Initiating and Strengthening Plasma Research in Developing Countries

A grass-roots effort begun 20 years ago has blossomed into today's Asian African Association for Plasma Training. The AAAPT has helped establish vigorous plasma-related programs, including materials processing and fusion studies, around the globe.

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Developing countries are, by definition, striving to develop their economies and infrastructures, along with educational and perhaps other social systems. The pursuit of physics might not spring to mind as the first way to engage in such development, but it can and often does work hand-in-hand with national and regional goals. (See "Promoting Physics and Development in Africa" by Edmund Zingu, PHYSICS TODAY, January 2004, page 37 and "Physics in Latin America Comes of Age" by José Luis Morán-López, PHYSICS TODAY, October 2000, page 38.)

The story of the Asian African Association for Plasma Training (AAAPT) provides an interesting case study of one group that has done much to strengthen plasma research in developing countries. Its core program is a practical, hands-on scientific enterprise that has been successful not only at building the educational, industrial, and research capacities at particular institutions, but also at propagating those capacities beyond the original recipients.[1] An important feature of the program is a long-range view that allows provision for follow-up equipment.

Today, the AAAPT is a network of 44 institutes in 24 Asian and African countries. Its history is one of practical scientific collaboration involving tabletop plasma experiments. Central to its achievements is the UNU/ICTP PFF—the United Nations University/International Center for Theoretical Physics Plasma Focus Facility—a research system[2] based on a 3-kJ plasma focus machine (see the box on page 34). A network of 12 UNU/ICTP PFFs is now operating at 10 institutions in 7 countries. The continuing research[3–5] includes work to develop new concepts of radiation enhancement and a host of applications. Overall, having produced more than 20 PhDs, 40 master's degrees, and 200 refereed research papers, the network has contributed significantly to the understanding of dense plasmas.

A focused beginning

At the 1983 Spring College on Plasma Physics at the ICTP in Trieste, Italy, a group of budding plasma physicists from developing countries gathered informally to discuss the difficulties they faced in starting experimental plasma research. They needed small devices that could be built back home and could sustain research efforts. Drawing on their own experience, the group quickly narrowed the list to the glow discharge, the linear pinch, the electromagnetic shock tube, and the plasma focus.

In 1984, one of us (Lee) submitted a proposal to various international agencies. The idea was for an existing group in a developing country to transfer its total research technology, in the form of a small experiment, to another group in order to initiate and strengthen research capacity in another location. The host center needed to have experience, technical infrastructure, and enthusiasm for sharing. The recipients needed to have a strong physics and technical background and the commitment to build up the project on a continuing basis after returning home.

The host center would identify an experimental system or "facility" based on its own experience and expertise, break that facility down into its basic technical subsystems, and plan a detailed program for the participants to acquire the expertise, technology, and components needed for each subsystem. The host center was to run an intensive training program, provide the needed equipment, and then follow up with helpful advice on setting up the facility in the home institute.

The proposal was accepted by the United Nations University, which agreed to fund an international training program to be conducted by the University of Malaya (UM) in Kuala Lumpur, Malaysia. (Perhaps unfamiliar to some readers, the UNU is based in Tokyo. It was established by the United Nations in 1973 as an international community of scholars working as a think tank for the UN and as an organization to build the learning and research capacities in developing nations. More information can be found at http://www.unu.edu/.) UNU's rector at the time, Koko Soedjatmoko, was enthusiastic about the idea and looked forward to developing countries acquiring practical knowledge and skills in plasma physics, including fusion.

As the program's initiator and director, in 1985 Lee conducted numerous visits to selected institutions, during which he interviewed 28 short-listed candidates—about half with PhDs—who had shown both interest and the potential to build up plasma and laser facilities. Eight candidates from six countries (Egypt, India, Indonesia, Nigeria, Pakistan, and Sierra Leone) were selected and eventually awarded UNU fellowships.

In October 1985 a six-month UNU training program in plasma and laser technology began at UM. The first three months were filled with an intensive and compre-

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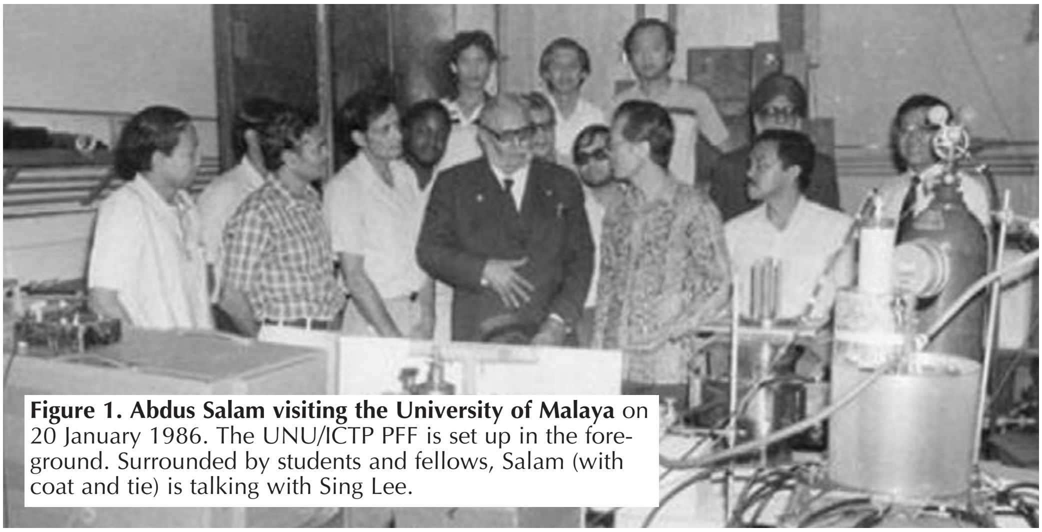


Figure 1. Abdus Salam visiting the University of Malaya on 20 January 1986. The UNU/ICTP PFF is set up in the foreground. Surrounded by students and fellows, Salam (with coat and tie) is talking with Sing Lee.

hensive program of lectures and experiments on existing facilities. Topics included pulsed electronic modules, power supplies, glow discharges, electromagnetic shock tubes, the plasma focus, computation packages, and various laser systems. Of crucial importance was the knowledge of the resources available at each home institution.

For example, the needs of a lecturer like Augustine Smith in Sierra Leone and of a PhD candidate like Muhamad Zakaullah in Pakistan were distinctly different. Hence, each fellow required individually tailored training and follow-up programs. Under the careful guidance of Lee and his team, each fellow chose an experimental facility—an electromagnetic shock tube, a glow discharge, or a plasma focus—and then carried out the system's planning, design, and construction, including the development of necessary subsystems. Most of the fellows chose the plasma focus, an excellent device for teaching plasma dynamics and thermodynamics, for studying fusion, and for materials-processing experiments (see the box on page 34).

We were excited by the prospect of studying nuclear fusion in an affordable tabletop device like the plasma focus. We modeled it and came up with a design that required us to purchase equipment no more expensive than a fast discharge capacitor and a rotary pump for the vacuum system. That economy was of paramount importance: Neither the UNU nor the home institutes would pay for follow-up equipment. All the other parts of the facility—including a high-voltage charger, a high-precision triggering system, and such diagnostic instrumentation as neutron detectors and a nanosecond laser shadowgraphic system—would be built with readily available materials and components. For example, a transformer from an ordinary television set could be used.

The 250-kg device cost about US$5000 and became portable when placed on a rack and trolley. Still, six sets of the low-cost, portable nuclear-fusion facility would cost US$30 000, not including freight and several oscilloscopes that some fellows needed. And there was no provision for follow-up equipment. We started a contingency fund for those purposes.

In the opening weeks of 1986, the first version of the UNU/ICTP PFF was developed, assembled, and tested. On 20 January 1986, Abdus Salam, the director of ICTP, visited us (figure 1). After seeing the activities, he provided on the spot the missing brick in the program's structure: an additional US$15 000 that eventually paid for much of the needed follow-up equipment.

Over the following six weeks, the UM physics workshop operated day and night, manufacturing six sets of the UNU/ICTP PFF. Each set was then assembled by its owner and tested for vacuum, voltage holding, and current conduction, then for full operation, which included obtaining focusing signatures in various gases. Finally, each UNU/ICTP PFF was run in deuterium, and fusion neutrons were detected with a paraffin-moderated silver activation counter.

We had only one suitable high-voltage fast discharge capacitor, so until one set had been fully tested, the next set could not be started. All six were thus assembled and tested, one after another (see figures 2 and 3). To complete the tests, several of the fellows practically lived in the laboratory during their allocated week. We remember a number of times wishing "Good night" to Ashok Gholap, from Nigeria, around midnight when he "still had a few things to do in the lab" and then, early the next morning, wishing him "Good morning" in the lab where he still had several more things to do!

During this period of testing, we also collected research data. We thus optimized the focus performance using different gases, optimized the neutron yield with deuterium operation, and gathered performance data for the high-current spark gaps used to discharge the capacitor. We also carried out numerical modeling of the plasma focus.

Figure 2. The first training program was held in 1985–86. **(a)** Widdi Usada from Indonesia, assembling his UNU/ICTP PFF. **(b)** A. G. Warmate (Nigeria) and Augustine Smith (Sierra Leone) with a crated set of UNU/ICTP PFF machinery, ready to be shipped.

By the end of March 1986, the fellows' work and reports were completed and we were ready to ship the equipment. From the research data, six papers were eventually published, two of them in international journals.[2,6] Walter Shearer represented the UNU in a ceremony in early April 1986, at which the equipment—in seven consignments, because Indonesia also received an electromagnetic shock tube—was handed over to the fellows and then to the company arranging the air freight. The fast discharge capacitors, at 80 kg each, were to be shipped directly from Maxwell Company of San Diego, California, to the fellows' institutions. Regional offices of UNESCO assisted with custom matters.

During the handing-over ceremony, Lee stressed that the aim of the program had not yet been achieved. Fellows had been trained. A low-cost, fully functional plasma focus facility had been developed. Research papers from experiments and modeling had been written. But success would be measured by the work achieved by the fellows back at their home institutes in the years to come.

Facilities transferred after training and attachment programs

Institution	UNU/ ICTP PFF	EMST flow simulator	Nitrogen laser system	Laser shadowgraph system	Glow discharge
Al Azhar Univ. Cairo, Egypt	Received facility; Have produced PhD/MSc theses using these facilities		Received facility	Received facility	
U. of Rajasthan Jaipur, India	Received facility		Received facility		
U. of Delhi Delhi, India	Received facility; Have produced PhD/MSc theses using these facilities		Received facility; Have produced PhD/MSc theses using these facilities	Received facility; Have produced PhD/MSc theses using these facilities	
Sri Pratap College Srinagar, India			Received facility		
LAPAN (Space research) Jakarta, Indonesia		Received facility; Have produced PhD/MSc theses using these facilities			
PPNY (Nuclear research) Yogyakarta, Indonesia	Received facility; Have produced PhD/MSc theses using these facilities		Received facility; Have produced PhD/MSc theses using these facilities	Received facility; Have produced PhD/MSc theses using these facilities	Received facility
Quaid-i-Azam Univ. Islamabad, Pakistan	Received facility; Have produced PhD/MSc theses using these facilities		Received facility; Have produced PhD/MSc theses using these facilities	Received facility; Have produced PhD/MSc theses using these facilities	
Rivers State U. of S&T Port Harcourt, Nigeria	Received facility; Have produced PhD/MSc theses using these facilities		Received facility; Have produced PhD/MSc theses using these facilities	Received facility; Have produced PhD/MSc theses using these facilities	
Njala Univ. College Freetown, Sierra Leone	Received facility; Have produced PhD/MSc theses using these facilities				
Prince of Songkla Univ. Hatya, Thailand	Received facility; Have produced PhD/MSc theses using these facilities		Received facility		
Univ. of Zimbabwe Harare, Zimbabwe	Developed the facility locally; Have produced PhD/MSc theses using these facilities				
Chulalongkorn Univ. Bangkok, Thailand	Developed the facility locally; Have produced PhD/MSc theses using these facilities				

EMST: Electromagnetic shock tube
- Received facility
- Have produced PhD/MSc theses using these facilities
- Developed the facility locally

Birth and growth of the AAAPT

Much has happened in the 20 years since that handing-over ceremony. In 1988, during the second six-month UNU/ICTP training program, a sequenced nitrogen laser[7] was invented with the idea of taking shadowgraphic "movie frames." The start of that program coincided with the Third Tropical College on Applied Physics, at which the AAAPT was formally inaugurated. The AAAPT council was elected with Lee as the founding president. The original council, shown in figure 4, remained almost unchanged through three elections until 2004. Our third ICTP-UM training program was held from December 1989 to June 1990, with an associated nitrogen laser training program in October and November 1990. By then, 24 fellows had been trained using funds from UNU, ICTP, the Third World Academy of Sciences, UNESCO, AAAPT, and UM.

In the meantime, regional centers were set up under the auspices of the AAAPT in New Delhi, India, and in Islamabad, Pakistan. Those centers, run by former UNU fellows, assisted in the propagation of the UNU/ICTP PFF technology beyond the original recipient institutes. Among other things, the centers facilitated joint work through "attachments"—short-term exchange visits of staff or students between member institutions of AAAPT.

By 1992, additional centers had arisen in Cairo, Egypt, and in Beijing, China. All of those centers, and the one at UM in Kuala Lumpur, have now run various programs and attachments, which have resulted in the training of another 20 scientists in UNU/ICTP PFF technology and in collaborations with other scientists already active in dense-plasma research. A UNU/ICTP PFF was placed at the ICTP with the help of Gallieno Denardo, the head of ICTP's office of external activities. In 1991 and 1993, training experiments were conducted there. Those ICTP sessions were attended by some 35 scientists.

More recently, intensive research attachments evolved at Kuala Lumpur and Singapore with new groups from Syria, Indonesia, Korea, India, Pakistan, Zimbabwe, and Thailand. The result has been new or strengthened research laboratories around the world. Altogether, the AAAPT has conducted and sponsored more than 30 intensive training and attachment programs and

Figure 3. The newest AAAPT Research and Training Center, at Chulalongkorn University in Bangkok, Thailand. Rattachat Mongkolnavin (right) and his colleague Kiranant Ratanathammapan (left), flank visitors Ye Mao Fu (second from left) and Li Yin-an from the AAAPT Research and Training Center in Beijing.

Anatomy of the Dense Plasma Focus

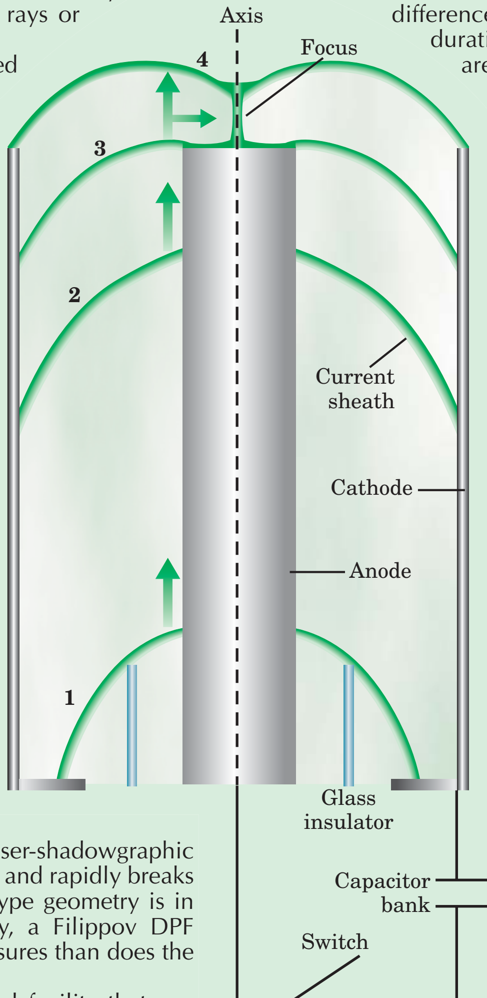
The dense plasma focus (DPF) is a machine that produces short-lived plasma so hot and dense that it becomes an intense multi-radiation source of high-energy photons, electrons, and ions; when it is operated in deuterium, nuclear fusion can occur. The DPF was developed by Joseph Mather and independently by Nikolai V. Filippov in the early 1960s. Today, the DPF is being refined for several potential applications including next-generation microelectronics lithography (using soft x rays or extreme UV radiation), micromachining, materials modification, and medical and security inspection applications using pulses of x rays or neutrons.

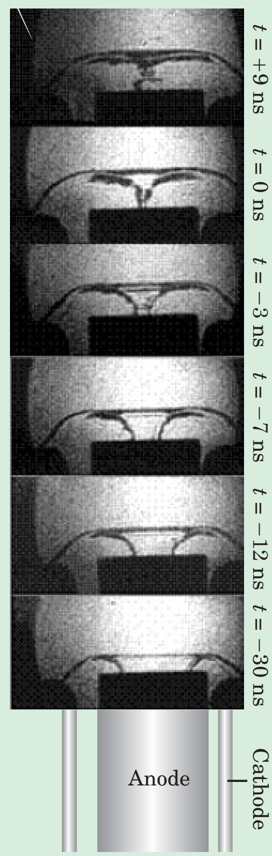
In the Mather-type DPF, like the one used for the projects described in this article, a current "sheath" is generated in a plasma, accelerated electromagnetically, and then focused tightly. It works as follows (see the schematic):

First, a charged capacitor bank is switched onto the anode in the vacuum chamber. The low-pressure gas (green) in the chamber then breaks down and a rapidly increasing electric current flows across the back-wall insulator (as depicted by the path labeled 1) in the form of a thin axisymmetric sheath. The current sheath then lifts off the insulator due to the **J** × **B** force and is accelerated axially along the length of the device to position 2, and then to position 3, ending the axial phase of the device. At that point, as the supersonic current sheath continues to move axially, the portion in contact with the anode slides across the face of the anode and converges on itself axisymmetrically (position 4). When the imploding shock front reflects from the axis, it travels outward until it meets the driving current sheath, forming the boundary of the "pinched" or focused hot plasma column. This phase is accompanied by a current dip and a voltage spike. The plasma column (labeled "Focus" in the schematic and shown in laser-shadowgraphic images on the right) undergoes instabilities and rapidly breaks up. The only difference for the Filippov-type geometry is in the insulator configuration. Operationally, a Filippov DPF works within a narrower range of gas pressures than does the Mather type.

The DPF is a multifaceted experimental facility that can operate with different gases. The axial phase provides a means to study plasma dynamics and energetics. The radial-pinch phase is a rich source of radiation, particles, and plasma phenomena. For example, with a deuterium gas, deuterons of hundreds of keV are typically beamed out along the axis, while relativistic electrons are beamed down into the anode where they can be sent into a mounted target or extracted through an axial hole. When optimized for fusion, the DPF becomes a reliable pulsed neutron source. Used with gases of high atomic number, the DPF is a source of abundant x rays.

Remarkably, with properly tuned parameters—including capacitance, gas pressure, and electrode dimensions—*all* DPFs produce the same plasma densities and temperatures in the focus region, the only substantive differences being in that region's volume and duration. Thus, the identical phenomena are available in our small DPFs (3 kJ, 100 kA, tens of ns) as in much larger ones (MJ, several MA, μs).





SEQUENCE OF COMPRESSION IN UNU/ICTP PFF (4.0 mbar deuterium)

workshops, and several conferences.

Consider the case of Chulalongkorn University (CU) in Bangkok, Thailand. There was a pre-existing collaboration on pulsed-power technology between its plasma group and ours at the University of Malaya. (For more on our other plasma work at UM, see http://fizik.um.edu.my/plasma/.) The CU group, led by Rattachat Mongkolnavin, was encouraged by one of us (Wong) to join the AAAPT plasma focus family. To help them jump-start their plasma research, the AAAPT agreed to transfer a UNU/ICTP PFF that was originally sent to Thailand's Prince of Songkla University in the town of Hatya.

Unfortunately, the capacitor was damaged during the transfer. Fortunately, a replacement capacitor that belonged to AAAPT was available at UM. However, the Malaysian–Thai border has a reputation for being a rough place. So Mongkolnavin led a team of two researchers, one student, and two security guards that drove all the way from Bangkok to Kuala Lumpur in a van and returned with the replacement capacitor.

That was in 1999. Today, CU operates two sets of the UNU/ICTP PFF. In 2002 the AAAPT transferred to CU a major research facility—a 40-kJ theta pinch spectroscopic source—from the AAAPT Research and Training Center at the Institute of Physics, Chinese Academy of Science, in Beijing. CU now hosts the most recently set up AAAPT Re-

Figure 4. AAAPT council meeting in Beijing, November 1989. From left, seated: Sing Lee (president, Malaysia); Tomader El-Khalafawy (vice president, Egypt); and Mahesh Prasad Srivastava (VP, India). Standing: Chaivitya Silawatshananai (coordinator, Thailand); Shih Tung Tsai (VP, China); Ah Chuan Chew (honorary treasurer, Malaysia); Siew Pheng Moo (VP, Malaysia); Ghulam Murtaza (VP, Pakistan); Yin-an Li (coordinator, China); Chiow San Wong (honorary secretary, Malaysia).

search and Training Center, shown in figure 3, and begins its own research attachment activities this year.

The table on page 33 shows a representative selection of recipient institutes and the facilities transferred to them after training and attachment programs.

The program's legacy

Most of the home institutions have made good progress.[3] Seven countries now have fully operational UNU/ICTP PFFs and strong postgraduate programs: Quaid-I-Azam University, Pakistan; University of Delhi, India; Al Azhar University, Egypt; University of Zimbabwe; Chulalongkorn University, Thailand; and several universities in Malaysia and Singapore.

UNU fellow Zakaullah, who took part in the original 1985–86 training program, tells an outstanding success story. He set up the UNU/ICTP PFF at Quaid-i-Azam University and used it to earn his PhD in 1988. He then built up a strong experimental group and has now supervised five PhD and 38 master's theses, mainly on the plasma focus, and produced more than 90 research papers in the process. He also took charge of the regional UNU/ICTP PFF training programs run by his university for AAAPT. Today, Zakaullah is an associate editor of the *Journal of Nuclear Fusion* and continues to lead a very active experimental plasma group at Quaid-i-Azam University.

Also in that first program was Gholap, to whom we wished good night and good morning. At the time, he was a lecturer at Rivers State University of Science and Technology in Port Harcourt, Nigeria. Now at the National University of Science and Technology in Bulawayo, Zimbabwe, he writes: "UNU fellowship program has benefited Nigeria and Zimbabwe to continue research . . . to establish links with other universities and to develop postgraduate programs at Masters and PhD levels, . . . publish research papers, [and] grow their educational facilities in the field of Experimental Physics in general and Plasma Physics in particular."

A second group of institutions includes Njala University College, Sierra Leone; University of Rajasthan, India; National Institute of Aeronautics and Space (LAPAN) in Jakarta, Indonesia; Yogyakarta Nuclear Research Center, Indonesia; Prince of Songkla University, Thailand; Rivers State University of Science and Technology in Port Harcourt, Nigeria; the Atomic Energy Agency, Syria; and a training facility at the ICTP, Trieste, Italy.

Most of the plasma laboratories in the second group have produced some research theses and papers. However, not all the facilities are still actively used. For example, Smith did set up his UNU/ICTP PFF in Sierra Leone and produced some results. But within a few years, some copper and brass current distributors and electrodes were stolen, presumably for scrap. Soon after, he left for Germany on a Humboldt fellowship and is no longer in Sierra Leone.

Of course, there are also happier, even unexpected stories. Mario Favre Dominguez of the Pontificia Universida Catolica De Chile insists that the plasma focus activities at his university (and perhaps in all of Chile) owe their beginnings to his participation in one of the training and collaborative programs in Kuala Lumpur.

Several groups have gone on to develop applications such as materials modification and deposition using both pulsed and continuous plasma devices. Following the 1988 training in Kuala Lumpur, ICTP fellow Rajdeep Singh Rawat returned to the University of Delhi to complete his PhD. He used the UNU/ICTP PFF for plasma processing[8] of thin-film materials including superconducting and fullerene films on silicon. More recently, he has worked with diamond-like carbon. He writes, "More than five PhD

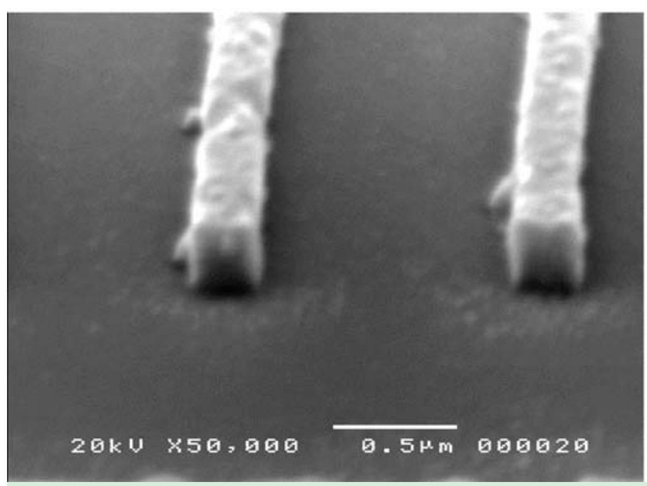


Figure 5. Scanning electron micrograph of a test lithography result by a plasma focus x-ray source in Singapore. (From ref. 14.)

Figure 6. The steering committee of the International Center for Dense Magnetized Plasmas (Poland) posing with the UNU/ICTP PFF at the University of Malaya's plasma research laboratory in 1994.

degrees have been awarded by Delhi University on plasma focus studies. . . . Twenty people were trained through AAAPT attachment programs at Delhi. One major success was to help Prof. A. Mishra establish a Plasma Focus at [the] Center for Plasma Physics, Guwahati, which is now one of the most active plasma focus groups in India." Rawat is now an associate professor at the Nanyang Technological University (NTU) in Singapore.

Developing tomorrow's science and industry

Today, the computational models[9] developed for the UNU/ICTP PFF are also used to model other plasma focus machines, including large ones. In fact, it is the only model being used to simulate both the Mather-type and the Filippov-type plasma focus[4,10] (see the box on page 34).

Using the model, we identified a drive parameter that was found experimentally to have a constant value for all Mather-type machines ranging from 3 kJ to 200 kJ.[11] The parameter is related to the constancy of the current drive speed over the whole range of optimized plasma focus machines and shows that they all operate, in deuterium at least, at the same magnetic pressure and thus at the same energy density or temperature. The modeling further suggests the possibility of speed enhancement of neutron yield,[12] from the observed $Y \sim I^4$ to $Y \sim I^8$, where Y is yield and I is current. That kind of enhanced yield could lead to greater potential for production of nuclear fusion energy.

Including radiative terms in the model for the radial-pinch phase[13] enables experimenters to optimize the soft x-ray yield—for example, when using neon. Thus, researchers in Singapore were able to develop a repetitive plasma-focus point source for producing features smaller than 0.2 μm for microelectronics lithography and micromachining (figure 5).[14]

Pulsed neutron activation[15] was used to determine the half-lives of indium-116, rhodium-104, and metastable sodium-24 and to study radiation safety. Today, the UNU/ICTP PFF is being used in deuterium–argon studies[16] to generate neutron-pulse profiles suitable for detecting explosives, illicit drugs, and other materials.

The UNU/ICTP PFF has also been used in PhD studies related not only to radiation—neutrons, ion beams, relativistic electron beams, soft and hard x rays—but also to plasma space propulsion, astrophysical situations, and even a problem in nonlinear deterministic mechanics.[3]

In summary, the UNU/ICTP PFF is the core program responsible for the success of the AAAPT. Over the years, the training, equipment transfer, and follow-up activities cost an estimated US$500 000, with most of the money coming from the recipient institutions and additional contributions from international agencies and the training institutions. The program contributed significantly to establishing seven active experimental research groups, and was an inspiration in the formation of the International Center for Dense Magnetized Plasmas in Poland (figure 6). The network of UNU/ICTP PFFs, coordinated by the AAAPT, has a rich legacy and continues to have a significant impact on the knowledge and practical use of pulsed dense plasmas. It is an example of what can be achieved by highly motivated scientists with the support of international agencies like the UNU and the ICTP.

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