP Workshop on Plasma Physics, November 2003

- **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 20 PhD's, 40 Masters, more than 200 papers in refereed research journals and conferences.**

- **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 and summarises the main scientific results achieved so far by the network.

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, **sustained research** could be carried out in their **home institutes**.

Various ideas were discussed and the ideas were reduced to the **glow discharge**, the **linear pinch**, the **electromagnetic shock tube** and the **plasma focus**.

In 1984 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,

· **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

· **provide follow-up help** for the facilities to be set up in the home institute.

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.

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** & **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**.

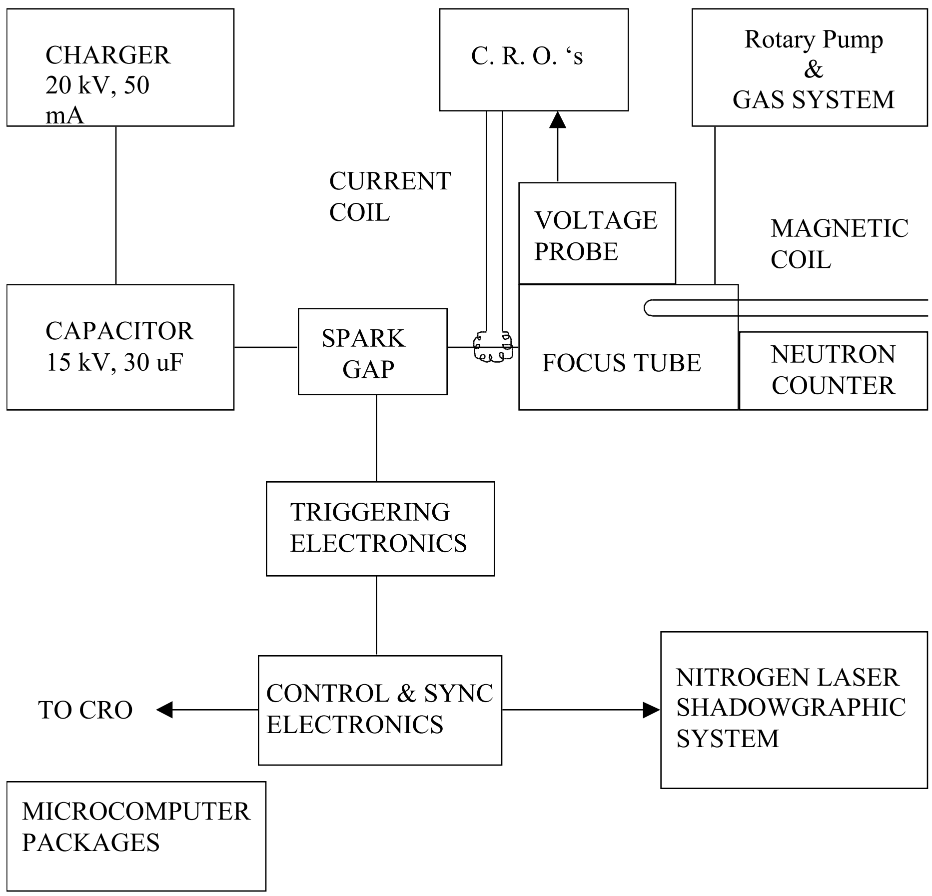

Fig1 Sub-systems of the UNU/ICTP PFF

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.

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 **EM 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 f**eatures** 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 in a simple manner so that we may effectively start 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 **simple 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** need **pulse forming lines** to reduce risetimes so that the pinch may be operated at **small radius** & **high 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** to achieve **better results**.

- 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 1 above)

In the **next month**, the **development, assembly** and **testing** of the first version of the UNU/ICTP PFF was carried out.

Professor Abdus Salam visiting the UNU/ICTP PFF at the University of Malaya, 20 January 1986

It was during this phase that the programme was visited by **Professor Abdus Salam**, Director of the ICTP.

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**.

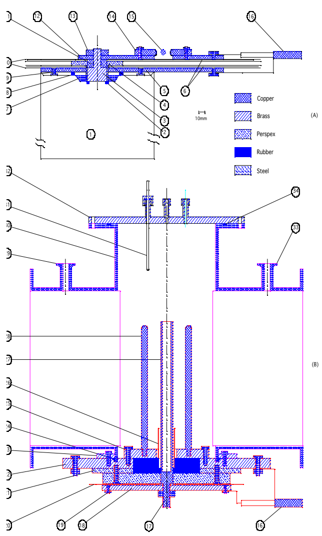

Fig 2 Design of the UNU/ICTP PFF

7. Assembing 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.

- The **parts** for **six sets** of UNU/ICTP PFF were **manufactured.**

- Each set was **assembled** and **tested** by its ‘owner’.

- Tests included **vacuum tightness**, **voltage holding, current conduction** and **full operation.**

- Full operational tests include **focussing** characteristics in **various gases**, including

- in **deuterium;** with **fusion neutrons** detected by a paraffin-wax moderated silver activation counter.

Six sets were thus manufactured, assembled and tested, one after another, **in a period of 6 weeks.**

Parts of several UNU/ICTP PFF

UNU Fellow Widdi Usada
assembling his UNU/ICTPPFF

Dr Walter Shearer of UNU
at presentation of follow-up
equipment

Dr A J Smith & A G Warmate with their
crated follow-up equipment

Research, Packing & Shipping

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 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 6 consignments weighing over 1000kg, was handed over to the Fellows and then to the company arranging the air-freight.

The equipment included **pulse trigger modules, high power chargers, capacitors, plasma focus chambers and electrodes**, nitrogen laser parts, insulator assemblies, glow discharge electrodes and several oscilloscopes.

The main equipment transferred was a **3 kJ plasma focus (six sets)** designated as the **UNU/ICTP PFF**.

8. Not the Training 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**.

9. Progress

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, Oct-Nov 1990.

A total of **24 Fellows** funded by UNU, ICTP, TWAS, UNESCO, AAAPT and UM were trained up to November 1990.

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, Beijing and Singapore Centres from 1992.

These have resulted in the training of **another 30 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, and **UNU/ICTP PFF** was placed at the **ICTP**.

In 1991 and 1993 **training experiments** were conducted at the **ICTP** during the **Spring College of Plasma Physics.**

These sessions were attended by some **35 scientists**

The following **table** (not comprehensive) shows the **facilities transferred** to the various recipient institutes after the first 3 Training Programmes.

Table 1

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

*** Have produced PhD/MSc theses from these facilities**

[+] Built locally

10. Progress at home Institutions

Good **progress** has been achieved back at the **home institutions** as a result of the training programmes and the follow-up equipment and assistance.

Plasma Focus facilities are now **fully operational** at

- **Quaid-I-Azam University, Islamabad, Pakistan**
- **University of Delhi, Delhi, India**
- **Rivers State University of Science and Technology, Port Harcourt, Nigeria**
- **Al Azhar University, Cairo, Egypt and**
- **Yogyakarta Nuclear Research Centre,** besides in
- **Malaysia and Singapore**.
- Also University of Zimbabwe
- Chulalongkorn University

Other facilities had been established at **Njala University College** (Sierra Leone), **University of Rajasthan** (India), **Shanghai Institute of Optics and Fine Mechanics** (P.R.China), **National Space and Aeronautics Board of Indonesia**, and a training facility at the **ICTP**.

Strong postgraduate programmes have been established at

- **Quaid-I-Azam University,**

- **University of Delhi**

- **Rivers State University of Science and Technology**

- and **Nuclear Research Centre, Yogyakarta** besides in

- **Malaysia and Singapore**

And more recently at:

Chulalongkorn university, Bangkok & at University of Zimbabwe & University of Science & Technology, Bulawayo, Zimbabwe.

11. Theses and Research Output

At last count research work on the UNU/ICTP PFF have produced **20 PhD's**, more than **40 MSc's** and more than **200 research papers.**

The UNU/ICTP PFF placed at the ICTP in Trieste
During the Spring College on Plasma Physics in 1991 and 1993, some 30 scientists carried out training/research experiments on this device in Trieste

12. What of the scientific reults?

A brief summary of the main scientific results achieved by the network of UNU/ICTP PFF's is collated as f**ollows**.

12.1 Plasma Dynamics:

Central to the study of dynamics in the UNU/ICTP PFF is the development of **theoretical understanding** based on **computational models**.

A model was developed using a **snowplow model for the axial phase**, followed by a **slug model** applied to an **elongating pinch** in the **radial phase**.

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 =** $\mathbf{(I/a)/\sqrt{\rho}}$ which has a constant value of **90 kA/cm per** $\mathbf{(torr)^{1/2}}$ for **all Mather type machines** ranging from small plasma focus of 3kJ to big plasma focus of 200kJ.

- This study has suggested the **concept of speed enhancement of neutron yield**, enhancing from the observed $Y \sim I^4$ to a **scaling of better than** **$Y \sim I^8$**.

- Inclusion of **thermodynamics** into the model shows that the **thickness** of **the radially collapsing current layer** and the **radius of the gross pinch** at maximum compression **depend on** γ, the specific heat ratio of the gas.

- A detailed study in Singapore 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**.

- Inclusion of **radiative terms** into an additional radiative phase 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.**

- **Since June 2000, this model has been e-published on the NTU/NIE website at http://sci.nie.edu.sg/ckplee**

- This model has also been used to predict a **new type of plasma focus** operating with several anodes to produce a **sequence of focussing**, hence a **sequence of neutron and SXR bursts**.

- The l-D axial phase has been modified in Zimbabwe by incorporation of **current sheath curvature** to improve the model in its design capability. Several other groups, including one in Egypt are making specific modifications of parts of the model to suit their own needs. A group in Iran has made major modifications so that their modelling can be applied more appropriately to the Filippov-type focus.

- The Islamabad group had developed a **2-D model** covering both axial and radial phases. The model sought to **optimise** the **Lawson parameter nτ** for plasma focus.

12.1 Machine Optimization / Scaling

This has been a major concern right from the beginning of the design of the UNU/ICTP PFF in Kuala Lumpur.

Going further the Islamabad group 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/ axisymmetry** and

· **lowers neutron fluence anisotropy.**

Lowering the **external parasitic inductance** towards the value of 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.

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.

- 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**, hence higher temperatures so as to take advantage of the **increased fusion cross-section?**

- The answer may be that at **higher speeds, drive-field, flow-field separation** towards the end of the axial phase tends to occur **because of the high**

Magnetic Reynolds Number (which depends on the fourth power of velocity).

· This **separation** is **detrimental** to proper radial **compression** mechanism.

An experiment has been carried out in Singapore using the UNU/ICTP PFF with a two stage anode.

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 increase in speed**, yet **short enough** to **limit** the **drive-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.

Experiments for speed enhancement effects could be carried out using a bigger plasma focus, where the currents could be varied at the same time as the anode geometry is varied to increase the drive parameter S whilst restricting the drive field, flow-field separation.
That would be a better test of speed enhancement.

12.3 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 **10^8n per shot** using a Indium foil activation counter.

In a series **of experiments** in Kuala Lumpur 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.

The effect of **different anode material and configuration and different operating pressures on neutron yield** was also studied in Islamabad.

Speed Enhancement of neutron yield had already been discussed under machine scaling.

Ion beams were studied using **Faraday cups**, **Thomson spectrometer** and Solid State Nuclear Track Detectors (**SSNTD**) such as CR-39 .

In Islamabad, **pin-hole images of** the charged particle **(deuterons) emission zone** 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 in conjunction **with SSNTD** to obtain the **ion energies**. The ion energies have also been estimated using Faraday cups in Delhi and in Singapore.

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.

In **deuterium** the **SXR** are from **Bremsstrahlung** and it was found in Singapore that there are indications that there **may be a speed enhancement effect.**

Neon operation may produce a **SXR** source suitable for **microelectronics lithography**. Calculations and experiments on the UNU/ICTP PFF in Singapore show that a **neon plasma temperature of 300-400 eV** is required to generate the desired **0.8 - 1.4 nm spectrum** mainly from a H-like neon line and a He-like neon line.

Using a combination of **calorimeter, crystal spectrometer** and **5-channel pindiode sp**ectrometer, an optimised yield of **5Joules** in wavelength range of **0.8 - 1.4 nm** is obtained from the **UNU/ICTP PFF**.

<u>12.4 Applications:</u> 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** of thin film materials on different substrates with different phase changes.

The following were achieved:

(a) **Crystallization** of an amorphous lead zirconate titanate (**PZT**) thin film
(b) **amorphization** of crystalline thin film of **PZT**
(c) observation of **n-type** doped behaviour of a **polyaniline** film after plasma ion bombardment
(d) observation of **p-n junction** diode formation in a **single polyaniline** film, cation doped chemically on one side and anion doped by plasma focus ions on the other side
(e) observation of **magnetite phase** from **hematite** thin film irradiated by plasma focus ions
(f) observation of a **rise in superconducting temperature** of a thin film of high T_c superconducting material **BPSCCO**
(g) **deposition** of **thin carbon film**
(h) **deposition** of **Fullerene films** of $\mathbf{C_{60}}$ and $\mathbf{C_{70}}$ on Si.

(i) In cooperation with Delhi, experiments were also carried out in Singapore in which plasma focus ions were used to **improve** the **crystallinity** of $\mathbf{Sb_2Te_3}$ (antimony telluride) thin films and to encourage a **preferred direction** of crystal orientation.

More recently Professor Srivastava has reported the use of the UNU/ICTP PFF for fabrication More of nano-scale structures, including possibly nanotubes. Increasing number of UNU/ICTP PFF's are also being used for experiments on materials fabrication & modification.

12.5 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 **powerful SXR point sources** (300W) in the world.

- This led to demonstration of **sub-0.2 μm lines** 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**.

- **Pulsed neutron activation** was used in Kuala Lumpur to determine the half-lives of ^{116}In, ^{104}Rh and ^{24}Na^{m}.

- An investigation is also being carried out by doping deuterium with argon in order to obtain **suitable neutron pulse profiles** for the **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 from the **safety** point of view.

- Such studies are useful, beyond the UNU/ICTP PFF context as they contribute to an understanding of **radiation safety** from **intense pulsed sources** in general.

- 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**.

- In Port Harcourt, Nigeria the possible application of the focussed plasma from the UNU/ICTP PFF to a situation of **astrophysical interest** has been studied.

- At the ICTP Trieste a statistical study of the plasma focus in its good-focus, bad-focus modes had enabled some conclusions to be made in terms of a model based on **non-linear deterministic mechanics.**

New devices have been suggested by experiments carried out during the UNU/ICTP Training Programmes.

- **A sequential plasma focus** device **and a sequential nitrogen laser system** were both invented during training programmes.

- The **sequential plasma focus** was later **modelled** in Malaysia/Singapore and subsequently **confirmed** in operation by both the Delhi and the Quaid-I-Azam 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**.

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**.

13. Conclusion

- The UNU/ICTP PFF programme started as an exercise to **initiate/strengthen experimental research** 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 intensively focussed on the **workings of each sub-system** of the device and facility to be transferred.

- The **sub-systems approach** was crucial to the success of the programme. The Fellow had to **assemble** and **maintain** his system back home. He **had to understand how each sub-system** worked.

- Over these 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 8 active experimental research groups.**

- It was instrumental in the **formation of the Asian African Association for Plasma Training** (AAAPT) with membership of 39Institutions from 22 countries. It contributed to the training and scientist exchange concepts adopted at the **formation of the International Centre for Dense Magnetised Plasmas (ICDMP)** now sited in Poland.

- The network of ICTP PFF's has produced **20 PhD's, more than 40 Masters and more than 200 research papers;** and has **a significant impact on the knowledge and practice of pulsed dense plasmas**.

It is a contemporary example of what can be achieved from the initiative and cooperation

of scientists with the support of international agencies like the UNU, ICTP and TWAS.