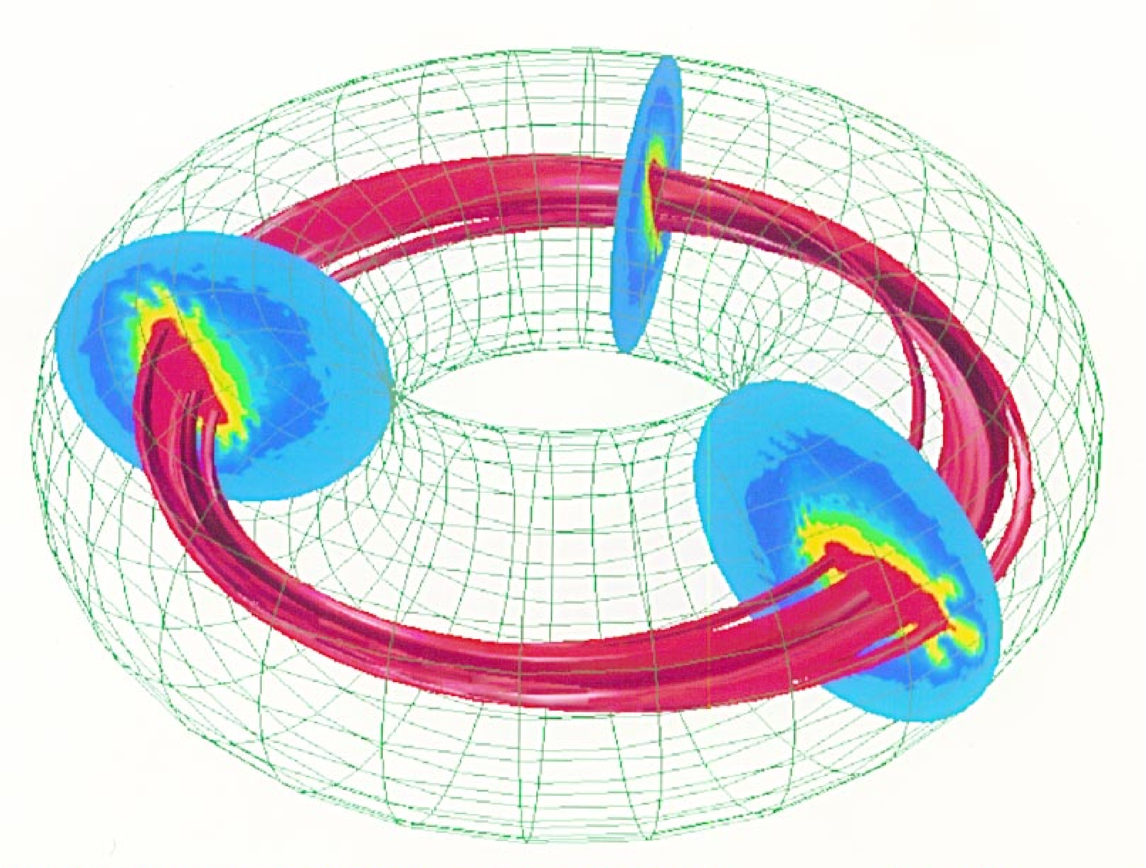
PPPL

HIGHLIGHTS



PRINCETON PLASMA PHYSICS LABORATORY

About PPPL

Established in 1951, the Princeton Plasma Physics Laboratory (PPPL) is dedicated to developing the scientific and technological knowledge base for magnetic fusion energy as a safe, economical, and environmentally attractive energy source for the world's long-term energy requirements. It is the site of the Tokamak Fusion Test Reactor, the most powerful magnetic fusion device in the world.

PPPL is managed by Princeton University under contract with the U.S. Department of Energy. The fiscal year 1996 budget was almost $66 million. The average number of full-time employees for the fiscal year was about 520 with about an additional 60 subcontractors, graduate students, and visiting research staff. The Laboratory is sited on 72 acres of Princeton University's James Forrestal Campus, about four miles from the main campus.

Through its efforts to build and operate magnetic fusion devices, PPPL has gained extensive capabilities in a host of disciplines including vacuum technology, mechanics and materials science, electronics, computer technology, and high-voltage power systems. In addition, PPPL scientists and engineers are applying knowledge gained in fusion research to other theoretical and experimental areas including beam-surface interactions and the plasma processing of materials. The Laboratory's Office of Technology Transfer assists industry, other universities, and state and local government in transferring these technologies to the commercial sector.

The Laboratory's graduate education and science education programs provide educational opportunities for students and teachers from elementary school through postgraduate studies.

On the Cover

Numerical simulation of a tokamak discharge illustrating the disruption phenomena which can limit the performance of tokamaks. The three vertical slices and the red iso-pressure surface show the three-dimensional structure of this instability. Recent advances in our ability to predict this phenomena allow experimental operation closer to the disruptive limits. For additional information on this topic see the Fusion Theory and Modeling section of this report. Graphic by W. Park.

This publication highlights activities at the Princeton Plasma Physics Laboratory for fiscal year 1996 — 1 October 1995 through 30 September 1996. For a more detailed account of the work described here, a comprehensive list of research references, and additional information on administrative support, see the PPPL fiscal year 1996 Annual Report.

Mission Statement

The primary mission of the Princeton Plasma Physics Laboratory is to play a leadership role in the national and worldwide development of the scientific foundations for fusion as a safe, economical, sustainable, and environmentally attractive energy source.

Supporting objectives include conducting frontier research on plasma science in areas as diverse as materials processing and space physics, and providing the highest quality of education in plasma physics.

Vision Statement

The Princeton Plasma Physics Laboratory will be the leading collaborative national center for innovation in plasma confinement and for research and education in plasma science.

Advantages of Fusion Energy

- Worldwide availability of inexhaustible low-cost fuel.
- No chemical combustion products and therefore no contribution to acid rain or global warming.
- No runaway reaction possible.
- Materials and by-products unsuitable for weapons production.
- Radiological hazards thousands of times less than from fission.

Contents

From the Director …

John A. Schmidt

Our vision for the Princeton Plasma Physics Laboratory (PPPL) is to be the leading collaborative national center for innovation in plasma confinement and for research and education in plasma science. Founded in 1951, the Laboratory has played a critical role in developing the experimental, theoretical, and technological underpinnings of magnetically confined plasmas under conditions suitable for — and recently demonstrating — fusion energy production. As we look to the future, there will continue to be major opportunities to optimize the performance and attractiveness of fusion systems as energy sources. In addition, plasma physics will remain a vibrant field of research, and non-fusion applications of plasma science and technology will have grown substantially in industrial importance.

Operated by Princeton University, the Princeton Plasma Physics Laboratory is the only single-program laboratory funded by the U.S. Department of Energy for the development of magnetic confinement fusion as a safe, economical, sustainable, and environmentally attractive energy source and for research and development in the underlying discipline of plasma science. The Laboratory has a highly skilled workforce and extensive capabilities for the experimental and theoretical study of fusion plasmas and for the integrated design, fabrication, and operation of experimental plasma facilities, including magnets, power supplies, and plasma heating and diagnostics systems. PPPL is the site of the largest magnetic confinement fusion device in the U.S., the Tokamak Fusion Test Reactor (TFTR), the site of the National Spherical Torus Experiment (NSTX), and other small-scale research devices. Management by Princeton University provides an outstanding institutional framework for a broad Laboratory-based program of education in plasma physics and related science and technology.

The purpose of this Highlights Report is to present a brief overview of the Laboratory's significant research accomplishments during fiscal year 1996. The activities covered include advances on the large projects, such as deepening of our understanding of alpha-particle physics on TFTR, progress on design of the NSTX, and engineering contributions to the International Thermonuclear Experimental Reactor (ITER) project, as well as the significant progress made in plasma theory, small-scale experiments, technology transfer, graduate education, and the Laboratory's program in science education.

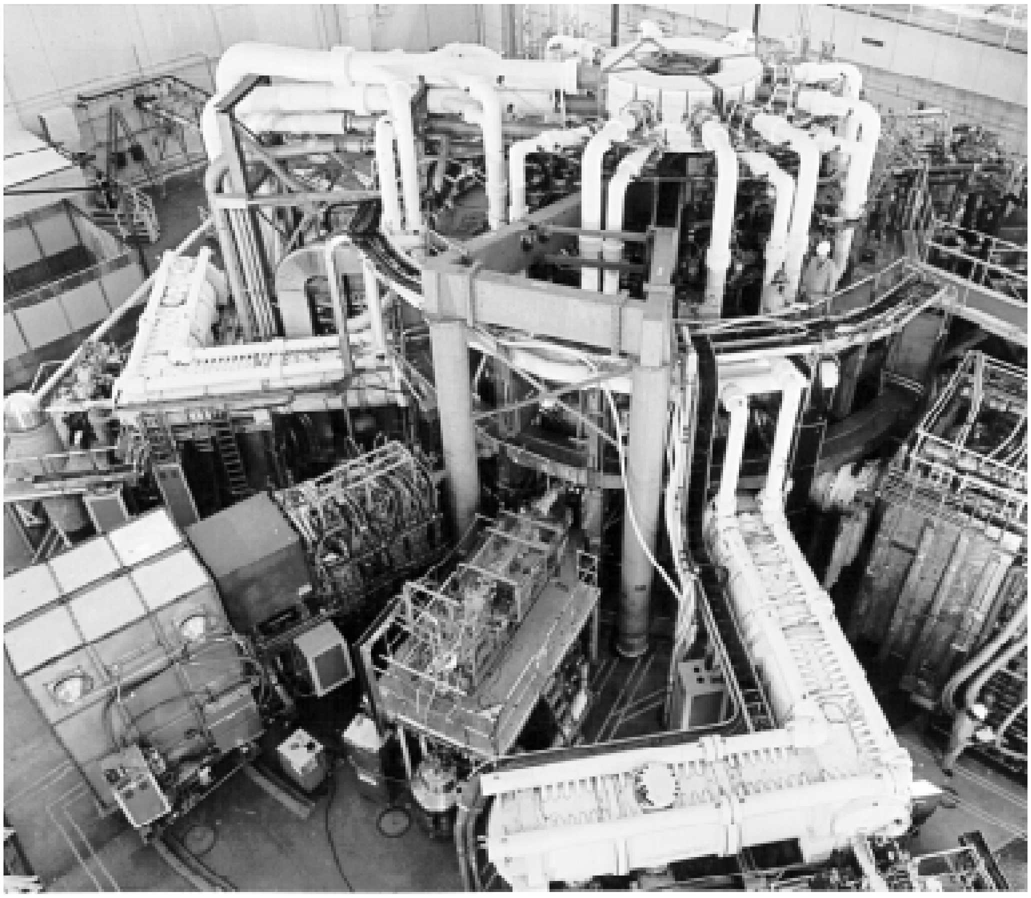
As fiscal year 1996 marks the last full year of operation of the TFTR, it is appropriate to acknowledge the historic progress in scientific understanding that has been accomplished with this device. The "supershot" regime of plasma confinement has convincingly revealed the connection of edge plasma conditions with core confinement. The discovery of the self-sustaining "bootstrap current" has made possible the steady-state advanced tokamak concept. The discovery of the enhanced reversed shear mode has both deepened our understanding of toroidal confinement and opened up new opportunities for improved performance. Finally, the extensive and thorough measurements of alpha-particle physics in deuterium-tritium plasmas on TFTR has prepared the world for the step forward to burning plasma physics. While the completion of experiments on TFTR next fiscal year will herald the end of a very productive era for the Princeton Plasma Physics Laboratory, we look forward to a strong, innovative program in plasma confinement, starting with the intermediate-scale NSTX device and expanding with another device at a similar scale. We also look forward to an invigorating program of national and international collaboration on tokamak and alternate concept experiments.

While the main emphasis in the report is on recent advances in fusion science and technology, it is important to recognize that fusion research is the principal engine that propels the development of plasma physics as a scientific discipline with a very broad range of applications. The Laboratory's outstanding capabilities in theoretical and experimental plasma science, and its strong engineering infrastructure, position it to make world-class contributions in a wide variety of scientific areas beyond specifically fusion science and engineering — ranging from technologically advanced methods of materials processing to space physics. At the same time our involvement in these areas of science helps to provide the intellectual vitality for innovations in fusion science. As is fitting for such a center of intellectual creativity, the Laboratory has an important educational role as well. Our educational mission is reflected in our outstanding graduate program, our programs for undergraduate students, and our large contributions to the improvement of science education for students at all levels.

John A. Schmidt
Interim Director

TFTR

Tokamak Fusion Test Reactor



Tokamak Fusion Test Reactor

The Tokamak Fusion Test Reactor (TFTR) carried out its third year of pioneering experiments using the deuterium-tritium fuel that will one day fire commercial fusion power plants. A total of 841 high-power deuterium-tritium plasma discharges have been studied since tritium operations began in late 1993. The deuterium-tritium discharges were interspersed with more than 19,000 deuterium-only plasmas. The safe operation of TFTR and its auxiliary systems while processing a cumulative total of nearly 90 grams of tritium has allowed physics studies to continue and has demonstrated the safe operation of a tritium fusion facility. A major project milestone to produce more than ten million watts of fusion power was achieved in November, 1994.

The diagnostic, tokamak, and neutral-beam capabilities have been maintained, and even enhanced, during the tritium phase, despite the higher radiation operating environment. This has facilitated the uninterrupted flow of new understanding about the characteristics of enhanced-energy-confinement regimes and the effects of tritium and energetic fusion-produced alpha particles upon the plasma. During 1996 much of the experimental effort on TFTR was devoted to two improved performance plasma regimes, the reversed magnetic shear and the high internal inductance modes, and to studies of effects specific to deuterium-tritium plasmas such as alpha-particle interactions and isotope influences upon confinement.

Reversed Magnetic Shear Plasmas

In work that evolved rapidly in 1995, TFTR researchers produced a magnetic configuration in which the change in pitch as a function of minor radius of the spiraling magnetic-field lines that hold the plasma was reversed in the interior of the plasma discharge. This was achieved by using time-dependent changes of the plasma current and the neutral-beam heating power to create hollow current profiles. TFTR researchers found that under certain conditions at heating beam powers above 16-20 megawatts (MW) plasmas with central reversed magnetic shear undergo a transition to a regime of extremely high confinement, with ion-thermal conductivities close to or below the neoclassical minimum calculated with previously existing theory, and greatly reduced particle diffusivities. This regime, which came to be called the enhanced reversed shear mode (ERS), might permit fusion power plants to be smaller and less expensive, thus augmenting their commercial attractiveness, if it can be maintained in power-plant-grade plasmas without engendering other problems, such as helium ash accumulation.

In 1996, experiments continued to develop understanding of the physical processes giving rise to the internal transport barrier which forms at or near the shear-reversal radius in these plasmas and to find paths leading to a steady-state control over the barrier. The maximum plasma current at which the transition to the ERS mode can be triggered was increased from 1.6 million amps to 2.2 million amps by injection of a lithium pellet to alter plasma conditions. In addition, the fraction of the plasma volume within the reversed shear region was increased, exposing more of the plasma to the benefits of high confinement. TFTR researchers produced the first deuterium-tritium ERS plasmas this past year. In a discovery which may have important implications for the eventual utilization of this mode in fusion power plants, TFTR researchers found that the neutral-beam-heating power required to induce the ERS transition was considerably greater (27 MW versus 21 MW) in deuterium-tritium plasmas compared to similar deuterium-only discharges.

The beneficial suppression of energy leakage which occurs in ERS discharges is correlated with a reduction inside the transport barrier in the magnitude of turbulent density fluctuations. These fluctuations are suppressed at the onset of the ERS transition and reappear when the plasma reverts to a more leaky confinement mode near the end of the neutral-beam-heating pulse.

High Internal Inductance Mode

Experiments continued with another enhanced-confinement regime, the high internal-inductance mode. Plasma discharges of this sort are produced in TFTR by decreasing the plasma current to produce a current profile which is more centrally peaked than would normally occur. This has been found to increase the magnitude of plasma pressure which a given magnetic-field strength can hold while maintaining stability. On TFTR, this regime has resulted in a deuterium-tritium fusion power of 8.7 million watts, while requiring less plasma current and toroidal magnetic field than discharges of comparable fusion power produced in the "supershot" regime of less peaked current profiles. Supershot is the name given to a plasma discharge that is steeply denser at its center than at its edge and is characterized by very high central temperature and an enhancement in core confinement time.

Energy Confinement Scaling of Deuterium-Tritium Plasmas

One of the first results of the deuterium-tritium campaign on TFTR was the discovery that for supershots the energy confinement was sharply improved relative to deuterium-only plasmas. The energy confinement time, τ_E, is proportional to $<A>^{0.85}$ in supershots, where <A> is the average isotopic mass of the plasma. More recently, TFTR experiments have studied the effect of the isotopic composition in other plasma regimes. In high internal-inductance mode plasmas, the scaling with mass is similar to the strongly favorable one found for supershots. Plasmas with the more ordinary type of confinement, dubbed "low-mode," exhibit a weaker improvement with isotopic mass. In these low-mode plasmas, τ_E is proportional to $<A>^{0.3\text{-}0.5}$ during heating by neutral-beam injection or with radio-frequency waves in the ion cyclotron range of frequencies. The scaling is weaker still in ohmically heated plasmas, where τ_E is proportional to $<A>^{0.0\text{-}0.3}$, and the scaling with isotopic mass appears to be essentially absent in ERS plasmas.

Alpha-Particle Physics

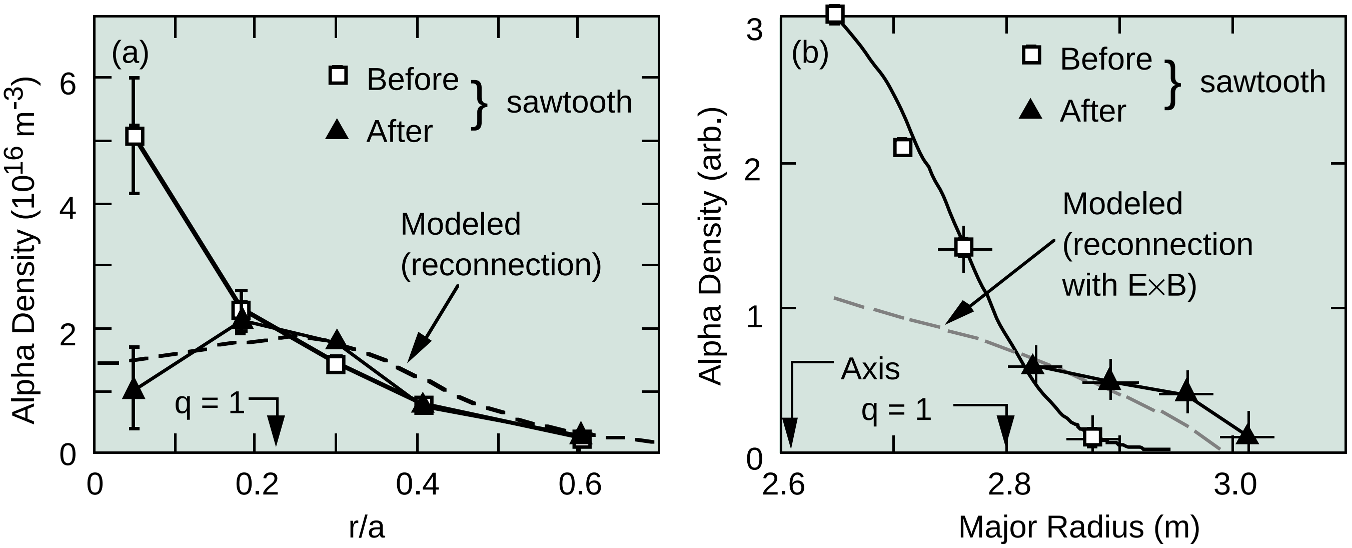
In order for fusion devices of the future to successfully ignite and sustain a thermonuclear burn, it will be necessary that the high-energy alpha particles produced with an initial energy of 14.1 million electron volts (MeV) by deuterium-tritium fusion reactions transfer their energy to the thermal plasma before they escape. Confinement and loss of alpha particles in fusion plasmas have been measured in TFTR experiments with several novel diagnostic techniques developed here at the Laboratory.

The energy distribution of the confined alpha particles slowing down in the TFTR plasma has been studied through two techniques. Alpha particles with energies in the range 0.5-3.5 MeV have been detected through conversion to neutral helium in the dense neutral cloud surrounding an ablating lithium pellet injected into the plasma at high velocity. The energy spectrum thus obtained is found to be in good agreement with the shape calculated, assuming that there are no unexpected loss processes at work. In the low-energy range of 0.1-0.6 MeV, the alpha-particle-energy distribution has been detected by absolutely calibrated spectrometry of light emitted by alphas recombining with electrons. The intensities of the detected signals are within a factor of two of the values calculated with a computer model based solely upon expected physical processes.

An important question for future fusion devices is whether large internal oscillations of the plasma cause the loss of a major fraction of high-energy-alpha particles before they can give up their energy to sustain the plasma burn. Measurements on TFTR show that, while fluctuations of this sort redistribute fusion alpha particles from the center of the plasma to regions somewhat farther out, the outright loss they engender is very small because it lasts for only a brief period. These observations, coupled with the measurements showing that the slowing-down distribution of the fusion-produced alpha particles appears to be in rough agreement with expectations, are reassuring for the future use of fusion as an energy source.

Theoreticians have suggested for years that the presence of high-velocity fusion alpha particles might drive plasma instabilities, which might require some accommodation in fusion power plant designs. This was not observed to occur in even the highest fusion power density discharges of the first years of the TFTR deuterium-tritium experiments. The lack of these instabilities prompted further refinements to the theory, leading to the realization that the threshold for exciting these instabilities should be sensitive to the plasma current profile and the ratio of the plasma pressure relative to the confining magnetic field.

Experiments this year on TFTR were carefully tailored to create the conditions under which the more refined calculations predicted the instability should be most likely to occur. Internal oscillations indeed did arise under the appropriate conditions. Moreover, the frequencies and location of these oscillations bore the signature expected for the instability. The theory predicted that the fast ions in the plasma resulting from the heating neutral-beam injectors would damp this alpha-driven instability. This prediction was also verified, since the instability arose only during the period after the beam injectors were turned off and their fast ions had slowed down. Thus, experiments on TFTR both demonstrated the possible significance of alpha-driven instabilities under conditions that might be



Radial profiles of confined fusion alpha particles near the center of a TFTR plasma before and after a sawtooth event — a common type of large-scale fluctuation of the plasma interior. Figure (a) shows the alphas with energy in the range 0.15-0.6 MeV, while (b) shows alphas at 1.2 MeV. The initial peaked profile is redistributed outwards by the sawtooth event.

used in some advanced reactor designs and showed that they might be controlled with beam-injected or perhaps wave-accelerated ions of appropriate velocities.

Wave-Interaction Experiments

In addition to high-energy neutral atom beams, radio-frequency waves are to be used to heat and drive part of the plasma current in future fusion devices. Radio waves at frequencies which resonate with the rate at which ions rotate around the confining magnetic fields within the plasma have been used in TFTR to successfully heat deuterium-tritium plasmas over a range of operating regimes, including high-performance supershots, low-mode plasmas, and cooler plasmas produced with the ohmic heating arising from the plasma current. The heating efficiency appears to be comparable to that obtained with neutral-beam injection, the principal heating technique used on TFTR.

Radio-frequency waves have also been used to heat the high-confinement ERS plasmas of TFTR, increasing the time under which this condition can be maintained. Other promising applications of radio-frequency waves demonstrated on TFTR include driving part of the plasma current either on or off the plasma axis as desired in deuterium-helium plasmas and observing conversion by a deuterium-tritium plasma of one sort of injected wave into another more useful type of wave. Experiments on TFTR with radio-frequency waves have validated parts of the physical basis for alpha channeling, a mechanism proposed by PPPL scientists for coupling part of the energy of fusion alpha particles directly into applications such as plasma current drive. Such innovative techniques afford the possibility of reducing the complexity of fusion power plants by enabling internal processes of the plasma to help maintain the conditions for confinement, with correspondingly reduced requirements for external inputs such as radio-frequency waves or neutral beams.

Collaborations

The TFTR experimental program has benefited from strong collaborations with researchers from more than thirty universities, fusion laboratories, and companies. Major collaborating universities include Columbia University, the Massachusetts Institute of Technology, the University of California at Irvine, and the University of Wisconsin. Collaborating fusion labs include the Oak Ridge National Laboratory, the Los Alamos National Laboratory, General Atomics, and the Ioffe Physical Technical Institute of St. Petersburg in the Russian Federation.

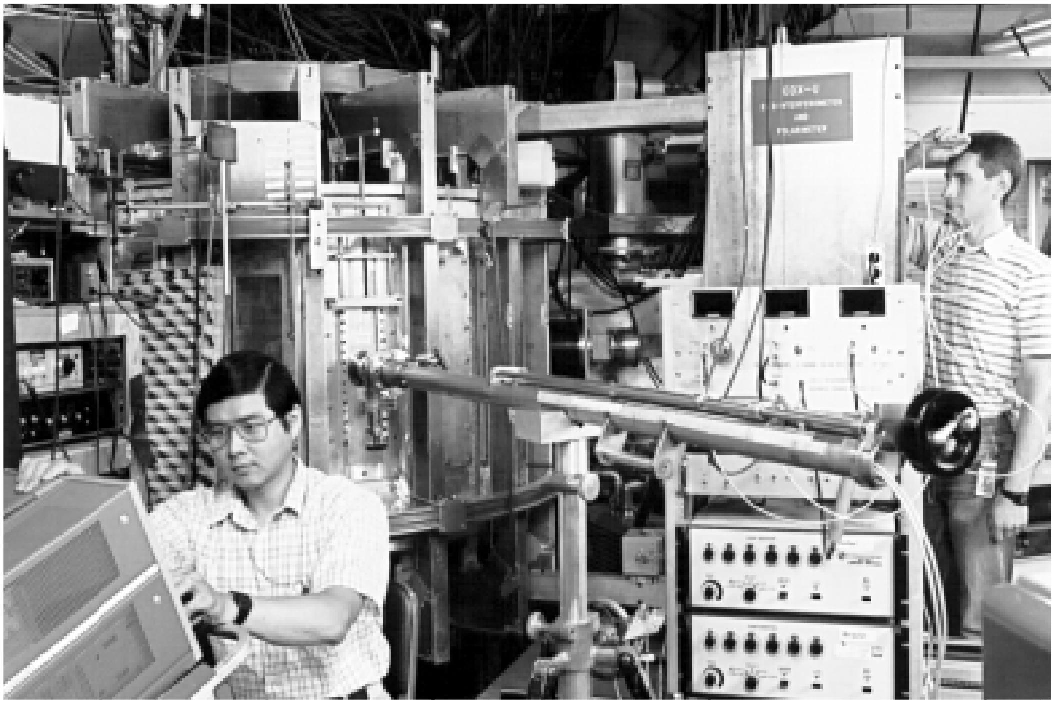
Improvements

The enhanced reverse shear plasmas which appear to hold promise as a route to smaller, less expensive fusion power plants are characterized by an internal transport barrier that greatly reduces leakage of energy and particles from the plasma core. This barrier is a region where the rotation velocity and the radial electric field change extremely rapidly over a short distance of a few centimeters or less. At the moment, these barriers are transient phenomena produced by increasing the total plasma current driven by an external solenoid over a period of time. At the end of operations this year, a new antenna was installed that will allow a special type of wave to be produced in the plasma which may allow steady-state control of the transport barrier. Control of the barrier might allow it to be continuously maintained in a power plant plasma, with periodic reductions in its strength to allow helium ash to leave and fresh fuel to enter. Further, a new diagnostic was added to observe the rotation of the transport barrier plasma in the direction around the plasma axis. This, coupled with the previously existing diagnostic to measure rotation in the direction parallel to the plasma axis, should facilitate a better understanding of the physical mechanisms at work in the transport barrier.

Studies capitalizing on these improvements are expected to form the heart of the final experiments of TFTR in 1997. When TFTR, the flagship of the modern era of great tokamaks, comes into harbor, it will leave in its wake a rich legacy of accomplishments. Before its high-power deuterium-tritium studies producing more than ten million watts of fusion power, before its discovery of the isotope enhancement of confinement, before it found a host of physics results from fusioning plasmas, it had already parted new waters. TFTR discovered the enhanced confinement modes that came to be called supershots, high internal-inductance plasmas, and the enhanced reversed shear plasmas with intense beam heating. In supershots, it found the first evidence of a self-driven current called the “bootstrap current” which is now expected to provide much of the current for a fusion power plant. Over the years, TFTR conducted a wide range of experiments that deepened our understanding of the plasma parameters and physical processes which govern the flow of energy and particles in a plasma. These results, insights, and innovations have increased the chances that fusion power plants will one day light the world.

CDX-U

Current Drive Experiment-Upgrade



Current Drive Experiment-Upgrade

The Current Drive Experiment-Upgrade (CDX-U) is the first U.S. fusion facility to conduct experiments on the spherical torus concept — an alternative approach to the conventional tokamak for achieving fusion energy. The spherical torus mode of operation is achieved when the plasma's aspect ratio (the ratio of the plasma's major radius to its minor radius) is reduced to well below 2 — as compared to a conventional tokamak plasma with an aspect ratio of about 3. The name "spherical torus" comes from the shape of the plasma. As the plasma's aspect ratio becomes smaller, the plasma elongates naturally and takes on a spherical shape instead of the donut-shape of standard tokamak plasmas.

An important characteristic of the spherical torus (ST) plasma is that it is predicted to sustain a higher pressure for a given magnetic field. Since a large part of the cost and size of a tokamak is determined by the toroidal magnetic-field strength and the coils to provide it, if the ST works as predicted, it could lead to a smaller, more economical fusion power system.

As a prototype for future ST devices, such as the proposed National Spherical Torus Experiment, the CDX-U serves as an ST test bed, providing information necessary for the design and future operation of these devices. The CDX-U group undertook three important ST-related research activities in fiscal year 1996: (1) Investigation of resistive-magnetohydrodynamic (MHD) mode characteristics using a soft X-ray array system and other diagnostics. These studies have provided a better understanding of the Internal Reconnection Event (IRE). (2) Investigation of halo-induced currents which occur during the IRE and a forced plasma disruption. (3) Implementation of a high-harmonic fast-wave heating system for heating and current drive of high-beta ST plasmas.

CDX-U Facility and Experimental Set-up

The CDX-U is a spherical torus facility with major radius R ≈ 32 cm, aspect ratio A = R/a ≥ 1.4, and toroidal magnetic field $B_{TF} \approx 1$ kG. Presently, an ohmic-heating (OH) power supply with 60 m V-Sec capability is operational. The facility has the capability to conduct experiments with plasma currents up to $I_p \approx 100$ kA and with a plasma edge safety factor q(a) ≥ 3.5.

New additions to the CDX-U diagnostics are the 36-channel soft X-ray array to study resistive-MHD instabilities and a pair of segmented Rogowski coils around the center stack to measure the halo-induced currents flowing in the center stack. Another significant addition to the CDX-U facility is the rotatable high-harmonic fast-wave heating system. A cross-sectional view of CDX-U with the fast-wave antenna is shown in Fig. 1(a). In Fig. 1(b) the 16-channel vertical soft X-ray array which detects the soft X-ray signal for various chordal vertical positions is shown. The plasma is sampled on a regularly spaced grid — a major simplification in data interpretation, especially when dealing with a highly shaped plasma as in CDX-U. Also, the detector system has 10 μsec fast-time resolution and, therefore, it is a very effective tool for observing MHD activity.

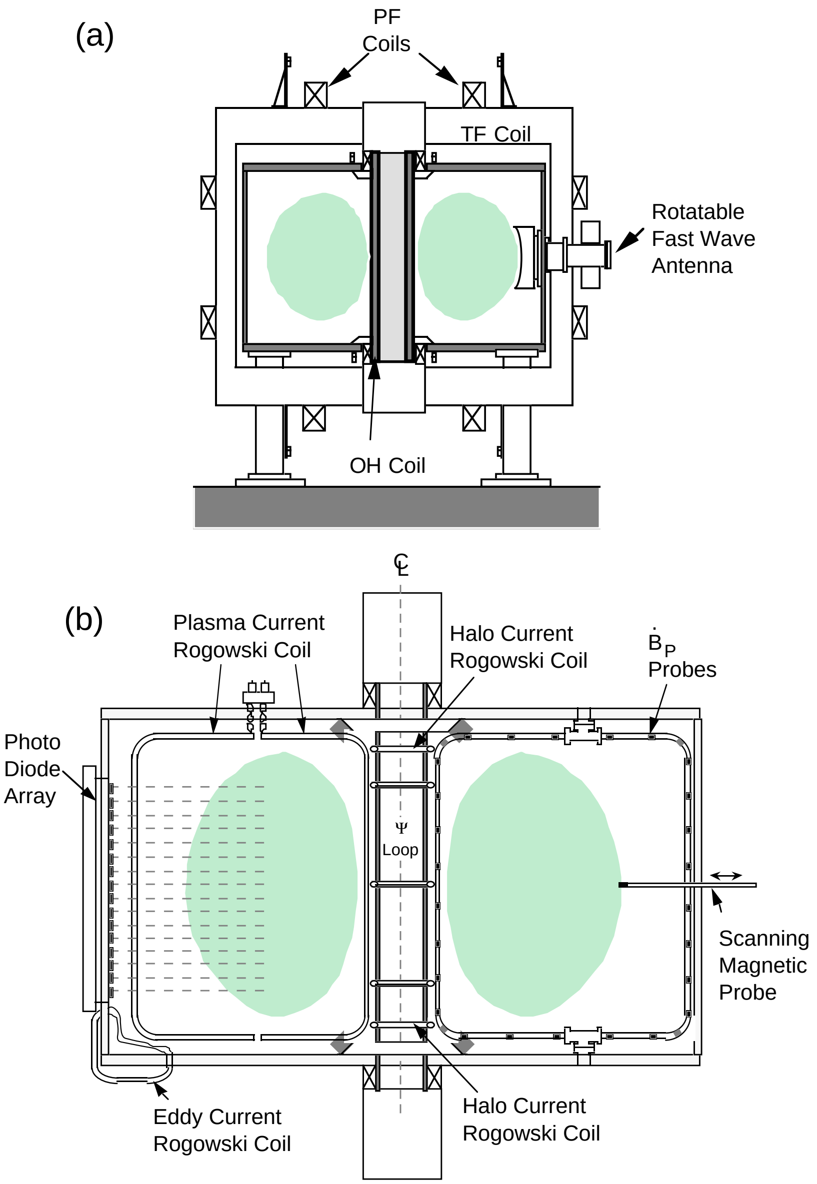


Figure 1. Schematic of the CDX-U device and diagnostics. (a) Cross-sectional view of the CDX-U device. (b) Magnetic and soft X-ray diagnostics.

Plasma Current Limit and Resistive-MHD Modes

Since ST power plant performance depends strongly on the amount of plasma current which can be supported, it is important to explore the current limit of STs. Experimentally, the current limit in CDX-U is reached when the plasma edge safety factor q(a) reaches about 3.5. The minimum edge safety factor value appears to be limited by resistive-MHD instabilities in CDX-U.

Studies of magnetic fluctuations revealed increasingly active coherent resistive-MHD oscillations as the edge safety factor is lowered. Temporal and spatial characteristics of the dominant oscillations were measured by the poloidal and toroidal magnetic pick-up coil array, the soft X-ray array, and the phase-contrast diagnostic. The dominant resistive-MHD modes observed thus far are mainly toroidal mode number n=1 and poloidal mode numbers m=1, 2, 3.

There are several modes of operation which can significantly change the resistive-MHD mode behavior. In Fig. 2, the soft X-ray (a) and magnetic fluctuation signals (b) are shown. The plasma leads to an Internal Reconnection Event (IRE) — in an IRE, the plasma suffers an internal disruption but recovers. The y-axis is the diode array position (from top to bottom) and the magnetic pick-up coil position covering the whole poloidal angle (top half is low-field side and bottom half is high-field side). To aid visualization, the signal amplitude for each soft X-ray diode array and magnetic pick-up coil array is indicated by the shading (i.e., the darker shading is for larger amplitude).

Figure 2(a) shows the soft X-ray "hot" spot (n=1/m=1) rotating in time with a frequency of about 8-9 kHz. The edge channel signal shown at the top of Fig. 2(a) also shows increased edge MHD activity approaching the IRE. Similar behavior can be seen with the magnetic pick-up coil array in Fig. 2(b). Here, the dominant mode at the edge appears to be n=1 and m=2. Interestingly, the low-field-side signals are quite coherent but the high-field-side signals are complicated by the presence of higher harmonic components.

As shown in Fig. 2, both internal and external modes grow in size and amplitude until the IRE occurs. This observation indicates that mode-coupling or island overlapping trigger the IRE. It is also noted that the phase-contrast-imaging diagnostic also detects similar plasma core MHD fluctuation signals with a radial coherence length consistent with the soft X-ray array result. As seen in the soft X-ray signal, during the IRE, the heat is transported rapidly from the plasma core to the outer region. When the IRE occurs, due to decreasing plasma core temperature, the current profile relaxes and the plasma inductance drops. This causes a spike-like increase in the plasma current and the plasma naturally elongates due to the decreased plasma internal inductance. It is interesting to note that even with the IRE, the plasma is still quite resilient, and it is observed that the central plasma core rapidly reheats after the event.

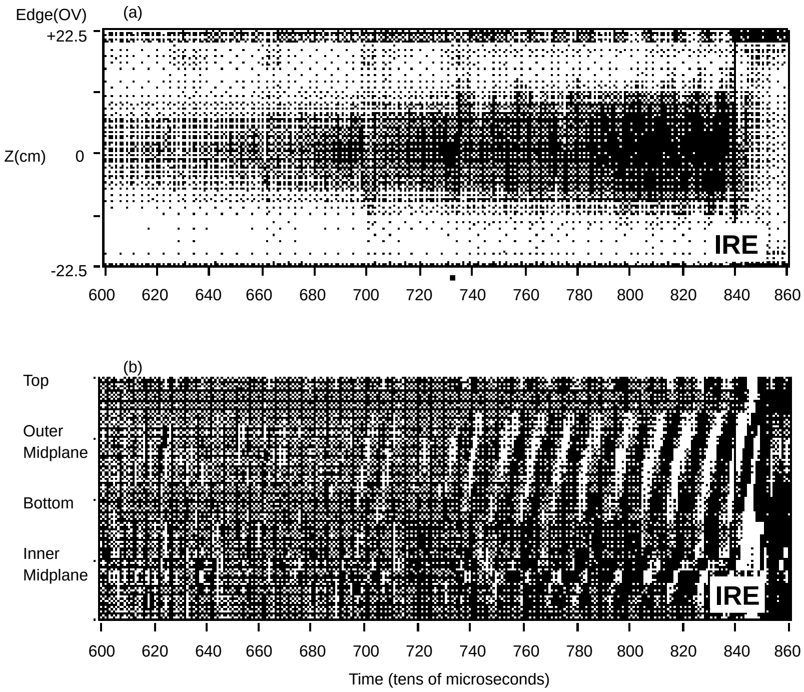


Figure 2. Temporal behavior of MHD modes leading to the Internal Reconnection Event. (a) Soft X-ray array and (b) magnetic pick-up coil array signals of an MHD-active plasma discharge, respectively. The shading depicts the MHD amplitude — the darker shading represents higher amplitude.

Halo-Current Study

When a tokamak plasma undergoes a strong MHD event, such as a plasma disruption, a variety of currents can be induced in the vacuum vessel wall. Moreover, since plasmas in the disruption phase often undergo violent nonaxisymmetric movements, the induced currents (often termed "halo" current) are not uniform around the torus. The unbalanced halo-induced currents in the inner wall (high-field side) can produce large stresses on the inner vacuum vessel wall. For a future ST device, this halo-induced current in the center stack (the inner leg of the toroidal-field coil) presents a potentially serious structural problem. It is therefore important to understand the nature of halo currents in ST plasmas.

To facilitate the study of halo currents, a segmented (four-element) Rogowski coil was placed in the upper and lower areas of the CDX-U center stack [see Fig. 1(b)], to measure the total poloidal current flowing in the center stack, as well as the up-down and toroidal asymmetry. The Rogowski coils are calibrated with the known toroidal-field current. As mentioned above, during an IRE, the plasma experiences a relatively violent increase in plasma elongation and plasma current, due to decreased plasma inductance. The halo-induced current is obtained by integrating the Rogowski coil signal and is typically less than 1% of the total plasma current for both of the top and bottom coils.

During the normal course of CDX-U operation, the IRE is the most serious MHD event in terms of the induced-halo current. Otherwise, the ST plasmas in CDX-U are remarkably stable and resilient. Perhaps largely due to this MHD stability and geometric factor, the halo-induced current in the center stack may be relatively small during an IRE and/or forced plasma disruption for the ST. While this is an encouraging result for future STs, it is important to understand the physical mechanism of the halo current in the ST geometry through further experimentation and theoretical modeling.

High-Harmonic Fast-Wave Heating Study

Implementation of the CDX-U high-harmonic fast-wave heating system was a major hardware undertaking during FY96. The centerpiece of the system is a rotatable fast-wave antenna — the first of its kind in the world. This capability is necessitated by the extreme magnetic field line pitch of spherical torus plasmas. In particular, it is very important to experimentally characterize the dependence of fast-wave power coupling on antenna strap orientation with respect to the equilibrium magnetic field.

Initial antenna loading measurements exhibited several features that indicate power is indeed being coupled to the fast wave. First, once impurities have been burned off after a vacuum opening, the plasma loading resistance is nearly independent of power, as expected for the fast wave. Further, the loading resistance measured at different strap angles agrees well with theoretical predictions. Future work will focus on the physics of heating and current-drive for high-harmonic fast waves.

Other Activities

Other activities for the CDX-U program in FY96 included the development of an electron-ripple-injection concept for plasma transport control and design of a phase-contrast-imaging system for plasma fluctuation studies.

The electron-ripple-injection concept proposes to create a radial electric field layer by external means in a nonintrusive manner to be used as a tool for ST plasma transport modification. To test some of the theoretical predictions, a series of experiments were performed to study the underlying physics issues of the concept. These include the observation of electron grad-B drifts, generation of ripple magnetic fields, observation of electron-ripple trapping and heating, and measurement of radial current in a simple field geometry. The results of the preliminary experiments are in reasonably good agreement with theoretical predictions.

The CO_2 laser-based tangential phase contrast imaging diagnostic can provide an accurate reconstruction of fluctuation profiles. The present diagnostic system can resolve density fluctuation amplitudes of approximate 1×10^9 cm^{-3} and wavelengths of 0.5 to 8 cm, at frequencies of up to 1 MHz. In the CDX-U device, resistive-MHD modes were found to be highly visible, and the results corroborated those of other diagnostics in the MHD studies. The k-spectrum of the background turbulence was also measured and found to peak at 1 cm^{-1} with a width of approximately 3 cm^{-1}.

Collaborations and Graduate Studies

CDX-U researchers collaborate with scientists at the A.F. Ioffe Physical-Technical Institute, St. Petersburg, Russian Federation, the Hebrew University, Israel, and the Johns Hopkins University, Baltimore, Maryland. In addition, CDX-U welcomed visiting researchers from several institutions, including the National Institute for Fusion Sciences, Japan, and the Small Tight Aspect Ratio Tokamak (START) experiment at the Culham Laboratory in England.

Finally, the CDX-U is an excellent experimental plasma physics facility for graduate student training. First-year graduate students play active roles in the research activities on CDX-U, and many go on to write their doctoral dissertations on their work. In fiscal year 1996, Wonho Choe was awarded a Ph.D. based on his research on the CDX-U. His thesis was entitled “Feasibility Study of Electron Injection for Tokamak Plasma Transport Control.” Another CDX-U student, Jonathan (Jon) E. Menard, received the highly competitive Princeton University Honorific Award for his Ph.D. work on spherical tori.

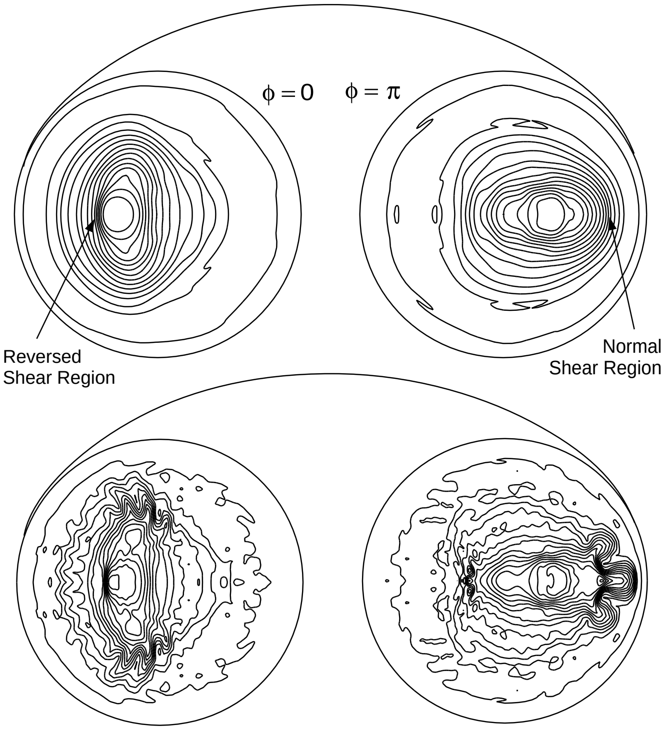
Fusion Theory and Modeling

During the past year, the Princeton Plasma Physics Laboratory (PPPL) Theory Division maintained its status as the leading center of excellence in plasma theory research. The Theory Group's high productivity and creativity continue to be evident in the many contributions they have made to help advance the scientific understanding needed for the fusion energy sciences program to continue to make progress. The endorsements and requests for enhanced collaborations by the national and international fusion research community have been stimulated not only by this Group's impressive record for generating key seminal concepts but also by its development and maintenance of the most comprehensive system of toroidal design and analysis codes. With exciting recent advances in computational power, the capabilities of the PPPL Theory Group's contributions to all areas of plasma science have greatly expanded.

Scientific Contributions

With its highly effective applications of state-of-the-art analytic and numerical analysis capabilities, PPPL theory has visibly aided significant progress in the fusion program by producing first-rate science results. This is illustrated by the following:

- Building on the successful interpretation of the physics behind the high-beta disruption phenomena which limited performance in the world-record fusion-power-producing deuterium-tritium experiments on TFTR, the unique nonlinear MHD instability analysis capabilities embodied in the MH3D suite of codes have been productively applied to key issues in advanced plasma configurations such as the reversed magnetic shear plasmas. Results have shown that major disruptions can result when nonlinear coupling of a saturated MHD kink instability to an MHD ballooning instability occurs (see figure).
- An exciting new gyrokinetic simulation code has been developed to realistically assess the neoclassical transport properties in magnetically confined plasmas. It has been successfully applied to resolve the apparent physics contradiction that the measured ion-thermal transport levels fall below the "irreducible minimum level" predicted by standard neoclassical theory. The key physics issue here is the finite-orbit excursion of the ions. This has reconciled the theoretical calculations with the results of experimental measurements.
- It was theoretically predicted that a new form of Alfvén mode, the core-localized Toroidicity-induced Alfvén eigenmode (TAE) would be more susceptible to destabilization by alpha particles than the conventional global TAE. Since understanding these instabilities is generally recognized to be a key issue for performance in planned ignition devices such as the International Thermonuclear Experimental Reactor (ITER), there was much excitement when this important prediction was recently borne out in TFTR experiments which, for the first time, clearly observed alpha-particle-driven TAE-type instabilities.



Numerical simulation results show the evolution of plasma pressure during a disruption. In the top figures, two local pressure steepenings are visible, one inside the reverse shear core region, the other outside in a normal shear region, as indicated by the arrows. The normal shear region shows explosive growth of a localized instability (bottom right), while the reversed shear core region (bottom left) remains stable even though the pressure steepening starts out much larger. This result agrees well with experiment.

External Collaborations

Evidence for highly productive collaborations between the PPPL Theory Division staff and prominent national and international institutions such as General Atomics, the Japanese Atomic Energy Research Institute, the Institute for Fusion Studies (IFS) at Texas, and others, as well as individual scientists from university programs at the Massachusetts Institute of Technology, the University of California at San Diego, and others were abundant in the past year. For example, numerous publications and co-authorship on American Physical Society Division of Plasma Physics invited papers resulted from the General Atomics DIII-D collaboration together with generous acknowledgments at the General Atomics Program Advisory Committee Meeting for the strong contributions of the PPPL Theory Group. Scientists at the Japanese Atomic Energy Research Institute expressed their appreciation and enthusiasm for enhanced collaborations which were further stimulated by highly valued visits from PPPL Theory Group members.

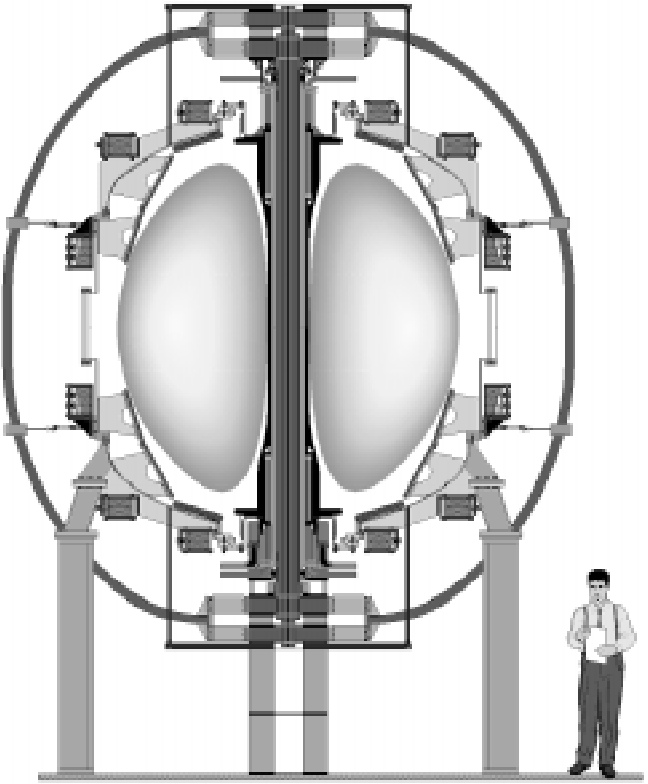
The continuing prominence of the IFS-PPPL transport model in interpreting many of the important confinement properties in TFTR, the Joint European Torus, and other world fusion devices is clearly evident in the numerous publications and invited presentations at major meetings. In addition to providing the seminal ideas responsible for the gyrokinetic and gyrofluid initiatives which drive the national grand challenge Numerical Tokamak Project, the PPPL Theory Group has led the much needed efforts to further improve the associated transport models. The Group has also further enhanced its key role of providing vital tools and concepts for ITER research and development needs through membership on ITER expert teams, letters of endorsement with requests for enhanced activity, as well as participation in other ITER-related activities.

Future Impact

The PPPL Theory Group continued in its role of scientific leadership not only in the essential long-range work providing the basic understanding to develop new analysis techniques and tools but also in the actual applications of state-of-the-art theoretical codes to the interpretation and design of key experiments. With the new emphasis on science in the restructured Office of Fusion Energy Sciences Program, it is expected that PPPL theory contributions will have an even greater positive impact in the future. New theory initiatives in the areas of stellarators and alternate concepts together with the demands for enhanced international collaborations will receive special attention.

Finally, PPPL theorists play an essential role in the education of first-rate young scientists for the fusion program by their participation and guidance in the education of graduate students and the training of postdoctoral students. For example, both of the U.S. Department of Energy Fusion Postdoctoral Fellowships granted in the past year went to PPPL theory students. Such activities are key elements serving the future health and vitality of fusion research.

NSTX



Schematic of the National Spherical Torus Experiment.

The National Spherical Torus Experiment (NSTX) is a mega-amp-level spherical torus (ST) facility designed to investigate physics issues that pertain to spherical torus plasmas. Spherical tori produce plasmas that are shaped differently from conventional tokamak plasmas; the minor radius of the plasma is close in magnitude to the major radius, making the overall plasma nearly spherical in shape. This configuration may have several advantageous features, a major one being the ability to confine a high plasma pressure for a given magnetic field. Since the amount of fusion power produced is proportional to the square of the plasma pressure, this alternative concept could play an important role in the development of smaller and more economical fusion reactors.

The NSTX Design Project is a national collaboration among several institutions including the Princeton Plasma Physics Laboratory (PPPL), the Oak Ridge National Laboratory, Columbia University, and the University of Washington at Seattle. PPPL has primary responsibility for the Project and the coordination of the design and construction effort. In July, 1996, the NSTX Design Team made successful presentations at the NSTX Department of Energy Engineering, Cost, and Schedule Review. The NSTX Project has entered the engineering design phase; construction is planned to begin in fiscal year 1997.

The NSTX device will be built at PPPL and placed in the D-Site Hot Cell to take advantage of existing equipment and infrastructure. This will save both time and money. An innovative and unique feature of the NSTX is its modularity. Machine components and structure have been designed for ease of removal and replacement for repairs, upgrades, and the tailoring of experiments in response to new information obtained through experiment and theory.

On the NSTX Program side, FY96 was marked by the decision to form a NSTX Program Advisory Committee and three national spherical torus working groups to study noninductive spherical torus (ST) plasma formation, heating and current sustainment, and high-beta and confinement. These working groups will provide early input to the NSTX research program preparation activities during FY98. These and other working groups, to be formed in fiscal year 1997, will evolve into the NSTX National Research Team during the fiscal years 1998-1999 time frame.

Mission

Reflecting the exciting scientific opportunities of the spherical torus, the NSTX research mission was established to evaluate the physics performance of spherical torus plasmas for:

- noninductive start-up, current maintenance, and current profile control;
- global plasma confinement and local transport physics;
- plasma beta-limit scaling; and
- plasma particle and heat handling.

The experiments will be carried out in scientifically interesting plasma conditions which are reactor- and volume-neutron-source-relevant:

- a high toroidal beta of about 30 to 45%,
- a high bootstrap-current fraction of about 40 to 80%,
- a fully relaxed, noninductively sustained current profile, an extreme low aspect ratio of about 1.25 with a natural elongation of about two or higher, and
- reactor-like low collisionality.

NSTX Physics Activities

The Physics Team has worked closely with the Engineering Team to address the key physics issues that impact critical design items such as the center stack, poloidal-field (PF) coil system and associated power supply requirements, radio-frequency power systems, and plasma facing components. Equilibrium calculations for both the up-down symmetric (double-null and natural divertor) and single-null (for coaxial helicity injection) configurations have defined the required positions and shapes of the PF1a and PF1b coils, along with the coil current levels required to produce the range of possible plasma shapes. Furthermore, shaping requirements have been key in setting the height of the new ohmic-heating (OH) solenoid. Calculations have been performed to determine the axisymmetric stray fields from such sources as the OH current during start-up and induced eddy currents in the vessel and passive plates, toroidal-field (TF) leads, TF loops, and toroidal eddy currents induced in the TF center-stack conductor due to ramping of the OH current. Only the OH and induced eddy currents were found to be significant. Calculations have been performed to determine the PF coil current levels required to compensate these stray fields and allow plasma initiation.

Other areas in which the Physics Team has contributed include Tokamak Simulation Code (TSC) scenario development for inductive plasma operation from near initiation to final OH current shutdown. This is important input for the Engineering Team in determining the resistive heating of the various coils and the PF power supply voltage requirements. Results from these code simulations have also been used as input to radio-frequency coupling calculations to assess heating and current-drive possibilities. Simulations using the TSC and TRANSP codes have been carried out for neutral-beam injection scenario development; this work is ongoing. The effect of the fast-ion population on the radio-frequency heating of the plasma is also an area of ongoing work.

The TSC has been used to develop radial and vertical plasma disruption scenarios; code output is used as a basis for determining stresses on the center stack due to induced and halo currents. Finally,

NSTX Machine Parameters.

Parameter	Value
Major Radius (R_o)	0.85 m
Minor Radius (a)	0.68 m
Toriodal Field (B_t)	0.3 T
Plasma Current (I_p)	1.0 MA
Elongation (κ)	2.0
Triangularity (δ)	0.4
Pulse Length	<5 sec
Heating and Current Drive	
Neutral Beam	5 MW *
High-Harmonic Fast-Wave	6 MW
Co-Axial Helicity Injection	—
Plasma Species	Deuterium
Close-Fitting Conducting Shell	

*Upgrade

zero-dimensional calculations have been used to estimate the expected heat loads on the center stack and divertor plates for predicted plasma configurations. One- and two-dimensional heat flux calculations are underway.

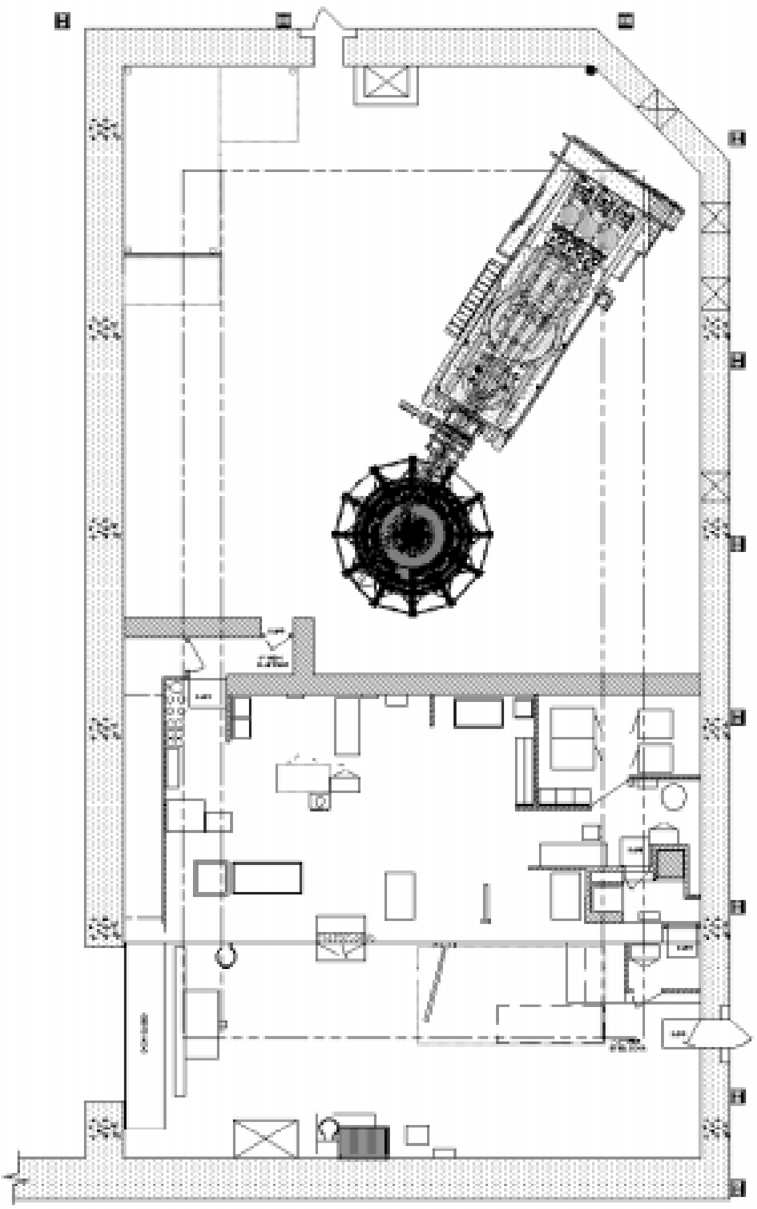
NSTX Engineering Activities

Engineering activities significantly increased in FY96 in preparation for the start of major hardware procurement activities next year. The center stack will be the first major component to be procured and therefore received the greatest emphasis. The center-stack design benefited both from expert peer reviews and, as fiscal year 1996 came to a close, the selection of the D-Site Hot Cell as the location of NSTX. The D-Site location permits the use of the Tokamak Fusion Test Reactor power supplies with their greater flexibility and power capability. Consequently, the center-stack design now features a demountable toroidal-field coil assembly with half as many turns as the former design and an ohmic-heating winding with a seamless copper conductor of constant cross-sectional area. Both of these changes are significant because they simplify the manufacturing of the center stack and improve maintainability. Analyses are proceeding on schedule to support the design. These analyses include finite-element stress analyses, cooling analyses, and halo-current analyses. The halo-current analyses are particularly notable for the insight they are providing to their behavior in low-aspect-ratio devices.

Much was also accomplished in other Project engineering areas. Engineering and Project Management requirements were formalized, subsystem costs were further refined, and design configurations were developed for the other major systems of NSTX. These include the power supplies and controls, vacuum vessel and plasma facing components, and the general machine arrangement. Activities in these other engineering areas will increase in the next fiscal year as the center stack moves to its procurement and construction stage.

Relocation of NSTX Device to D-Site

The existing facilities and capabilities located at D-Site at the Princeton Plasma Physics Laboratory represent the single largest asset in the U.S. national fusion energy sciences program at this time, and it is important both in terms of money and time to take advantage of this asset. Since the Tokamak Fusion Test Reactor will conclude ex-



The NSTX device in the D-Site Hot Cell.

perimental operations in fiscal year 1997, the possibility of locating the NSTX device in the D-Site Hot Cell area instead of at C-Site was examined. The study showed that the NSTX is compatible with the existing D-Site infrastructure and that there are several significant advantages in placing the NSTX there, including:

- A flexible power system that is better suited to the challenging power requirements of the NSTX Base Experimental Program and also better suited for any future upgrades to the device.
- The immediate use of one of the existing TFTR neutral-beam sources to provide NSTX with the desired neutral-beam-injection capability of 5 sec duration at 5 MW (80 keV) power. Additionally, this will save the time and money associated with research and development of a new neutral-beam capability and a reduction in installation costs will also be realized.
- The use, after modifications, of the much larger TFTR Control Room by the National Research Team. The lack of control room space at C-Site was a major concern raised at the NSTX Engineering, Cost, and Schedule Review in July, 1996.

On the basis of the study, the NSTX Project baseline was revised to specify installation of the NSTX device in the D-Site Hot Cell area at the Princeton Plasma Physics Laboratory. The first plasma is presently scheduled for April, 1999.

ITER

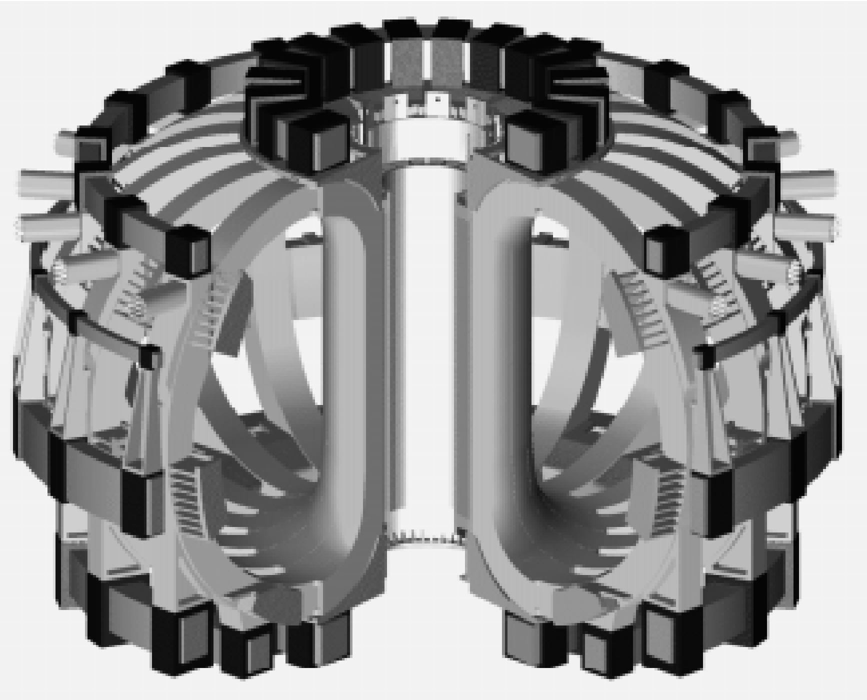
International Thermonuclear Experimental Reactor

The International Thermonuclear Experimental Reactor (ITER) Project focused on the development of the Detailed Design Report and the physics basis in fiscal year 1996. The Princeton Plasma Physics Laboratory (PPPL) increased its role in ITER physics and engineering work with more assignments to the Joint Central Team (now three physicists in San Diego; one engineer in Garching, Germany; and one tritium engineer in Naka, Japan), increased support to the U.S. Home Team Design activities, and increased participation and coordination of the physics research addressing the ITER Physics R&D Needs (including hosting an extensive U.S. ITER Physics Information Meeting and Workshop). Also in FY96, PPPL continued its leadership roles in the positions of the Head of the ITER Joint Central Team Physics Integration Unit, the Physics Manager for the U.S. Home Team, the Chair of the ITER Technical Advisory Committee, and three Task Area Leaders in physics design.

The ITER Project reached the “two-thirds point” in its six-year Engineering Design Activities phase in July, 1996. Design tasks were focused on delivery of the Detailed Design Report in November, 1996. This report will be reviewed by the Technical Advisory Committee in December, 1996, and by the four ITER Parties (European Union, Japan, Russian Federation, and the United States) early in 1997, leading to consideration by the ITER Council in Summer, 1997.

PPPL Physics Design Activities

PPPL’s physics design activities in FY96 were focused primarily in the areas of plasma control, disruption modeling, and diagnostics design.



The International Thermonuclear Experimental Reactor’s poloidal and toroidal magnetic-field coils are made of superconducting strand to permit very long plasma pulses. The machine design is targeted at supporting a “self-heated” plasma for pulse lengths of more than 15 minutes.

PPPL's state-of-the-art Tokamak Simulation Code (TSC) was applied to the development of plasma scenarios and the derivation of poloidal-field performance requirements for the control of plasma disturbances. The TSC was also applied to the development of a range of plasma disruption scenarios, including cases that stayed at the vessel's midplane and cases that moved vertically, driving "halo currents" that flow between the plasma and the plasma-facing components, causing challenging forces on the in-vessel structures. The TSC model was enhanced to simulate the generation of runaway electrons by a collisional process that may convert a significant fraction of the ITER plasma current to runaway electron current; the TSC model is being enhanced to address injection of impurity pellets, which is a promising technique for fast and safe shutdown of a disruptive plasma with minimal runaway electron generation.

Diagnostics design addressed the refinement of measurement requirements and conceptual design of plasma control diagnostics. PPPL provided the Task Area Leader for coordination of U.S. diagnostic design. PPPL began design of the visible bremsstrahlung array, the edge and position reflectometer, the edge Thomson scattering system, and support in active spectroscopy, neutron flux monitor, and neutron activation systems.

PPPL Engineering Design Activities

PPPL's engineering design activities in FY96 were focused in the areas of an alternative design for a major poloidal-field magnet system and analysis of the loads and responses of in-vessel structures.

PPPL, working as part of a U.S. team, is assessing the opportunity for a modified poloidal-field magnet configuration, targeted at improving plasma control capability and possibly reducing overall magnet system cost and increasing maintainability by permitting the conversion of several poloidal-field coils from niobium tin to niobium titanium. The alternative or "hybrid" design improves control flexibility by providing a larger number of independently powered coils.

PPPL in-vessel design work has focused on: (1) the derivation of current flow in the in-vessel components driven by the plasma behavior simulated by TSC, (2) calculation of the disruption loads on the first-wall and the supporting structure, and (3) suggestions of improved designs for the attachment of the remotely replaceable first wall/ blanket modules to the structure.

U.S. ITER Physics Information Meeting and Workshop

In May, 1996, PPPL hosted a U.S. ITER Physics Information Meeting and Workshop. Presentations by the ITER Director, members of the ITER Joint Central Team, Home Team, and Physics Expert Groups provided an overview of physics and engineering aspects of the design, including the status of Technology R&D projects. Subsequent parallel sessions on major physics topics (confinement, heating, and plasma performance; operating scenarios, plasma control, current drive, MHD, and disruptions; power and particle handling; and energetic particles) provided opportunities for 125 members of the U.S. community to become involved in the identification of both physics issues and U.S. actions that could address the critical issues. The participants gave particularly high priority to making the ITER design more flexible, due to the desire for the ITER device to be able to accommodate future techniques for performance enhancement. Particular emphasis was given to near-term U.S. contributions on beta-limiting phenomena, disruption characterization and modeling, transport prediction and performance modeling, and divertor modeling.

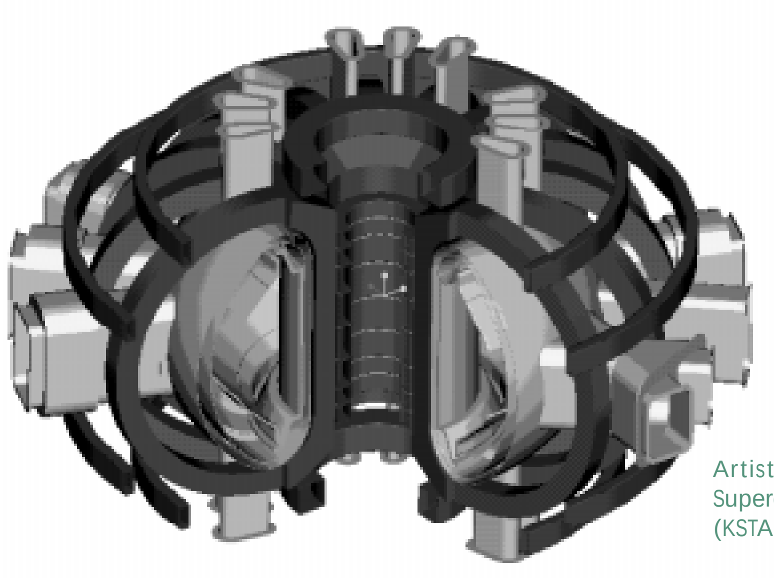
These challenging opportunities for U.S. contributions have been referred both to community leaders and to the U.S. Department of Energy. Research on these generic physics issues was cited as being fully consistent with the U.S. fusion program's emphasis on fusion science, tokamak concept improvement, and international collaboration.

Detailed Design Report Machine Parameters for the International Thermonuclear Experimental Reactor.

Parameter	Value
Major Radius (R)	8.1 m
Minor Radius (a)	2.8 m
Elongation	1.6
Toroidal Field (B)	5.7 T
Plasma Current (I_p)	~21 MA
Power and Particle Control	Single-Null, Poloidal Divertor
Auxiliary Power	0.1 GW
Fusion Power	1.5 GW

KSTAR

Korea Superconducting Tokamak Research Project



Artist's rendering of the Korea Superconducting Tokamak Research (KSTAR) device..

The legacy of the Tokamak Physics Experiment (TPX) has had a strong international impact on the vision of the "Advanced Tokamak" and has demonstrated a positive management model for national collaboration among laboratories, universities, and industry for fusion research. The international importance of the TPX work became apparent in 1996 with the initiation of the Korea Superconducting TokamAk Research Project (KSTAR) as the flagship device for the budding Korea National Fusion Program. This Program was officially launched in January, 1996, with the establishment of a National Fusion R&D Center at the Korea Basic Science Institute in Taejeon, Republic of South Korea. Following the TPX model, the Korea National Fusion Program is a collaborative venture among Korean laboratories, universities, and industry. The mission of the Program is to:

- Develop and construct a superconducting tokamak (the KSTAR Project) capable of steady-state operation.
- Develop advanced, flexible tokamak operating scenarios that address global and localized plasma confinement physics issues; and
- Establish a Korean physics and technology base for superconducting steady-state fusion reactors to support and complement future fusion reactors, including the International Thermonuclear Experimental Reactor.

The parameters and mission of the KSTAR Project closely parallel those of the TPX Project. As a result, the Korea Basic Science Institute entered into a collaborative program in June, 1996, with the Princeton Plasma Physics Laboratory for the Laboratory to coordinate a U.S. team effort to assist the Korean team in designing and building the KSTAR Project, to provide opportunities for Korean team members to obtain the necessary technical knowledge and expertise in designing fusion devices, and to assist the Korea Basic Science Institute in setting up the requisite engineering and management programs to monitor and control the Project. PPPL in turn involved many of the U.S. fusion institutions and personnel that held key leadership positions in the TPX Project. In 1996, this included the Massachusetts Institute of Technology, the General Atomics Company, and the Northrop-Grumman Corporation.

The KSTAR device closely resembles the TPX device in that both the toroidal-field and the poloidal-field magnet systems will be superconducting, the pulse length will be very long, and the plasma parameters are similar. Nominal KSTAR parameters are given in the table.

The 1996 phase of the U.S.-Korea collaboration was characterized as the “preconceptual design phase” in which system-level engineering studies were conducted on a wide range of options to narrow the design point range. This phase was successful not only in a technical sense in that a consensus design point was quickly arrived at, but also in that the cooperative nature of the collaboration was proven. By the end of the year, a total of seven Korean team members were assigned at the Princeton Plasma Physics Laboratory for long-term assignments and were integrated into the U.S. design team effort. The year ended with the completion of a very successful Concept Design Review in November with Ambassador Kun Mo Chung, Korea’s Ambassador to the International Atomic Energy Agency, and Professor Duk In Choi, President of the Korea Basic Science Institute, in attendance. This meeting was the first opportunity in which key members of both the Korean and U.S. teams were able to meet and discuss their mutual design efforts.

The initial phase of the collaboration accomplished the following:

- The mission was identified.
- High-leverage system-level engineering studies were completed.
- Top-level physics requirements were developed.
- A first draft of the Physics Requirements Document was developed.
- A design point (machine parameters and radial build) consistent with the physics requirements in the Physics Requirements Document is being finalized.

In 1997, the “conceptual design phase” of the Project will begin. Participating U.S. fusion institutions in the KSTAR Project will expand to include the Lawrence Livermore National Laboratory and the Oak Ridge National Laboratory.

There are three major milestones planned for 1997. These are:

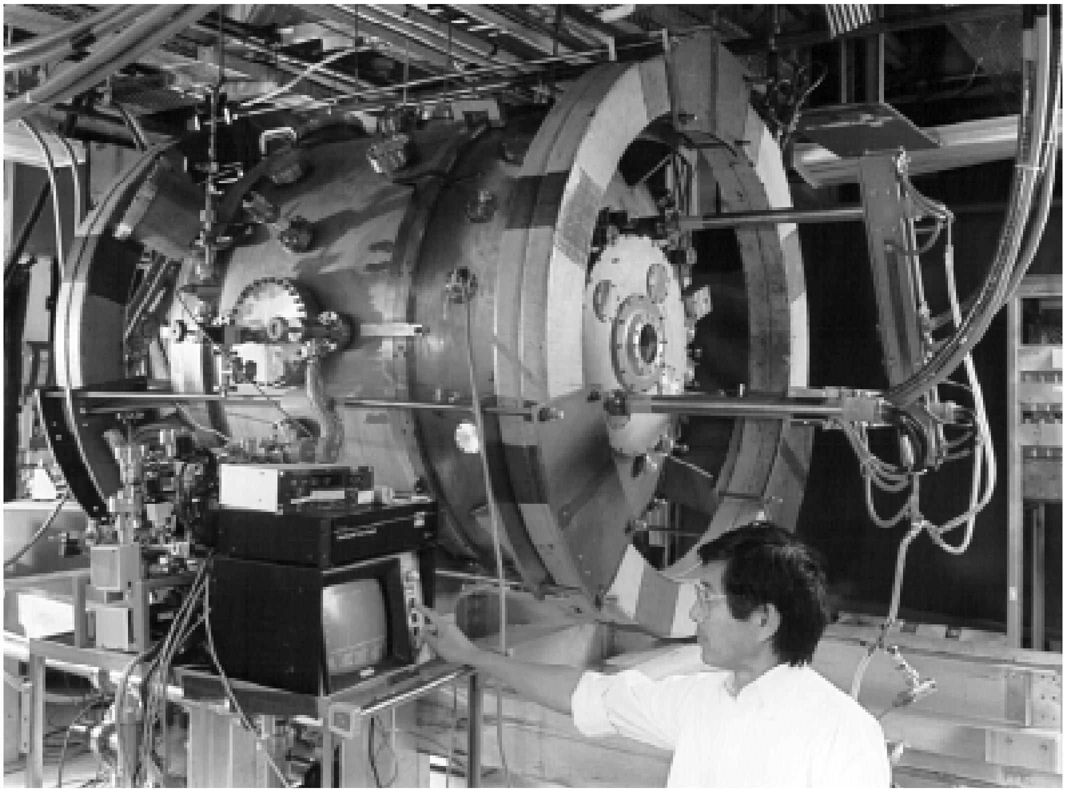
- A “Design Point Definition Workshop” to be held in February, 1997, at the Princeton Plasma Physics Laboratory. This meeting will confirm the configurational basis for the conceptual design effort.
- A “Physics Validation Review” and an “Engineering Workshop” to be held back-to-back in late June, 1997, at the Korea Basic Science Institute. The first meeting will first serve as a forum for international fusion experts to review and comment on the specific KSTAR Project physics mission and on the role the KSTAR Project is intended to fulfill in the world fusion program. The second meeting will be a “working” Engineering Workshop where members of the Korean and U.S. KSTAR teams will discuss their respective design progress.
- A “Tokamak Systems Engineering, Cost, and Schedule Review” to be held in December, 1997, at the Korea Basic Science Institute. The purpose of this meeting will be to verify the overall KSTAR system requirements; develop the system-level design of the tokamak (including establishing subsystem design envelopes and locating interfaces); and to establish the technical, cost, and schedule feasibility of these design envelopes.

KSTAR Major Parameters.

Plasma Parameter	Value
Major Radius (R_O)	1.8 m
Minor Radius (a)	0.5 m
Toriodal Field (B_t)	3.5 T
Plasma Current (I_p)	2.0 MA
Elongation (κ)	2.0
Triangularity (δ)	0.8
Pulse Length	20 sec < τ_{pulse} < 300 sec
Heating and Current Drive	
Neutral Beam	8 MW
Ion Cyclotron	6 MW
Lower Hybrid	1.5 MW
Electron Cyclotron	TBD
Plasma Species	Hydrogen or Deuterium

MRX

Magnetic Reconnection Experiment



Magnetic Reconnection Experiment

A new basic plasma physics research facility — the Magnetic Reconnection Experiment (MRX) — began operation at the Princeton Plasma Physics Laboratory in October, 1995. Experiments on MRX study the physics of magnetic reconnection — the topological breaking and reconnection of magnetic field lines in plasmas. Scientists at PPPL hope to understand the governing principles of this important plasma physics process and gain a basic understanding of how it affects plasma characteristics such as confinement and heating.

Gaining an understanding of magnetic reconnection will have relevance to solar physics, astrophysics, magnetospheric physics, and the physics of laboratory plasmas. Because magnetic reconnection is regarded as a key phenomenon in solar flares, MRX results could play an important role in interpreting data from satellites such as Yohkoh and GEOTAIL.

Magnetic reconnection also occurs as one of the relaxation processes in fusion plasmas; it often plays a dominant role in determining the confinement characteristics of high-temperature fusion plasmas. The small size and rich plasma physics of MRX make it an ideal facility for studying the interplay between plasmas and magnetic fields and for educating graduate students.

The design and construction of the MRX facility were completed entirely at PPPL. Components from earlier experimental devices were used. In particular, part of the vacuum vessel from Proto S-1 and the equilibrium-field coils from the S-1 Spheromak were recycled.

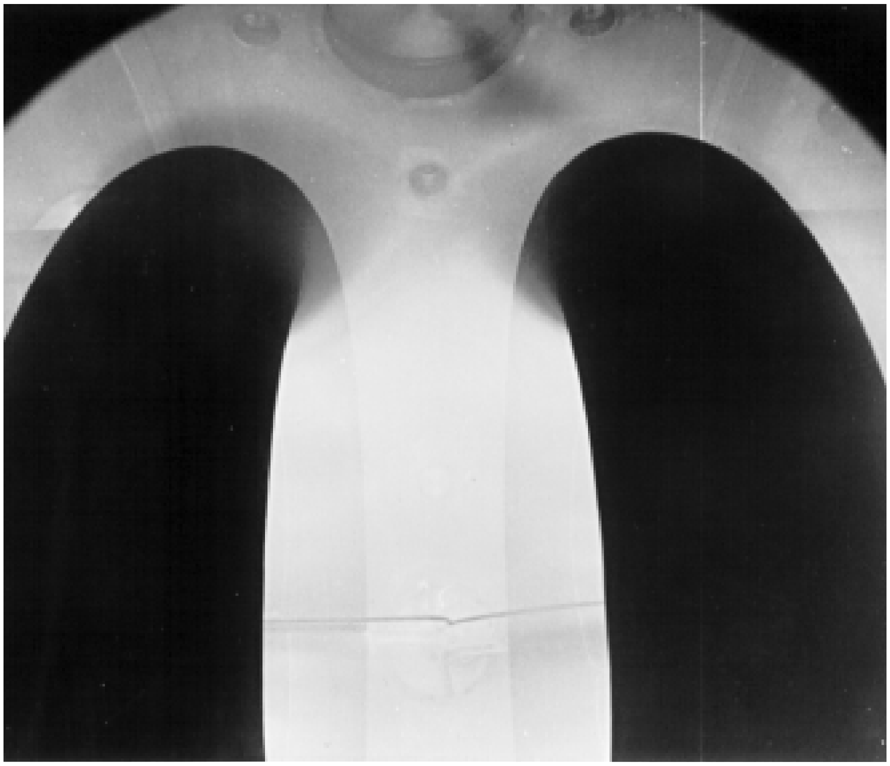
Because of the strong impact of this experiment on many fields of plasma physics, MRX is jointly supported by the National Science Foundation, the National Aeronautics and Space Administration, the Office of Naval Research, and the U.S. Department of Energy.

How It Works

In the MRX experiment, two plasma toroids with identical toroidal currents are created. Eventually the plasmas merge due to the attractive forces created by the toroidal currents and by the external fields. The merging plasmas induce magnetic reconnection. Understanding this interplay between plasma and magnetic field is important to the development of magnetic fusion as an energy source. This is because the magnetic-field bottles which confine the plasma can open up or tear when uncontrolled reconnection events occur; this results in a loss of confinement.

Experimental Objectives

The primary objective of experiments on MRX will be the comprehensive analysis of the physics of magnetic reconnection both locally and globally in a magnetohydrodynamic (MHD) plasma. This will be accomplished by investigating the coupling between micro-scale reconnection layers for local reconnection and global forcing and MHD flows for global reconnection issues. Fully three-dimensional magnetic reconnection experiments are now possible on this device.



A MRX plasma. Visible are the two flux cores and the two annular plasmas touching at the “X-point” (faintly visible near the top center of the photo).

Research on MRX is addressing several key questions:

- Are two-dimensional models of reconnection adequate?
- If not, how does the third component of the magnetic-field vector affect reconnection rates and flows?
- How does patchy, fully three-dimensional reconnection, where plasmas contact at a point instead along a line, proceed?
- How do global MHD forces determine reconnection regions?
- How is magnetic energy, initially released as hydrodynamic flows, transformed into heat?
- Will turbulence arise and entrain the neutral line?
- Under what circumstances is reconnection a steady or bursty process?

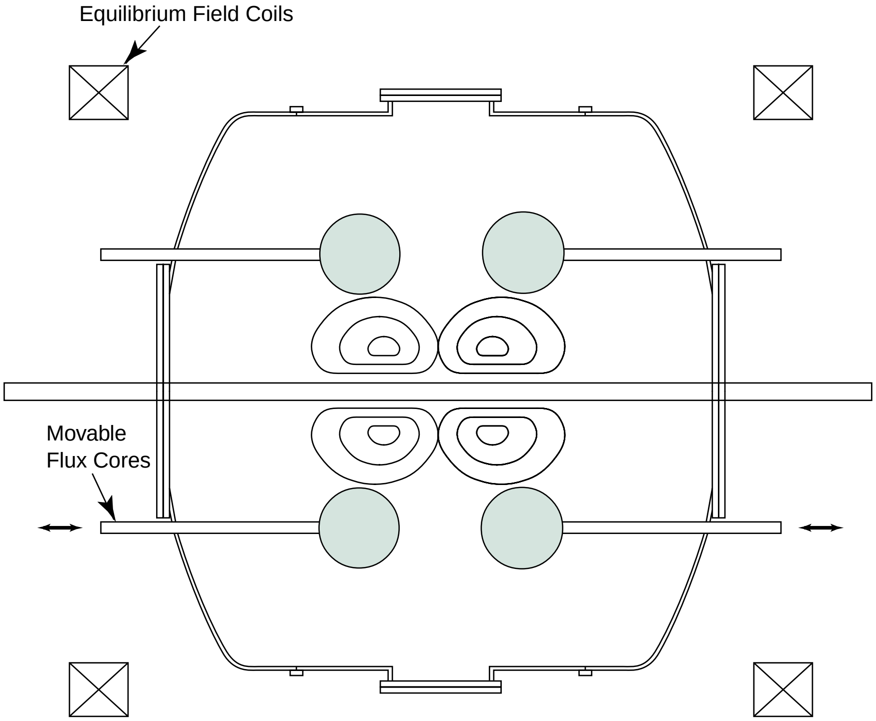
Answers to these questions will contribute to the advancement of fusion energy research and directly impact theories of reconnection in the solar atmosphere and the earth’s magnetosphere. Information pertaining to how the magnetic energy, initially released as hydrodynamic flows, is transformed into heat will relate directly to improved understanding of the physics of solar flares.

A set of carefully chosen diagnostics is providing insight into the physics of magnetic reconnection and real-time monitoring of MRX plasmas. These include Langmuir probes (for measuring electron density and temperature) and Faraday cups and spectroscopy (for measuring ion temperature and impurity concentration). Installation of a laser-induced fluorescence diagnostic for nonperturbative measurements of local ion temperature and flows is being considered.

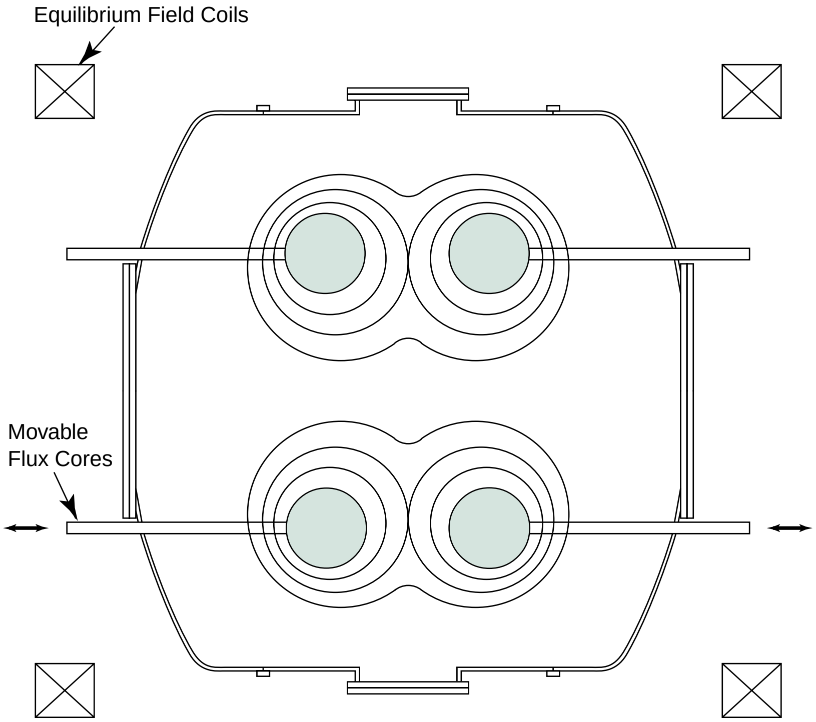
Initial Results

In MRX experiments to date, a Lundquist number (which represents the effective conductivity of the plasma) S > 700 has been achieved in 50-60 kA plasma discharges. For higher currents (100 kA), S > 1,500 is expected, with plasma sizes approximately equal to 30-100 ion gyroradii. External coils, which exert force on the plasma and alter its large-scale configuration, have been found to affect merging rates and resultant plasma properties.

A Y-shaped neutral sheet region has been identified in null-helicity merging, and an O-shaped region is seen in co-helicity merging. To the best of our knowledge, this is the most detailed experimental documentation of neutral current sheets in MHD plasmas. The sheet thickness has been verified with a high-resolution (5 mm) magnetic probe array and has been found to be as thin as one centimeter, which is approximately equal to the ion



Cross-sectional view of the MRX device illustrating the external equilibrium-field coils, the (movable) flux cores which contain the internal field windings, and two typical plasma merging configurations, the double spheromak (above) and the double annular plasma (below).

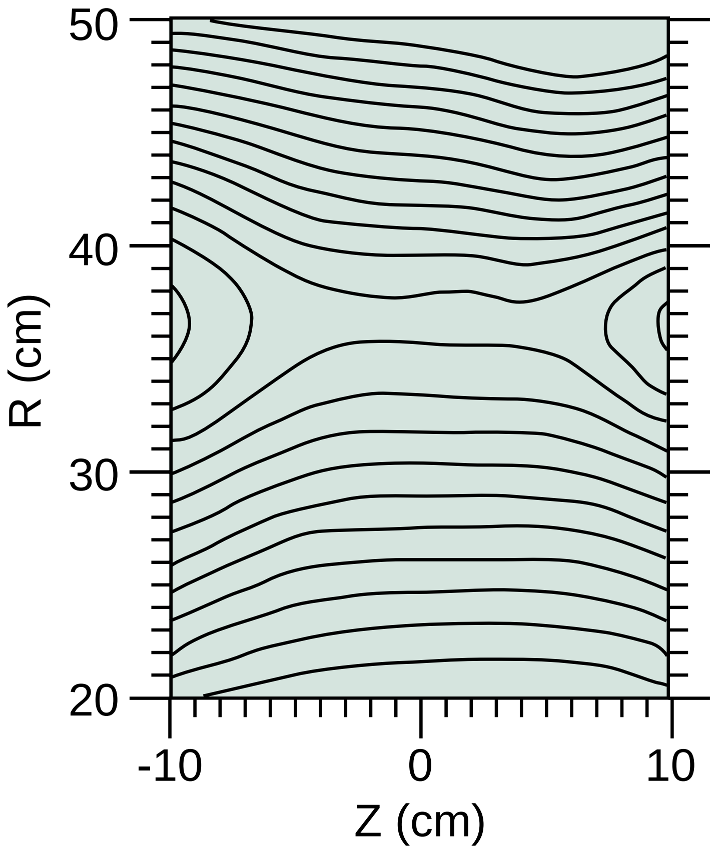


gyroradius and much less than the machine size, in the null-helicity case.

The present emphasis for MRX research is on finding a relationship between the reconnection rate and plasma conditions such as the merging angle of the field lines, plasma conductivity, and Lundquist number. A simple Ohm's law has been examined for various cases, and an enhancement of resistivity over its classical value has been observed in most cases of null-helicity merging.

Future Experiments

Future experiments on the MRX device could include a comparative study of plasma characteristics of compact toroids such as the spheromak, the field-reversed configuration, and the ultra-low-aspect-ratio tokamak (ULART). Studying these configurations is important for developing and understanding alternative fusion concepts which might lead to smaller and less expensive fusion reactors.



Poloidal flux contours inferred from experimentally determined magnetic-field structure as measured by a two-dimensional array of pick-up coils with 4 cm spatial resolution. The "double-Y" shape region near R = 37 cm reproduces the theoretical two-dimensional picture of magnetic reconnection.

Space Plasma Physics

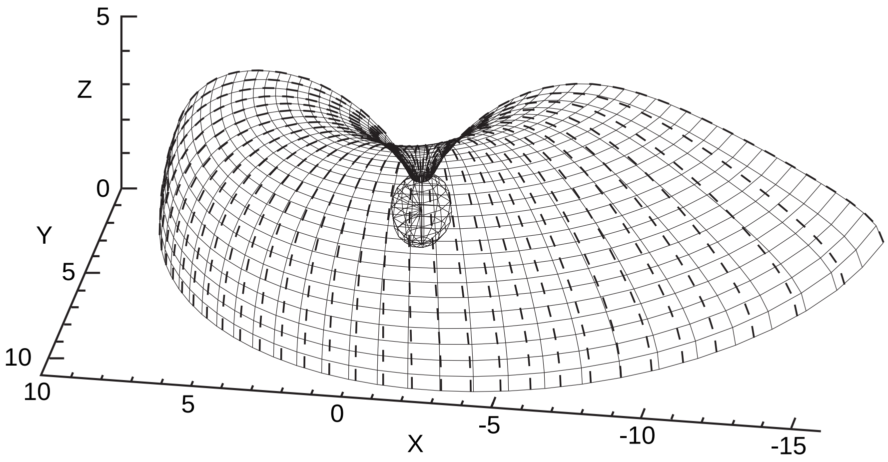
Space plasma physics research at the Princeton Plasma Physics Laboratory is focused on studying the Earth's magnetosphere and the solar atmosphere. One of the principal goals of magnetospheric physics research is to understand the three-dimensional magnetospheric structure of magnetic field, current, and plasma pressure under various solar wind conditions. Another goal is to determine how energy, mass, and momentum are transported across the magnetopause from the solar wind into the magnetosphere. Solar activities, such as the solar wind and prominence eruption, can strongly affect the Earth's magnetosphere. Initial solar physics research has centered on understanding the formation of the thin current sheet in the solar atmosphere. Such plasma configurations can lead to solar prominence eruption and corona mass ejection through magnetic reconnection processes.

3-D Magnetospheric Equilibrium

A self-consistent modeling of realistic magnetospheric equilibria is necessary for accurate study of the critical dynamical processes, such as substorms and associated plasma transport, in the magnetosphere.

A three-dimensional (3-D) magnetospheric equilibrium code, the MAG-3D code, was developed to compute the magnetospheric equilibrium solutions within a closed flux surface. This code has been extended to cover regions of open magnetic-field lines that connect to the interplanetary magnetic field by specifying the boundary condition that models the solar wind condition and magnetopause shape.

With this new capability the MAG-3D code can be used to study the full, self-consistent structure of the field-aligned current (both Region 1 and 2 currents), which is essential for studying magnetosphere-ionosphere coupling processes. The generation of field-aligned currents results mainly from a geodesic magnetic-field curvature in the flux surface which gives rise to a magnetic drift parallel to the plasma gradient direction.The figure shows a quadrant of the outer flux surface with the three-dimensional equilibrium magnetic-field lines (pointing upward) shown by the dashed lines and the constant toroidal-angle lines by the solid upward lines. On the northern hemisphere the magnetic field has a toroidal component pointing toward the midnight direction (with geode-



A quadrant of the outer flux surface with the three-dimensional equilibrium magnetic-field lines (with the magnetic field pointing upward) shown as dashed lines and the constant toroidal-angle lines as solid upward lines.

sic curvature in the opposite direction) on the nightside and pointing toward the noon direction on the dayside.

Kinetic Alfvén Waves and Transport at Magnetopause

Significant progress has been made in understanding magnetohydrodynamic (MHD) wave activity at the magnetopause and its consequences to plasma transport. In the magnetosheath, magnetic fluctuations are primarily compressional. However, during magnetopause crossings, the wave polarization suddenly changes to transverse with large amplitude.

To explain these MHD wave observations, a scenario for magnetopause wave activity in which compressional MHD waves convert into kinetic Alfvén waves at the magnetopause was proposed. The results of the kinetic-MHD calculations show a remarkable resemblance to observation.

For cases of both northward and southward interplanetary magnetic field (IMF), substantial transport can occur. Using quasilinear theory it has been shown that diffusion can occur with a diffusion coefficient, $D \approx 10^9$ m^2/sec, and convective transport with convection velocity, $V_c \approx 1$ km/sec, as required to maintain the low-latitude boundary layer.

Stochastic transport which can result from the presence of large amplitude MHD waves in a strongly sheared background magnetic field also has been investigated. It was found that when the wave amplitude is increased above a certain threshold the particle orbits become stochastic and particles become spread out in both the space and velocity domains. The transport roughly scales with $(\delta B/B)^{1.85}$, which is close to the scaling expected for a diffusive process. For typical observed values of $(\delta B/B) \approx 0.1$, the diffusion coefficient obtained for a single MHD wave is $D \approx 10^9$ m^2/sec. When multiple waves are present, the plasma transport is expected to be enhanced.

Global Mirror Modes in the Magnetosheath

Identification of observed compressional waves in the magnetosheath has been somewhat controversial. Some satellite observational analysis identified the bulk of the observed waves near the magnetopause to be mirror modes. On the other hand, others suggested that the same waves were the slow mode. The controversy centers around whether the waves have finite phase velocity relative to the bulk plasma flow.

To clarify this controversy, an analysis of global mirror modes at the magnetopause based upon the kinetic-MHD approach, which includes kinetic effects as well as global effects due to background gradients, was done. The calculations support the idea that compressional waves observed in the magnetosheath are global mirror modes.

It was demonstrated that diamagnetic drift effects resulting from a realistic magnetopause profile produces a significant real frequency in the global mirror mode with an increase in amplitude near the magnetopause boundary. When the plasma flow is introduced, the global mirror mode develops a phase velocity in the direction of the flow which is slower than the flow velocity. The result is that the wave propagates toward the bow shock in the frame of the moving plasma and has a finite real frequency in the plasma frame.

Thin Current Sheets in the Solar Atmosphere

It is generally believed that magnetic reconnection plays an important role in solar flares, coronal heating, and solar prominence formation. Because the plasma is collisionless with a magnetic Reynolds number on the order of 10^{14} in the solar atmosphere, magnetic reconnection is expected to occur only if a very thin current sheet exists with a width on the order of an ion gyroradius. Without fast dynamical solar flare disruption, solar plasmas are generally in quasi-static equilibrium states under the influence of slow changes in the boundary motions or thermodynamic properties.

Investigations have been made into how the equilibrium plasma and magnetic field configuration evolves in a gravitational field when thermal properties of the whole atmosphere change or when field-line footpoints are slowly moved. Critical values of control parameters exist over which the plasma equilibrium changes its topology from a smooth configuration to form a thin current sheet.

The studies are based on two-dimensional MHD equilibrium solutions with quadrupolar field geometry that mimic four sunspots with different polarities. Different current sheet topologies can result from changes of the plasma temperature, depending on the mass distribution as a function of magnetic flux. If the plasma mass density is higher in the inner flux tubes, a current sheet is formed where the field lines from each bipolar region come into contact when the plasma is uniformly heated. The current sheet in this case grows in height from the bottom boundary. This type of current sheet configuration can also be achieved by sheared field-line footpoint motions, because an increase in shearing motion corresponds to an increase in the plasma heat content. However, if the mass density is higher in the outer tubes than in the inner ones, a current sheet configuration is formed with a sharp-pointed end of the current sheet hanging at a distance above the bottom boundary when the plasma temperature is lowered. When resistivity is applied to these thin current sheet configurations, magnetic reconnection occurs and the field topology changes into those similar to the observed solar flares and prominences.

Engineering and Technology Development

All systems continued to achieve high levels of availability and reliability at operating parameters equal to or exceeding original design criteria. The TFTR has completed more than 800 deuterium-tritium experiments, since the start of tritium operations in 1993. The TFTR systems have processed more than 800,000 Curies of tritium safely and without impact to the environment.

Despite a demanding six month experimental campaign, important engineering upgrades to TFTR were completed. Four new ion cyclotron radio-frequency antennas were designed, fabricated, and installed on the TFTR and two more of the radio-frequency power sources were modified for 30 MHz operation. Engineering analysis coupled with a neutral beamline internal inspection was completed, allowing for a more than 65% increase in the maximum neutral-beam pulse length.

The Tritium Purification System, a specialized cryogenic distillation system developed by the Canadian Fusion Fuels Test Program, was operated with tritium and incorporated into TFTR's operating tritium systems. The Tritium Purification System achieved an output product of greater than 98% tritium purity, thereby completing the TFTR fuel cycle.

TFTR engineering staff developed techniques to open, repair, and reseal neutral-beam high-voltage switch tubes that had suffered "end of life" failures. Both an oven to bake out and a test stand to recondition the switch tubes were commissioned and three tubes have been repaired in house. Operation of the TFTR Energy Conversion Systems was streamlined and four of the eight Energy Conversion System compression capacitor banks were sent to the University of Wisconsin for use on their PEGASUS Project.

National Spherical Torus Experiment

Engineering activities significantly increased in FY96 as the National Spherical Torus Experiment (NSTX) Project entered its design and construction phase. Detailed design and analysis of the critical central stack was emphasized. Device details such as the vacuum vessel and plasma facing component configurations, the bakeout system design, plasma diagnostics, and power and control systems were defined, leading to a satisfactory Engineering Cost and Schedule Review in July, 1996. Other activities included the selection of C- or D-site as the location of the NSTX. Ultimately, the D-site Hot Cell was chosen due to its superiority in power availability and greater flexibility.

International Thermonuclear Experimental Reactor

Support to the International Thermonuclear Experimental Reactor (ITER) U.S. Home Team efforts was provided in primarily two areas: the development of a new segmented solenoid design and analysis of ITER's first-wall design.

The segmented solenoid design improves the current carrying capacity of the plasma and provides better plasma shape and position control. It also improves coil failure recovery and reduces costs by approximately $40 million.

Analyses were performed on ITER's blanket and shield, divertor cassette, and vacuum vessel to determine the electromagnetic loads on these components from plasma disruptions. A study was also completed which considered the broader issues of shield and/or blanket module attachment to the backplate, including possible reductions of electromagnetic disruption loads on the blanket and shield modules which could be achieved by modifying the electrical connection points between the modules and backplate.

Computer Systems

Computing efforts have focused on the "Shot Clock Rollover" Project. The initial design of the TFTR computing system assumed a maximum of 20,000 plasma discharges. Systems hardware, software, and applications were designed to accommodate a five digit shot number, positioning us with an issue much like the universally recognized "Millennium" or "Year 2000" computer problem. In July, at the end of the FY96 experimental run period, the Shot Clock stood at more than 96,000. To accommodate a FY97 experimental run, with the Shot Clock expected to exceed 100,000, major modifications to hardware and hundreds of software modules had to be designed, implemented, and tested. These modifications have been successfully tested and the FY97 experimental run is scheduled to begin at shot 101,000.

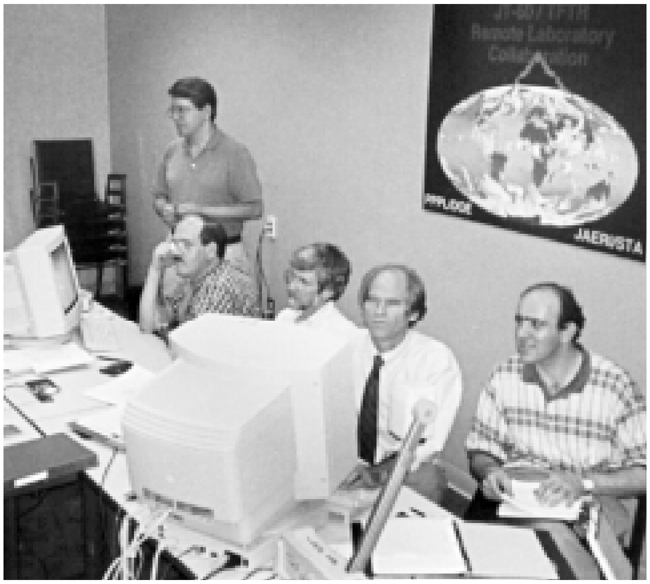
Continued implementation of collaborative technologies was another area of major thrust in the computing arena. Weekly physics meetings, colloquia, workshops, and forums are routinely broadcast over the Internet, as well as over Integrated Services Digital Network (ISDN) teleconferencing lines. These communication systems were used by PPPL physicists in the first real-time remote international fusion collaboration with the physics experiment JT-60U at the Japanese Atomic Energy Research Institute in Naka, Japan.

Environmental Restoration and Waste Management

The Environmental Restoration and Waste Management organization serves to protect the health and safety of Laboratory personnel, property, and the environment from hazards due to regulated wastes.

In fiscal year 1996, dedicated low-flow groundwater sampling pumps were installed in all monitoring wells, reducing the generation of purge water by approximately 93%. An investment of $50,000 has saved more than $110,000 in the first year of operation.

A "drum bubbler" concept was proposed to provide a backup to the Type-A Disposable Molecular Sieve Beds in the event that the supply of Type-A's became inadequate. The drum bubbler has the capability of replacing seven 30-gallon Type-A Disposable Molecular Sieve Beds. The "Big Bubbler," as it was nicknamed, operated successfully at its design parameters and removed about 100 Curies of tritium from the TFTR's stack effluent during the maintenance outage in 1996.



The first real-time remote international fusion collaboration between TFTR researchers and Japanese JT-60U scientists. The top photo shows TFTR scientists viewing data from Japan on their computer monitors. The bottom photo shows the two groups viewing each other on video conferencing screens; on the left are the JT-60U participants and on the right are the TFTR participants.

Collaborations

The Princeton Plasma Physics Laboratory actively collaborates on experiments and research activities with more than a hundred institutions around the world. These joint efforts link our researchers with those at other laboratories, educational institutions, and industry.

Collaborations are performed in a variety of ways, including hosting visiting researchers at PPPL, sending Laboratory personnel to other institutions to participate in research, and, increasingly, through electronic telecommunications. Researchers visiting PPPL take part in experiments and analyses on TFTR and CDX-U, and in the theory program. Laboratory personnel visiting other institutions participate in fusion research on such devices as the DIII-D (General Atomics, United States), Alcator C-Mod (Massachusetts Institute of Technology, United States), JET (JET Joint Undertaking, United Kingdom), JT-60U (Japan Atomic Energy Research Institute, Japan), and other fusion devices worldwide.

New activities were started this year on the National Spherical Torus Experiment (NSTX), planned to be built at PPPL, and also in assisting in design of the Korean tokamak, KSTAR. Other initiatives lay in the areas of Cooperative Research and Development Agreements, Work for Others, and participation in education programs.

The Laboratory presently collaborates with the following organizations:

Laboratories

A.F. Ioffe Physical-Technical Institute, St. Petersburg, Russian Federation
Argonne National Laboratory, Argonne, IL
Asociacion Euratom-CIEMAT, Madrid, Spain
Association Euratom-CEA, Cadarache, France
Associazione Euratom-ENEA, Frascati, Italy
Ecole Polytechnique Federale de Lausanne, Lausanne, Switzerland
Ecole Royal Militaire, Brussels, Belgium
Environmental Measurement Laboratory, New York, NY
Idaho National Engineering Laboratory, Idaho Falls, ID
I.V. Kurchatov Institute of Atomic Energy, Moscow, Russian Federation
Institute of Plasma Physics, Academia Sinica, Hefei, China
Forschungszentrum, Jülich GmbH, Germany
ITER Joint Work Site, Garching, Germany
ITER Joint Work Site, Naka, Japan
ITER Joint Work Site, San Diego, CA
Japan Atomic Energy Research Institute, Naka Fusion Research Establishment, Ibaraki, Japan
JET Joint Undertaking, Abingdon, Oxfordshire, United Kingdom
KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

Korea Advanced Institute of Science and Technology, Taejeon, Republic of Korea
Korea Basic Science Institute, Taejeon, Republic of Korea
Lawrence Berkeley National Laboratory, Berkeley, CA
Lawrence Livermore National Laboratory, Livermore, CA
Los Alamos National Laboratory, Los Alamos, NM
Max Planck Institut für Plasmaphysik, Garching, Germany
National Institute for Fusion Science, Toki, Japan
Oak Ridge National Laboratory, Oak Ridge, TN
Sandia National Laboratories, Albuquerque, NM
Sandia National Laboratories, Livermore, CA
Savannah River Plant, Aiken, SC
Southwestern Institute of Physics, Chengdu, China
Textile Research Institute, Princeton, NJ
Troitsk Institute of Innovative and Thermonuclear Research, Troitsk, Russian Federation
UKAEA, Government Division, Fusion, Culham, United Kingdom

Industries

ABB, North Brunswick, NJ
Allied Signal, Morristown, NJ
Amoco, Atlanta, GA
AT&T Bell Laboratories, Murray Hill, NJ
BASF, Charlotte, NC
Bristol-Myers Squibb, Lawrenceville, NJ
Canadian Fusion Fuels Technology Project, Canada
Charged Injection Corporation, Monmouth Jct., NJ
Cookson Fibers, Bristol, PA
DuPont Chemical Corporation, Wilmington, DE
Exide Corporation, Reading, PA
Fusion Physics and Technology, Inc., Torrance, CA
General Atomics, San Diego, CA
Hoechst Celanese, Charlotte, NC
ITT, Charlotte, NC
Lodestar, Boulder, CO
Mission Research Corporation, Newington, VA
Monsanto, Pensacola, FL
MTECH Technologies, Cambridge, MA
Northrop Grumman Aerospace and Electronics Corporation, Bethpage, NY
Plasma Technology, Inc., Santa Fe, NM
PPG, Pittsburgh, PA
Princeton Electronic Systems, Inc., Princeton, NJ
Princeton Research Instruments, Princeton, NJ
Princeton Scientific Instruments, Inc., Princeton, NJ
Radiation Science, Inc., Belmont, MA
Roy F. Weston, Inc., West Chester, PA
Wellman, Charlotte, NC
Xerox Corporation, N. Tarrytown, NY

Universities and Educational Organizations

Colorado School of Mines, Golden, CO
Columbia University, New York, NY
The Contemporary Physics Education Project, Palo Alto, CA
Drexel University, Philadelphia, PA
The Franklin Institute, Philadelphia, PA
Georgia Institute of Technology, Atlanta, GA
Hebrew University, Israel
Institute for Fusion Science, Austin, TX
Iowa State University, Ames, IA
Jackson State University, Jackson, MS
Johns Hopkins University, Baltimore, MD
Lehigh University, Bethlehem, PA
Massachusetts Institute of Technology, Cambridge, MA
Mid-Atlantic Eisenhower Consortium, U.S. Department of Education, Philadelphia, PA
Nagoya University, Nagoya, Japan
New York University, New York, NY
Oak Ridge Institute for Science and Engineering, Oak Ridge, TN
Princeton Center for Leadership Training, Princeton, NJ
Princeton University, Princeton, NJ
Sigma Xi, the Scientific Research Society, Princeton, NJ
Stevens Institute of Technology, Hoboken, NJ
The Tech Museum of Innovation, San Jose, CA
Trenton Schools System, Trenton, NJ
University of California, Irvine, CA
University of California, Los Angeles, CA
University of California, San Diego, CA
University of Illinois, Urbana, IL
University of Maryland, College Park, MD
University of Texas, Austin, TX
University of Tokyo, Japan
University of Toronto, Canada
University of Wisconsin, Madison, WI
University Fusion Association, Washington, DC

Technology Transfer

The Technology Transfer Office at the Princeton Plasma Physics Laboratory (PPPL) promotes transfer of technology developed at the Laboratory to the private sector. This is accomplished through a variety of programs, the main one being Cooperative Research and Development Agreements or CRADAs.

A CRADA is a contractual agreement between a Federal Laboratory and one or more industrial or university partners. CRADAs allow researchers from industry, universities, and Federal Laboratories to work on programs of mutual interest. With a CRADA, collaboration costs and the results of the project are shared between the Laboratory and the partner.

PPPL, which is funded by the U.S. Department of Energy (DOE), can enter into a CRADA if the CRADA research is in a programmatic area related to PPPL funding or if any office within DOE is willing to sponsor a particular CRADA.

PPPL is presently collaborating with six industrial partners on research and development projects and is actively seeking partners for new projects. These collaborations range from computer modeling to experimental applications in areas related to fusion science and plasma technologies.

Plasma Chemical Synthesis

PPPL is working with a major chemical company to explore the potential for synthesizing chemicals with commercially viable purity and yields that are of proprietary interest. The CRADA supports a proof-of-principle study in which a small-scale reactor will be constructed and a plasma created composed of the feedstock chemicals.

Advanced Computer Modeling Environment Project

This CRADA between PPPL and the Dynamic Research Corporation is directed at the development of a high-level computational environment that allows diverse computational modules to be rapidly and easily integrated into a computer model by the end user. Applications exist both in the fusion energy program and the commercial sector.

The American Textile Partnership — AMTEX

The American Textile Partnership (AMTEX) is a multi-laboratory Master CRADA that spans the entire textile industry throughout the United States. AMTEX has a number of subtasks of which the On-line Process Control Project (OPCon) is one. The Princeton Plasma Physics Laboratory and the Oak Ridge National Laboratory are collaborating with the Princeton Textile Research Institute to develop noncontact diagnostic instruments for use in U.S. synthetic textile manufacturing to assure that synthetic fibers conform to required specifications through measurements made in real time. PPPL has completed the second year of this CRADA with demonstration measurements made at the facilitates of several industrial partners.

Modeling for Chemical Synthesis and Waste Treatment

A great need has arisen in recent years for environmentally safe, efficient, and economical methods of treating both toxic and nontoxic waste. Induction-coupled plasma processing of waste is a promising alternative to conventional incineration because it is possible to tailor the chemistry to produce environmentally benign, or even usable, byproducts. PPPL, Drexel University's Center for the Plasma Processing of Materials (in Philadelphia, Pennsylvania), and Plasma Technology, Inc., a small business in Santa Fe, New Mexico, will perform spectroscopic diagnostics on an experimental reactor at Drexel. The goals are to identify the chemical species present and to make measurements of the concentrations of key species. These measurements will be computer modeled (using a chemical kinetics code) in order to identify the key reaction pathways and to suggest possible ways to improve the efficiency of the process.

Verification of a Tokamak-based Lithography Concept

This CRADA is between PPPL, the Massachusetts Institute of Technology's Plasma Science and Fusion Center, and Applied Physics Technologies, Inc. to investigate the possibilities for using tokamak X-ray radiation for applications in X-ray lithography. X-ray Lithography is used in integrated circuit fabrication and in biological studies.

Photocathode Electron Projection Lithography

PPPL and AT&T Bell Laboratories, Murray Hill, New Jersey, are researching Photocathode Electron Projection Lithography, an electron lithography technique that could be used to pattern semiconductors at the deep submicron level using the concept of magnetic compression. The objectives of this CRADA are to verify the concept (by direct numerical simulations of the electron trajectories) and to design a system with the desirable magnetic and electric field qualities for demonstrating engineering feasibility. An initial study indicates that the magnets needed for this system can be readily constructed using present-day superconductor technology.

CRADAs (Cooperative Research and Development Agreements) are an important mechanism for transfefring technology developed at government facilities to the private sector. One such CRADA between PPPL, Drexel University, and Plasma Technology, Inc. is the development of a novel technique that will covert toxic wastes and other materials to useful chemical products. The Tekna commercial plasma torch used in this process is shown above.

Other Technology Transfer Programs

In addition to CRADAs, the PPPL Office of Technology Transfer is engaged in other programs to promote the transfer of technology to industry, including Work for Others, Licensing of Inventions and Technologies, and Employee Exchanges. In Work for Others, industry pays for work performed at PPPL, while in the Employee Exchange program, researchers from industry assume a work assignment at the Laboratory or PPPL staff work in the industrial setting.

PPPL has a Work For Others agreement with Princeton Electronic Systems, a minority-owned, small business where PPPL staff will work with Princeton Electronic Systems employees to evaluate and develop monitoring technology for use in nuclear nonproliferation applications.

Licensing agreements for PPPL technologies are handled by Princeton University's Technology Transfer Office. Past royalty bearing licenses include those for XMACRO (software that was developed at the Laboratory for the transmission of documents in which many equations are embedded) and for the Chemical Waste Management and Report Generating System software.

Patent Awareness Program

The Laboratory supports and encourages innovation through its Patent Awareness Program. Through this program, staff receive a modest monetary compensation when a disclosure is filed and additional compensation when a patent is issued. In fiscal year 1996, two patents were issued, another patent was applied for, and twenty additional inventions disclosures were filed.

Graduate Education

Graduate students in the Program in Plasma Physics, Department of Astrophysical Sciences, Princeton University, in fiscal year 1996.

The Princeton Plasma Physics Laboratory supports graduate education through the Program in Plasma Physics in the Department of Astrophysical Sciences of Princeton University. Students are admitted directly to the Program and are granted degrees through the Department of Astrophysical Sciences. With more than 178 graduates since 1959, the Program has had a signifcant impact on the field of plasma physics, providing many of today's leaders in plasma research and technology in academic, industrial, and government institutions.

Both basic physics and applications are emphasized in the Program. There are opportunities for research projects in the physics of the very hot plasmas necessary for controlled fusion, as well as for projects in solar, magnetospheric and ionospheric physics, plasma processing, plasma devices, nonneutral plasmas, lasers, materials research, and in other emerging areas of plasma physics.

At the beginning of FY96, there were 42 graduate students in residence in the Program in Plasma Physics, holding between them one Department of Energy Magnetic Fusion Science Fellowship, one Hertz Fellowship, one Princeton/Hertz Fellowship, one National Science Foundation Fellowship, one Department of Defense National Defense Science and Engineering Graduate Fellowship, and one Princeton University Honorific Fellowship.

Five new students were admitted in FY96, two from the People's Republic of China, one from the Republic of Korea, and two from the

Students Admitted to the Plasma Physics Program in Fiscal Year 1996.

Student	Undergraduate Institution	Major Field
Gian Marco Felice	Massachusetts Institute of Technology	Nuclear Engineering
Ce Li	University of Science and Technology of China	Plasma Physics
Kyle Morrison	University of Florida	Physics, Math
Yuan Ping	University of Science and Technology of China	Physics
Seunghyeon Son	Korea Advanced Institute of Science and Technology	Physics, Math

U.S. Three students graduated in FY96, two receiving postdoctoral positions in plasma physics at the Princeton Plasma Physics Laboratory, one of whom won a prestigious postdoctoral research fellowship from the Department of Energy. One graduate took a position in private industry at ISYS Technology Corporation.

Three awards were given out this year, one to a 1994 graduate and two to present students. Dr. Michael A. Beer (1994 graduate) won the American Physical Society 1996 Simon Ramo Award which provides recognition to "exceptional young scientists who have performed original doctoral thesis work of outstanding scientific quality and achievement in the area of plasma physics." Mr. Mark C. Herrmann, a fifth-year graduate student, won the Princeton University Ray Grimm Memorial Prize in Computational Physics given to a graduate student of outstanding research achievements, academic merit, and creativity in the area of computational physics. Mr. Jonathan Menard, also a fifth-year graduate student, won the Princeton University Harold W. Dodds Honorific Fellowship for scholarly excellence.

First-year graduate students in the Program in Plasma Physics in 1996. Front row (l-r): Seunghyeon Son and Ce Li. Back row (l-r): Gian Marco Felice, Yuan Ping, and Kyle Morrison.

Recipients of Doctoral Degrees in Fiscal Year 1996.

Yanlin Wu		
	Thesis:	Wave-particle Interaction in Tokamak Plasmas
	Advisor:	Roscoe B. White
	Employment:	ISYS Technology Corporation
Zhihong Lin		
	Thesis:	Gyrokinetic Particle Simulations of Neoclassical Transport
	Advisors:	Wei-li Lee and William M. Tang
	Employment:	Princeton Plasma Physics Laboratory
Wonho Choe		
	Thesis:	Feasibility Study of Electron Injection for Tokamak Plasma Transport Control
	Advisor:	Masayuki Ono
	Employment:	Princeton Plasma Physics Laboratory

Jonathan Menard (left), a fifth-year graduate student, received the Princeton University Harold W. Dodds Honorific Fellowship, Dr. Michael A. Beer (middle), a 1994 graduate, won the American Physical Society 1996 Simon Ramo Award, and Mark C. Herrmann (right), also a fifth-year graduate student was awarded the Princeton Ray Grimm Memorial Prize in Computational Physics.

Under the PPPL-Trenton Partnership, Princeton University Student Volunteers tutor Trenton inner-city youth during the summer.

The Princeton Plasma Physics Laboratory's (PPPL) Science Education Program continued to build on its past successes during fiscal year 1996. In addition to continuing its history of offering long-term programs to teachers, students, and the community at-large, a number of new and creative initiatives were launched.

Community Outreach and Partnerships in Northern New Jersey

The Science Education Office at PPPL offered, for the first time in 1996, the Princeton Research Enrichment Program (PREP), a residential scientific enrichment experience for talented high school students. The Program is part of the Laboratory's outreach efforts in northern New Jersey which have led to a collaboration between the Stevens Technical Enrichment Program (STEP) of the Stevens Institute of Technology and the Princeton Plasma Physics Laboratory. PREP builds on the 25-year success of the Stevens Technical Enrichment Program and the unique capabilities of PPPL.

The goals of the six-week Princeton Research Enrichment Program are to build self-esteem, sharpen academic skills, and expose talented students to a scientific work environment. The main features of the Program include career explorations in science and engineering, scientific enrichment using real-world problems to teach scientific content, and hands-on research experience as part of a team of scientists, engineers, and technicians.

Students who are participants in the Pre-College Upward Bound Program at Stevens Institute of Technology are selected to participate in PREP. In 1996, seven students participated in the Program — five were from the Stevens Technical Enrichment Program and two were from Trenton Central High School. See the Table for a listing of the participants and their projects.

Community Partnership Development

With the goal of reaching significant numbers of Latino and African-American students, PPPL is collaborating with colleges and universities, community-based programs, and the systemic reform efforts of individual school districts to form partnerships to improve the science skills of students in several northern New Jersey communities including Jersey City, Bayonne, and Elizabeth. Laboratory scientists and staff work with teachers and students to enrich science curriculum and to engage students in inquiry-based science experiments.

Fusion Outreach Efforts

The Science Education Program staff participated in Science Teachers' Day activities and the Plasma Physics Energy Sciences Open House, which is sponsored by the American Physical Society Division of Plasma Physics as part of their Annual Meeting. Several PPPL volunteers took the opportunity to share their work and ideas with classroom teachers and students.

Interactive Plasma Physics Education Experience

The Interactive Plasma Physics Education Experience (IPPEX) was designed by a PPPL team drawn from the Laboratory's Physics, Computer, and Science Education Divisions to provide internet-based physics curriculum modules for middle and high school students on the World Wide Web. The IPPEX includes interactive WEB pages (the WEB address for IPPEX is: http://ippex.pppl.gov/ippex/) on matter, electricity and magnetism, energy, and fusion. The JAVA-based "Virtual Tokamak" and "Stability Module" allow the user to control several variables in order to study their effect on outcomes, such as total fusion power output, temperature, and plasma positioning. The IPPEX also includes pages that guide the student in analyzing data from the Tokamak Fusion Test Reactor. Funding for this effort was provided by the Center for Improved Engineering and Science Education at Stevens Institute of Technology through a National Science Foundation grant.

A new program, the Princeton Research Enrichment Program (PREP), was begun in 1996. Its goals are to help build self-esteem, sharpen academic skills, and expose talented students to a scientific work environment. The first participants in the Program were: front row (l-r), Dena Toney, Rashedah Fant, and Qianna Snooks and back row (l-r), Ledawn Hall, Alfred Okomo, Steven Gomez, and Tamara Coley.

Participants in the 1996 Princeton Research Enrichment Program.

Participant	High School	Mentor	Project
Tamara Coley	Kent Place School	Carl Szathmary	Tritium Testing at the Radiological Environmental Monitoring Laboratory
Rashedah Fant	Weequahic High School	Dennis Mueller	The Avoidance of Disruptions on TFTR
Steven Gomez	Academic High School	Charles Gentile	Tritium Breeding in Helium Gas using TFTR Neutrons
Ledawn Hall	East Orange High School	Robert Ellis, III	Radio-Frequency Antenna Development
Alfred Okomo	Highland Park High School	Robert Ellis, III	Radio-Frequency Antenna Development
Qianna Snooks	Trenton Central High School	Timothy Bennett	Construction of a Plasma Processing Device
Dena Toney	Trenton Central High School	Jerome Siegel	Development of a Database

National Teacher Enhancement Project

Fiscal year 1996 marked the second year of the three-year National Teacher Enhancement Project which is funded by the National Science Foundation and the U.S. Department of Energy. The Project is designed for middle school science and mathematics teachers and features an integrated mathematics, science, and technology curriculum, as well as assessment techniques and leadership skills.

The first year of the Project at PPPL concentrated on the content areas of genetics and molecular biology, terrestrial ecology, and biological and chemical testing of surface waters. In the second year, attention was given to the quality of the teacher's scientific thinking with emphasis placed on the impact of group leadership issues on group learning.

A number of significant changes were noted in the teachers' ability to design and conduct experiments in an orderly fashion, organize data in a way that allows meaningful conclusions to be drawn, and to critically analyze data and to defend their conclusions. These are seen as skills essential to a teacher charged with building the same skills in students.

New Jersey middle school science and mathematics teachers took part in a summer workshop as part of the National Teacher Enhancement Project that began in 1995.

PPPL-Trenton Partnership

The Trenton Partnership was established in November, 1990, when it became apparent that a band-aid approach to working with students in the Trenton School District would not be sufficient to foster true improvement in their performance in math and science. Since that time, the Science Education Program at PPPL has worked closely with the District, focusing on key elements of systemic reform.

During the first two years, Partnership endeavors centered on those activities that would be of immediate value to students and teachers and that would begin to establish a relationship of trust and understanding among all stakeholders.

Years three and four saw a major change in the Partnership's focus as the District began to undertake more long-term efforts in math and science reform. PPPL's technical assistance to the District was stepped up, teacher development activities by PPPL were greatly increased, and technical assistance was provided to the Curriculum Revision Committee. During fiscal year 1995, PPPL helped develop a curriculum activities book for grades kindergarten through sixth to be used to implement the newly developed science curriculum. In recognition of these efforts, the Princeton Plasma Physics Laboratory/Trenton Public Schools Partnership was awarded the New Jersey Exemplary State and Local Partnership Award by the National Center for Public Productivity.

To plan for FY96, a needs assessment was conducted by District administrators, teachers, and PPPL staff. Six key areas where additional work was needed were identified. These are teacher staff development in science and math, science magnet school enrichment, support for year-round school during the summer, in-school science advisors, summer interns in Trenton, and parental involvement and outreach. In 1996, focus was given to three of these needs: science magnet school enrichment, summer interns in Trenton, and parent involvement and outreach.

Undergraduate Research Programs

The Office of Fusion Energy's National Undergraduate Fellowship Program in Plasma Physics and Fusion Engineering was held again during the summer of 1996. Additional topics were offered and new lecturers participated in the week-long introductory course in plasma physics given at PPPL. Fifteen undergraduates from colleges and universities throughout the United States participated.

In FY96, PPPL hosted seven students from Historically Black Colleges and Universities, Women's Colleges, and Hispanic Serving institutions as part of the Undergraduate Research Opportunity Program which was started in 1995. Several of the students from both programs had the opportunity to join members of the American Physical Society Division of Plasma Physics in presenting the results of their summer research at the Annual Meeting held in Denver, Colorado, in the fall.

Participants in the 1996 National Undergraduate Fellowship Program in Plasma Physics and Fusion Engineering.

Participant	School	Research Location	Mentor
David Abrams	Harvard College	General Atomics and the University of California at San Diego	Professor William Heidbrink
James Aguirre	Georgia Institute of Technology	General Atomics	Dr. Charles Lasnier
Shamin Alpha	Yale University	Lawrence Berkeley National Laboratory	Dr. Andris Faltens
Jeffrey Andersen	University of California at San Diego	Rensselaer Polytechnic Institute	Professor K.A. Connor
Brian Demsky	University of Texas at Austin	Institute for Fusion Studies, University of Texas at Austin	Professor Herbert Berk
Lisa Dyson	Brandeis University	Princeton Plasma Physics Laboratory	Dr. W.W. Lee
Stefan Gerhardt	University of Wisconsin	Princeton Plasma Physics Laboratory	Dr. Hantao Ji
Thomas Humensky	Carnegie Mellon University	Princeton Plasma Physics Laboratory	Dr. Norton Bretz
Avi Kogan	Yale University	Princeton Plasma Physics Laboratory	Professor Nathaniel Fisch
Suparna Murkherjee	New York University and the Stevens Institute of Technology	Lawrence Livermore National Laboratory	Dr. David Hwang
Ryan Riddols	Massachusetts Institute of Technology	Massachusetts Institute of Technology	Professor M.C. Lee
Miroslav Shverdinovsky	Cornell Univeristy	University of California at Berkeley	Professor C.K. Birdsall
Stephen Walkauskas	Boston College	Massachusetts Institute of Technology	Professor Jay Kesner
Loretta Weathers	Michigan State University	University of California at Irvine	Dr. Frank Wessel
Melissa Wessels	Smith College	University of California at Berkeley	Professor Michael Lieberman

Awards and Honors

Laboratory Awards

Recognition Award

68th Annual Governor's Occupational Safety and Health Awards Program
for the Princeton Plasma Physics Laboratory's
"Outstanding Performance" for Safety

Recognition Award

68th Annual Governor's Occupational Safety and Health Awards Program
for TFTR Employees'
"Outstanding Performance" for Safety

Individual Honors

Michael A. Beer

1996 Simon Ramo Award
American Physical Society

Chio Z. "Frank" Cheng

PPPL Distinguished Research Fellow
Princeton Plasma Physics Laboratory

Taik Soo Hahm

Fellow
American Physical Society
Division of Plasma Physics

Philip Heitzenroeder

PPPL Distinguished Engineering Fellow
Princeton Plasma Physics Laboratory

Mark Herrmann

Ray Grimm Memorial Prize in Computational Physics
Princeton University

Janardhan Manickam

Fellow
American Physical Society
Division of Plasma Physics

Lewis Meixler

Excellence Award
Northeast Region of the Federal Laboratory Consortium

Jonathan Menard

Harold W. Dodds Honorific Fellowship
Princeton University

Ned Sauthoff
Fellow
American Physical Society
Division of Plasma Physics
and
Divisional Professional Leadership Award
IEEE United States Activities Board

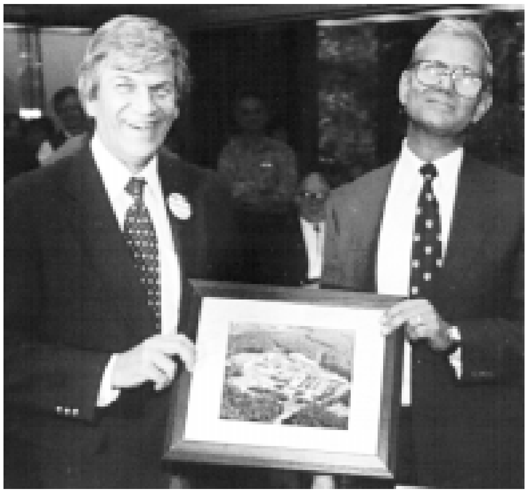
Robert Woolley
PPPL Distinguished Engineering Fellow
Princeton Plasma Physics Laboratory

Stewart Zweben
PPPL Distinguished Research Fellow
Princeton Plasma Physics Laboratory

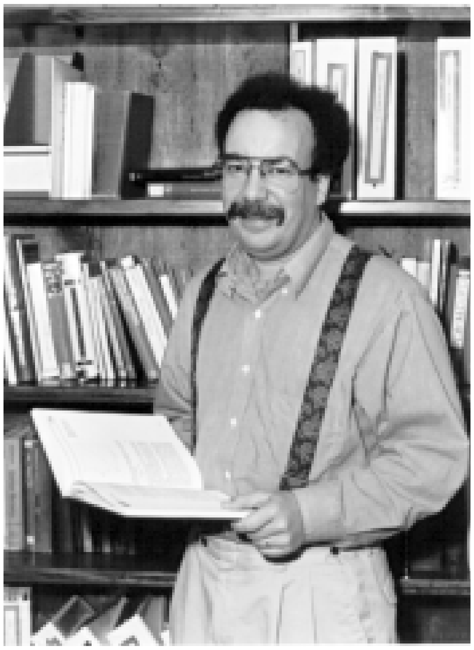
1996 PPPL Employee Recogntion Award Recipients

Honored by their co-workers for their "outstanding professional achievements and personal characteristics," twenty-eight PPPL employees received the newly created Employee Recognition Program Award in 1996. They are, from left (seated): Dori Barnes, Virginia Zelenak, Barbara Sarfaty, Dolores Lawson, Connie Cummings, and Christine Ritter; (standing) Lloyd Ciebiera, James Chrzanowski, John Krzywulak, J.W. Anderson, Larry Jones, Paul Kivler, Antonio Morgado, Kenneth Tindall, Richard Palladino, John Robinson, Michael Bell, and Lane Roquemore. Not pictured are Wilbert Barlow, Robert Cancel, Michael Diesso, John Garboski, Gerald Hart, Sue Hill, Subrahmanya "Raki" Ramakrishnan, James Taylor, Walter Weyman, and Raymond Whitley.

The Year in Pictures



Paul Rutherford stepped down as Associate Director for Research at PPPL in October after 30 years of service to the Laboratory, Princeton University, and the national and international fusion programs. PPPL Director Ronald C. Davidson (left) presents a photo of the Laboratory to Rutherford during the retirement party.



Robert Goldston, Head of the PPPL Research Council and formerly Chief Scientist for the Tokamak Physics Experiment, became Associate Director for Research at PPPL in October.

The Magnetic Reconnection Experiment (MRX) produced its first plasma in October. Shown at the celebration are, from left, Raymond Pysher, who helped on MRX, Masaaki Yamada, Head of the MRX Project, and MRX team members David Cylinder, Hantao Ji, and Scott Hsu.

U.S. Department of Energy Office of Energy Research Director Martha Krebs (left) toured the Tokamak Fusion Test Reactor during a visit to the Lab in November. In the photo, TFTR Project Head Richard Hawryluk leads the tour through the Test Cell. Behind Krebs and Hawryluk is PPPL Deputy Director Dale Meade.

Congressman Rodney Frelinghuysen visited the Laboratory in April. Frelinghuysen (left), a Republican representing New Jersey's 11th Congressional District, gets a tour of the Lab from PPPL Director Ronald C. Davidson.

In April, more than 40 girls visited the Laboratory for "Take Our Daughters to Work Day," which was a Director's Advisory Committee on Women activity that included demonstrations, a tour of PPPL, and hands-on learning with mentors.

During the fourteenth annual Patent Awareness Program Dinner in May, twenty-nine PPPL inventors were honored for their inventions. Among those who attended the ceremony are, from left, Thomas Kozub, Sylvester Vinson, Thomas Walters, Henry Kugel, Robert Woolley, Mark Herrmann, Forrest Jobes, John Desandro, Edward Nartowitz, Nathaniel Fisch, Leonard Kralik, Gary Gibilisco, Jan Wioncek, Stephen Paul, Szymon Suckewer, and Enoch Durbin.

Through a collaborative research agreement signed in June between PPPL and the Korea Basic Science Institute, PPPL is assisting in the planning and design of the Korean *Super-conducting* T*okam*A*k* R*esearch (KSTAR) facility. Through the collaboration, a team of Korean physicists and engineers from the KSTAR Project are working closely with a U.S. team of scientists. PPPL researchers working on the KSTAR Project include, from left (seated), James Sinnis and Wayne Reiersen and (standing) Robert Simmons and John Schmidt.*

Good food, sunshine, and plenty of camaraderie marked the PPPL Employee Appreciation Picnic Lunch in August. Catherine Saville (right) dishes up a plate as volunteers Joyce Bitzer and Masa Ono help out on the serving line.

PPPL Advisory Council

The Princeton Plasma Physics Laboratory Advisory Council advises Princeton University on the plans and priorities of the Laboratory. Members of the Advisory Council are appointed by the Board of Trustees and are chosen from other universities and organizations, and from the Board of Trustees. The Council meets annually and reports to the University President through the Provost.

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Covington and Burling

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Raytheon Corporation

Professor Robert W. Conn
Dean
School of Engineering
University of California, San Diego

Professor Jerome Friedman
Physics Department
Massachusetts Institute of Technology

Mr. Gerald Greenwald
(Trustee Associate)
Chicago, Illinois

Professor Robert A. Gross
Chapel Hill
North Carolina

Mr. Edwin E. Kintner
Norwich, Vermont

Dr. William L. Kruer
Lawrence Livermore National Laboratory

Dr. John Nuckolls
Lawrence Livermore National Laboratory

Professor W.K.H. Panofsky
Stanford Linear Accelerator Center

Dr. Paul-Henri Rebut
Commission of the European Communities

Dr. Andrew Sessler
Lawrence Berkeley National Laboratory

PPPL Oversight Committee

The Princeton Plasma Physics Laboratory Oversight Committee, chaired by the Provost, provides general oversight of the operations of the Laboratory, provides guidance and recommendations on Laboratory policies and priorities, and advises the Princeton University President on Laboratory matters.

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