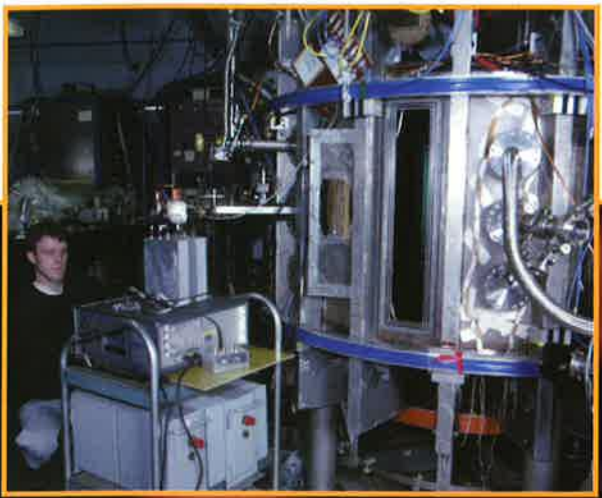
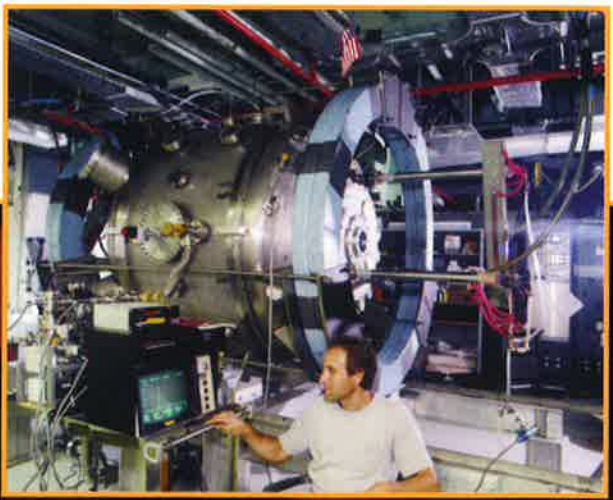
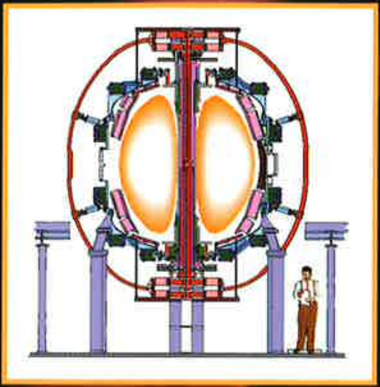
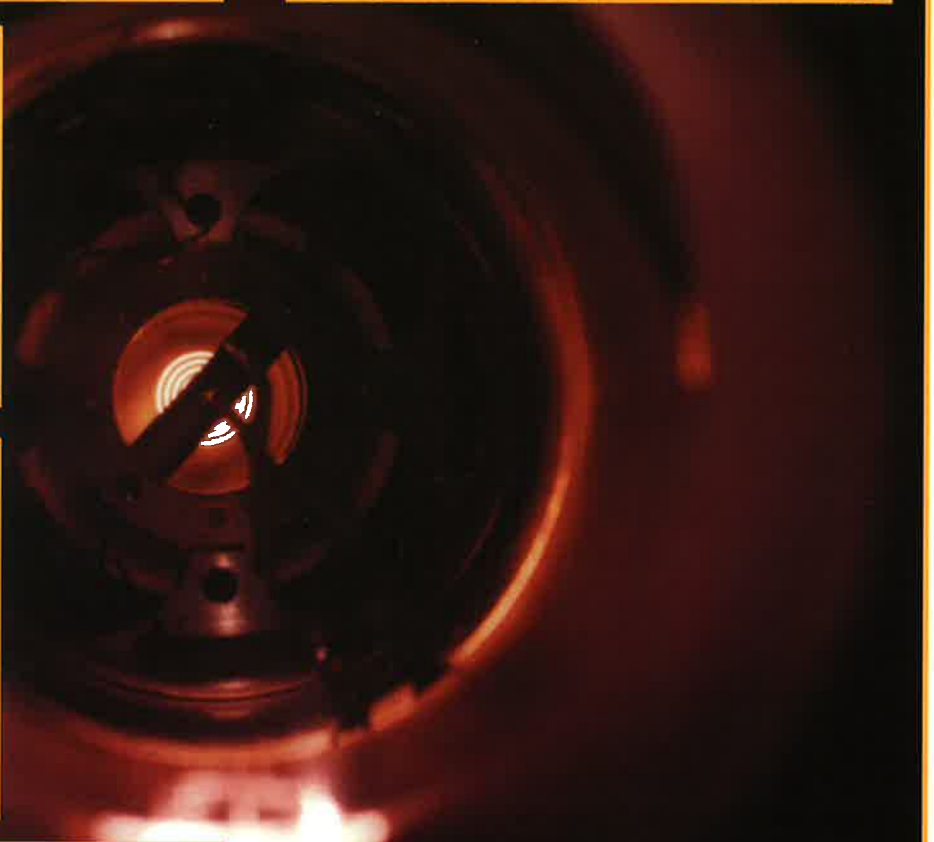
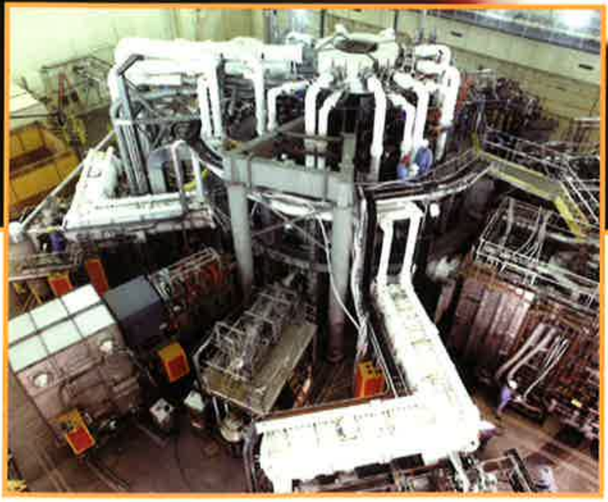








# 1997 Annual Highlights



PPPL
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 has been the site of the Tokamak Fusion Test Reactor which recently completed a historic series of experiments using deuterium-tritium fuel. A new innovative facility, the National Spherical Torus Experiment, is under construction.

PPPL is managed by Princeton University under contract with the U.S. Department of Energy. The fiscal year 1997 budget was approximately $65 million. The number of full-time regular employees at the end of the fiscal year was about 390, not including approximately 26 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, 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 plasma processing of materials and propagation of intense beams of ions. 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

Counter clockwise from upper right-hand corner: Magnetic Reconnection Experiment, Current Drive Experiment-Upgrade, schematic of the National Spherical Torus Experiment, artist's conception of the Korea Superconducting Tokamak Advanced Research device, and the Tokamak Fusion Test Reactor. In the background is the Electron Diffusion Gauge Experiment.

This publication highlights activities at the Princeton Plasma Physics Laboratory for fiscal year 1997 — 1 October 1996 through 30 September 1997.

## Mission Statement

*The U. S. Department of Energy's Princeton Plasma Physics Laboratory is a Collaborative National Center for plasma and fusion science. Its primary mission is to develop the scientific understanding and the key innovations which will lead to an attractive fusion energy source.*

*Associated missions include conducting world-class research along the broad frontier of plasma science and providing the highest quality of scientific education.*

## Vision Statement

*To create the innovations which will make fusion power a practical reality.*

## 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 . . .


Robert J. Goldston

The U.S. Department of Energy's Princeton Plasma Physics Laboratory (PPPL) is a collaborative national center for plasma and fusion science. Operated by Princeton University since its founding in 1951, the Laboratory has played a critical role in developing the experimental, theoretical, and technological advances that have led to the attainment of plasma conditions suitable for fusion energy production.

PPPL 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 experimental, theoretical, and computational studies of magnetically confined fusion plasmas and for the integrated design, fabrication, and operation of experimental plasma facilities, including magnets, power supplies, and plasma heating and diagnostics systems. Princeton University provides an outstanding institutional framework for a broad Laboratory-based program of education in plasma physics and related technology.

The purpose of the Annual Highlights Report is to present a brief overview of the Laboratory's research and programmatic accomplishments during Fiscal Year 1997 (October 1, 1996 through September 30, 1997). Included are the final experiments on the Tokamak Fusion Test Reactor (TFTR); design and component fabrication for the National Spherical Torus Experiment (NSTX), which is scheduled to begin operation at PPPL in April 1999; initial work on the conceptual development of a compact stellarator proof-of-principle experiment; contributions of PPPL to the design of the International Thermonuclear Experimental Reactor (ITER); and our significant progress in plasma theory, small-scale experiments, technology transfer, and science education.

The highlights in plasma theory feature a strong coupling to advances in computational simulation and modeling. This is an area which promises to be a growing part of the research portfolio of the Department of Energy. PPPL is well qualified to play a leadership role in computational initiatives both in fusion energy sciences and in crosscutting collaborations with other research disciplines.

TFTR produced its final plasma in April, 1997. Therefore, 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 marked the end of one very productive era for PPPL, we look forward to a strong, innovative program in plasma confinement, starting with the intermediate-scale NSTX device and expanding with the proposed addition of a compact stellarator. We also look forward to an invigorating program of national and international collaboration on tokamak and alternate concept experiments. Continued participation in the ITER process is a high priority for the Laboratory.

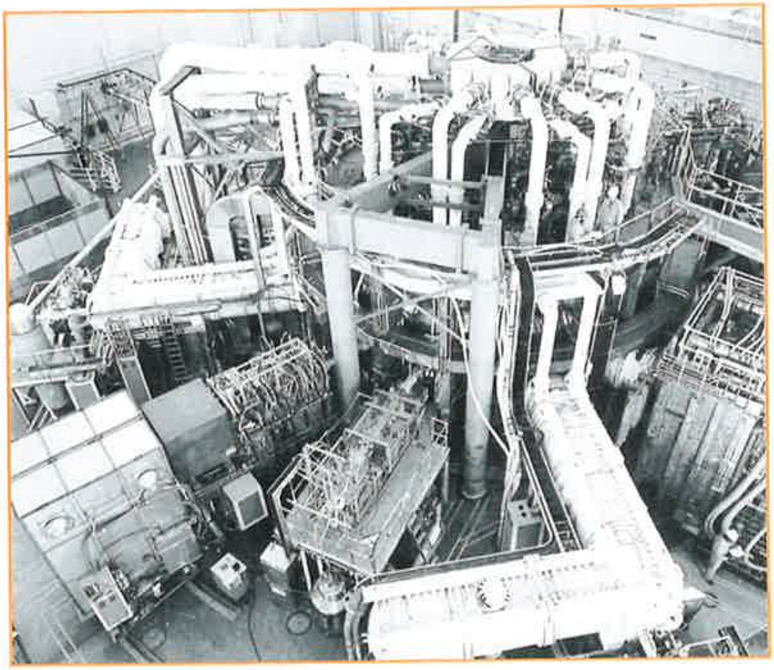
While the 1997 Annual Highlights Report emphasizes advances in fusion science and technology, it is important to recognize that fusion research is the principal engine that propels the development of plasma physics as a scientific discipline, with a very broad range of applications. The Laboratory's 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 applications beyond fusion science and engineering — ranging from plasma chemical synthesis to monitoring the properties of synthetic fibers, on-line, during their fabrication. At the same time, our involvement in these technologies helps provide the intellectual vitality for innovations in fusion science. As is fitting for such a center of intellectual creativity, the Laboratory also has a key educational role. This mission is reflected in our outstanding graduate program, our programs for undergraduate students, and our contributions to the improvement of science education at all levels.

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 continue to grow in importance.

Robert J. Goldston
Director

# TFTR

## Tokamak Fusion Test Reactor



Tokamak Fusion Test Reactor

The Tokamak Fusion Test Reactor (TFTR) completed its last series of experiments on April 4, 1997 after beginning operation on December 24, 1982. During nearly fifteen years of operation, more than 65,000 high-power discharges were run, including 23,500 discharges with neutral-beam-injection (NBI) heating and 6,300 discharges with radio-frequency (rf) wave heating. From the start of operation with deuterium-tritium (D-T) plasmas in December 1993, 1,031 plasma discharges were run either with tritium NBI or with tritium gas puffed into the plasma. Approximately 100 grams of tritium was processed through the tritium-handling system. Tritium operation in a closed cycle with cryo-purification of the exhaust from the plasma and neutral-beam injectors was successfully demonstrated.

In its early years, TFTR made major contributions to understanding the confinement and stability of plasmas with intense NBI heating, particularly in regimes with high fusion reactivity. The roles of fueling and plasma-wall interactions on confinement were clearly demonstrated. In the pioneering D-T experiments, TFTR investigated the physics of fusion alpha particles and the effects of isotopic mixture on the heating and confinement of plasmas in reactor-like regimes. More recently, through its unparalleled diagnostics and operational flexibility, the TFTR has furthered our understanding of the physics of anomalous transport and the possibilities for controlling it in advanced tokamak regimes.

### Upgrades in 1997

The 1997 fiscal year (FY97) began during a planned opening of the TFTR vacuum system for installation of the following upgrades to the heating, diagnostic and limiter conditioning systems in preparation for the final series of experiments.

- The radio-frequency group installed three new antennas to launch waves in the ion-cyclotron range of frequencies (ICRF). Two of these antennas were designed to launch fast waves, both for plasma heating and current drive, and one was designed to launch ion-Bernstein waves (IBW) directly. The new antennas were configured and ready for operation during the three month TFTR experimental run.
- A spectroscopic diagnostic to measure the poloidal flow of the

plasma was installed and then brought into operation in February 1997. Considering its complexity and requirements for precise alignment, remarkably little time was needed to commission and qualify this system. Data was acquired for a variety of TFTR plasma scenarios. Very exciting results showing large velocity shear were obtained.

- A major modification to the motional-Stark-effect (MSE) diagnostic (installed by Princeton Plasma Physics Laboratory in collaboration with Fusion Physics and Technology, Inc.) added viewing fibers and detector channels for polarimetric measurements on the Balmer-alpha line emission from the half-energy component in one of the neutral beams injected to heat the plasma. By analyzing the emission from both the full-energy and half-energy components in the beam, it was intended to measure both the poloidal magnetic field and the radial component of the electric field in the plasma. Commissioning and calibration of this system was completed at the beginning of March 1997 and data was acquired in several critical transport experiments. Combined with poloidal rotation measurements, these data are being used to understand transport barrier dynamics.
- A system for introducing lithium into the plasma periphery to modify the interaction of the plasma with the limiter was installed. This apparatus, known as DOLLOP, employed a repetitively pulsed Nd:YAG laser to eject an "aerosol" of lithium droplets from the surface of a cauldron of molten lithium at the bottom of the vacuum vessel. The DOLLOP system operated successfully in several experiments.

The opening of the vacuum vessel, which was internally contaminated with tritium from almost three years of deuterium-tritium operation, was completed with very low levels of personnel exposure and tritium release. The success of this activity demonstrates the feasibility of maintaining the large and complex tritium-handling systems which will be required for eventual fusion reactors.

After the vacuum vessel was closed and pumped down at the end of October 1996, preparations for the experimental run were carried out in November and December, including bakeout, glow-discharge cleaning, pulse-discharge cleaning, and disruptive-discharge cleaning, as well as conditioning of the neutral-beam sources and the new ICRF antennas. Full experimental operation resumed in January 1997.

On April 4, 1997 shortly before 2:00 A.M., the final experimental run on TFTR concluded. PPPL staff, family, friends, and reporters, gathered around the computer monitors in the Control Room for the results.

## Experiments to Characterize Internal Transport Barriers

The characterization of the physics of the transport barrier including the effects of flow shear and magnetic configuration was a major effort for FY97. Several experiments were conducted to study the transport barriers which form spontaneously during neutral-beam heating of plasmas with reversed magnetic shear. The aim was to measure the plasma flow characteristics for comparison with theories for the stabilization of the microturbulence responsible for the anomalous cross-field transport in tokamaks. These detailed experiments were made uniquely possible in TFTR by the combination of the poloidal flow diagnostic and the upgrade to the MSE diagnostic to measure directly the equilibrium radial electric field over part of the plasma. Extraordinarily detailed spatial and temporal data were obtained in plasmas which underwent transitions to the Enhanced Reversed Shear (ERS) mode, showing the occurrence of localized, transient precursors in the poloidal flow velocity in the region where steep gradients in the density, characteristic of the transport barrier, evolve. An example of the flow transient attending the ERS transition is shown in Figure 1. The MSE diagnostic detected corresponding perturbations which show the development of a region of strong radial electric field. These new diagnostics supplemented the existing diagnostics for the temperature, density and toroidal flow profiles to measure for the first time all terms in the radial force balance equation for the plasma equilibrium in a tokamak.

An experiment was also conducted on the scaling of the transition process with magnetic field to assess the contributions of different terms in the expression for the plasma shearing rate, the quantity suggested by theory to be critical for turbulence suppression. By exploiting the unique capability of TFTR to vary the NBI momentum input, the role of the shearing rate in the transition was confirmed at the lower fields. These, and other experiments using deuterium and tritium NBI to change the average ion mass, point to the necessity for developing and testing self-consistent theoretical models for turbulence suppression and have stimulated theoretical efforts in this direction. Measurements have also been made in L-mode, H-mode, and supershot plasmas to assess the role of flow shear in the enhancement of confinement occurring in the latter two regimes. Reports on these experiments and their analysis have been made at several scientific meetings, including the Transport Task Force Meeting (April 1997), the European Physical Society Conference (Berchtesgaden, Germany, June 1997), the International Energy Agency Tripartite Workshop on High-Performance Regimes [Joint European Torus (JET), U.K., June 1997), the H-mode Workshop (Kloster Seeon, Germany, September 1997), and the 39th American Physical Society Division of Plasma Physics Annual Meeting (Pittsburgh, PA, USA, November 1997).

Deuterium-tritium plasmas were studied in the reversed-shear regime during FY97. These experiments focused primarily on the effects of isotopic mass on the ERS transition and ERS confinement. Data on the confinement of the beam-injected deuterons and tritons in reversed-shear plasmas were presented at the International Atomic Energy Agency Technical Meeting on Alpha Particles in Fusion Research at the JET Laboratory, U.K., September 1997.

## Experiments to Improve Tokamak Performance

Improved tokamak performance was also an objective of the 1997 experimental run. Run time was devoted to the direct launch scheme for IBW heating. These experiments attempted to produce an internal transport barrier similar to the "core H-mode" previously observed with this heating scheme in the Princeton Beta Experiment-Modification. Two different launching schemes and two antenna phasings were explored in TFTR, resulting in an increased understanding of the difficulties of IBW excitation with loop antennas. Up to 1.7 MW of ICRF power was launched into the plasma although only a fraction of this was coupled into the IBW mode. With a coupled IBW power of about 0.4 MW, plasma heating was observed as well as the first direct measurement of sheared poloidal flow arising from IBW absorption. This result is of fundamental importance since it serves to test the theory of ICRF generation of sheared poloidal flow and suggests that, with suitable antenna development, this technique may be applicable to internal transport barrier control in advanced tokamak regimes.

An alternative method for generating IBW involves mode conversion of fast waves in a mixed-species plasma. The ability to drive plasma current by this mode-conversion process, Mode Conversion Current Drive (MCCD), had previously been demonstrated in mixed D-$^{3}$He plasmas in TFTR, but in D-T plasmas a competing absorption of the waves on $^{7}$Li impurity ions, present in the plasma as a result of lithium-pellet injection, had precluded

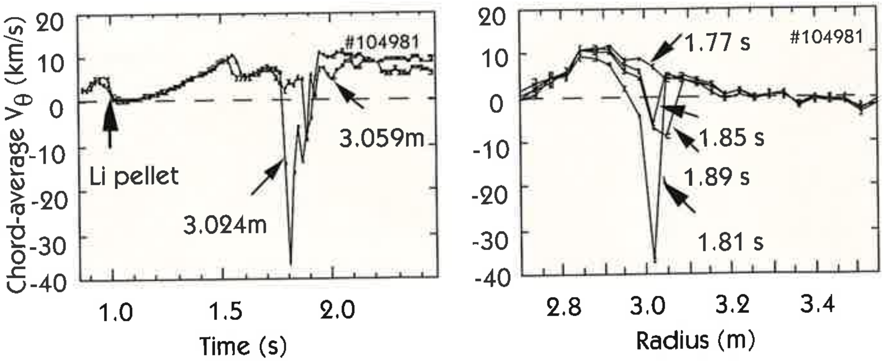


Figure 1. Measured poloidal flow velocity as a function of time (left) and space (right) in a plasma which undergoes a transition to the enhanced reversed shear (ERS) regime. The transition to improved confinement occurs after the development of the localized region of poloidal flow shear.

MCCD in D-T plasmas. The experiments in FY97 demonstrated that the damping on $^7$Li ions had been eliminated with the changeover to isotopically pure $^6$Li pellet injection and produced localized ion or electron heating through mode conversion in D-T plasmas. Initial results of the rf experiments were reported at the 12th Topical Conference on Radio-Frequency Power in Plasmas (Savannah, GA, USA, April 1997).

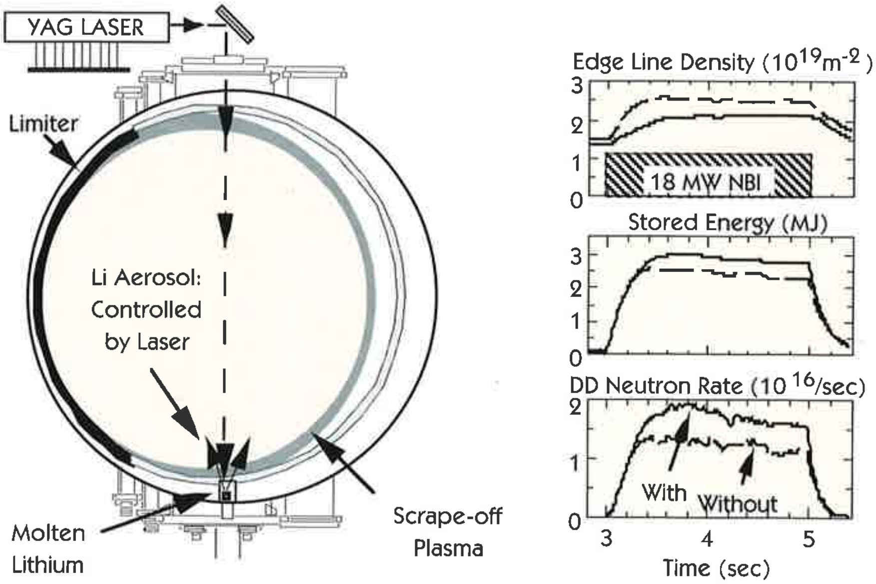


Figure 2. Left: Schematic diagram of the DOLLOP apparatus for introducing lithium into the plasma periphery from where it is deposited on the surface of the carbon limiter. Right: Comparison of two otherwise similar discharges with and without DOLLOP operating. The effect of the lithium coating is evident in the decreased edge density and the increased plasma stored energy and the rate of deuterium-deuterium fusion reactions.

In earlier experiments on TFTR, plasmas with highly peaked current profiles (high-$\ell_i$) had demonstrated improved stability, and a technique of plasma initiation at very low edge safety factor, $q_a \approx 2.3$, had been developed to achieve the high current needed for high fusion power production. The experiments in FY97 integrated this high-$\ell_i$ technique with two other elements of improved operation to demonstrate their compatibility for advanced tokamak designs. First, the confinement was improved using new methods of coating the limiter surface with lithium. Second, the peak power flux to the limiter surface was reduced by creating a radiating boundary layer, or mantle, around the plasma through controlled injection of impurities.

The DOLLOP system for limiter coating contributed to suppressing the particle influx from the limiter below the level produced by lithium-pellet injection alone. Figure 2 shows a schematic diagram of the system and data from two otherwise similar discharges with and without DOLLOP operating. The improvement brought on by the lithium coating is evident.

The radiative mantle was formed by injecting krypton or xenon gas into the plasma during neutral-beam heating. The injection was controlled by feedback to achieve a predetermined level of global radiated power. The fraction of input power radiated was raised to 90% in these plasmas with no reduction of the energy confinement time or fusion rate. With appropriate control of the radiated power level, these plasmas did not suffer deleterious thermally induced influxes from the limiter for the pulse duration of the NBI (typically 1 sec). By combining the high-$\ell_i$ startup with DOLLOP conditioning and the radiative mantle at the highest deuterium-tritium NBI power, a peak fusion power of 7.7 MW was produced in the final discharge on TFTR.

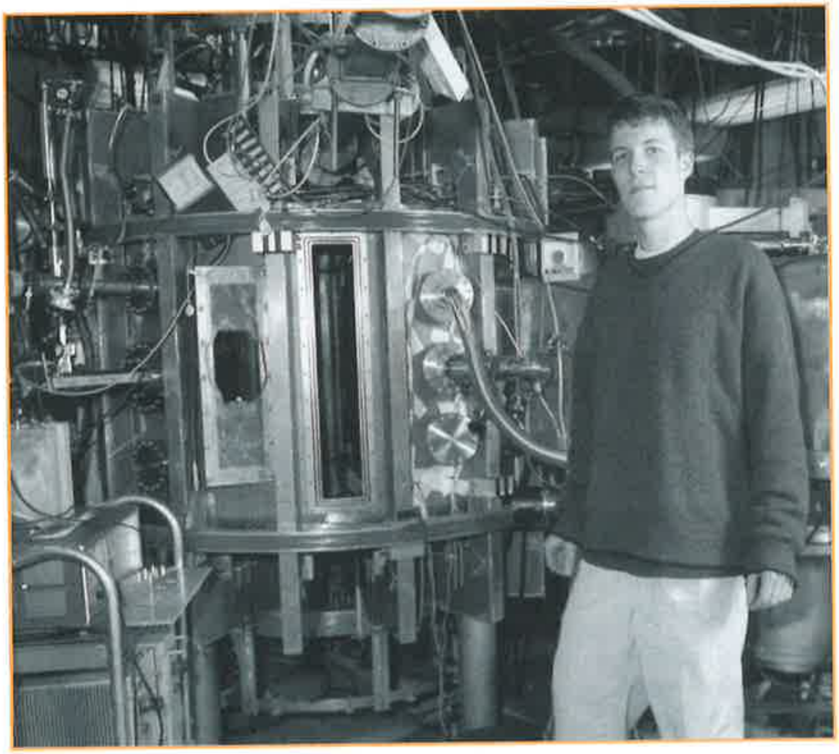
## Activities Following the TFTR Experimental Phase

Following the termination of the TFTR experiments, the tokamak and its ancillary systems have been placed in a safe shutdown condition in preparation for ultimate removal and disposal. The tokamak vacuum vessel has been purged of all but tenaciously held tritium by a combination of techniques including pulse discharge cleaning, bakeout and repeated moist-air purges.

The efforts of the TFTR physics group have turned to analysis of the immense body of high quality data accumulated in fourteen years of operation, particularly that taken during the nearly 3-1/2 years of operation with D-T plasmas. The initial phase of this data analysis has involved rapid communication of the results obtained from the final TFTR experimental run, focusing on the results from experiments with systems brought into operation during the run and the results from new diagnostics such as the poloidal rotation and radial electric field measurements. These results have been widely publicized in the community through colloquia presented at other laboratories and presentations at conferences and workshops in the U.S. and abroad.

# CDX-U

## Current Drive Experiment-Upgrade



Current Drive Experiment-Upgrade

The Current Drive Experiment-Upgrade (CDX-U) is the first fusion facility to conduct plasma heating experiments in a spherical torus (ST) with radio-frequency (rf) heating. The ST concept represents an alternative approach to the conventional tokamak for achieving fusion energy, and the name “spherical torus” comes from the shape of the plasma. As the ratio of the plasma radius (a) to the distance from the center of the torus to the middle of the discharge (R) becomes smaller, the plasma naturally elongates vertically and takes on a spherical shape instead of the doughnut shape of standard tokamaks. The compact nature of the ST could lead to a more economical fusion reactor, since much of the cost and size of a tokamak is determined by the size of the coils providing the necessary toroidal magnetic field strength.

The CDX-U plasmas (Figure 1) typically have a toroidal magnetic field $B_{TF} \approx 1$ kG, major radius $R \approx 32$ cm, and aspect ratio $A = R/a \geq 1.4$, where a is the plasma minor radius ($\approx$22 cm). The plasma current can be driven inductively with an ohmic-heating power supply that routinely provides about 30 millivolt-seconds. Typical discharges have plasma currents of 65 kA and electron densities in the $10^{12}$ cm$^{-3}$ range.

A key mission of CDX-U is to test concepts for future ST devices, such as the National Spherical Torus Experiment (NSTX) now under construction at the Princeton Plasma Physics Laboratory. In this capacity, the CDX-U group focused on two important ST-related research activities in fiscal year 1997 (FY97): (1) Investigation of plasma heating with rf “fast Alfvén” waves at high har-

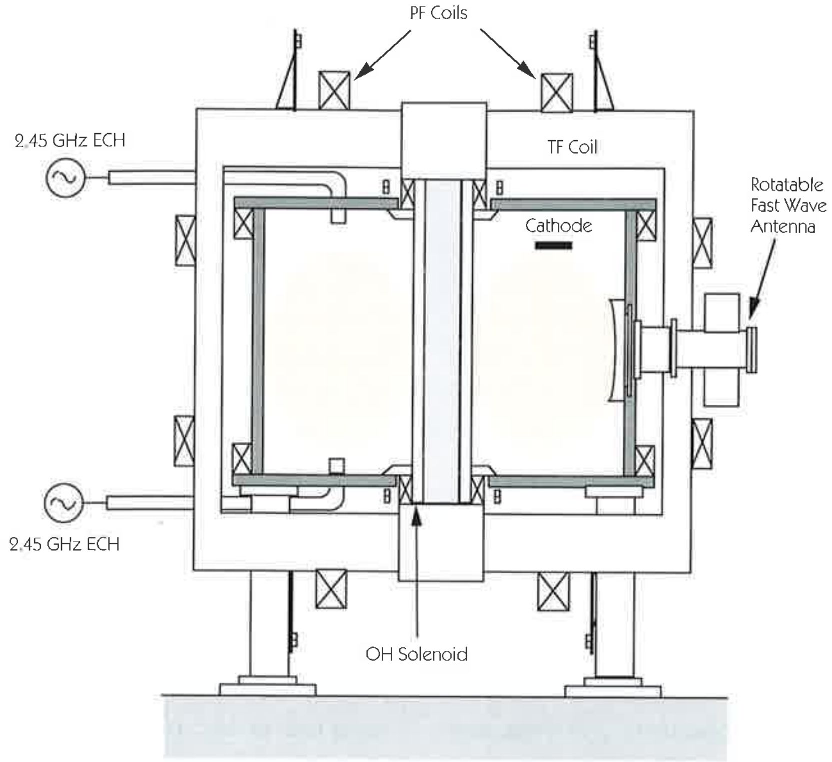


Figure 1. Schematic cross section of CDX-U, showing elongated plasma with low aspect ratio.

monics of the ion cyclotron frequency. (2) Development of plasma diagnostics to address specific ST measurement needs.

## Experiments in CDX-U with Radio-Frequency Waves

The low-aspect-ratio ST discharges that are most relevant to fusion reactors are expected to have high values of $\beta$, the ratio of the plasma pressure to the pressure of the confining magnetic field. Under these conditions, the plasma dielectric constant will be much larger than those in conventional tokamaks. In this case, rf waves launched at high harmonics of the ion cyclotron frequency are effectively absorbed in plasmas with $\beta$'s from 5% up to about 50%. The use of higher harmonic fast waves (HHFW) thus extends the range of plasma current drive in the ST.

The alignment of the antenna straps relative to the local magnetic field pitch is potentially critical to good coupling of the rf waves to the plasma. The extreme magnetic field line pitch makes the magnetic geometry of spherical torus plasmas differ from conventional tokamaks. The CDX-U device is particularly well-suited to investigate this dependence, since the magnetic field line angle is comparable to NSTX (≈35°).

These considerations motivated the installation of an antenna that is designed for high-frequency rf operation and is also unique in its rotating capability (Figure 2). The CDX-U system is designed for 100 kW at 12 MHz with variable phase between straps. Diagnostic techniques in support of rf experiments include magnetic probes and Langmuir triple probes to monitor wave fields and local electron temperatures and densities, interferometry for observing density modulation, and spectroscopy for detecting impurities.

Perturbations to the edge plasma were minimal when the rf power was applied, so there was no evidence for the excitation of slow rf waves in this region. A decrease in the power loading was observed as the antenna straps became parallel to the mag-

Figure 2. Interior of CDX-U vacuum vessel, showing rotatable antenna with insulating shield (light color).

netic field. The application of HHFW resulted in a modulation in the central plasma density, and its dependence on the antenna angle was consistent with the profiles of the wave field. On the other hand, the measurements also showed that a significant angle between the antenna and the magnetic field can be tolerated, so the careful control of the antenna orientation may not be critical in NSTX and other future ST devices.

Fast wave electron heating was observed with a Langmuir triple probe. Temperature data were taken on the side of the machine opposite to the antenna at a normalized minor radius of r/a = 0.6, or about two-thirds of the way out from the center of the plasma. The measurements indicate a temperature increase of about 10 eV, which corresponds to a 30% increase in the local electron temperature. A time trace of electron temperature and rf power for this measurement is shown in Figure 3.

Non-inductive startup, i.e., the ability to initiate a plasma without an ohmic-heating transformer to drive a toroidal current, is a necessity for an ST-based reactor. To take full advantage of the low aspect ratio in a compact ST, there would be no room in its center section for the ohmic-heating coils. For this reason, discharge initiation with the HHFW system is being tested in CDX-U.

Plasma ionization in CDX-U is usually effected with a separate rf system for electron cyclotron resonance heating (ECRH). The latest results demonstrated non-inductive startup with HHFW alone, and plasma densities up to $\approx 10^{12}$ cm$^{-3}$ were obtained. This is about an order of magnitude higher than the values obtained previously with ECRH alone. These experiments will be repeated with additional rf sources operating near the ion cyclotron frequency. Using this lower frequency, it should be possible to achieve plasma densities in the $10^{13}$ cm$^{-3}$ range.

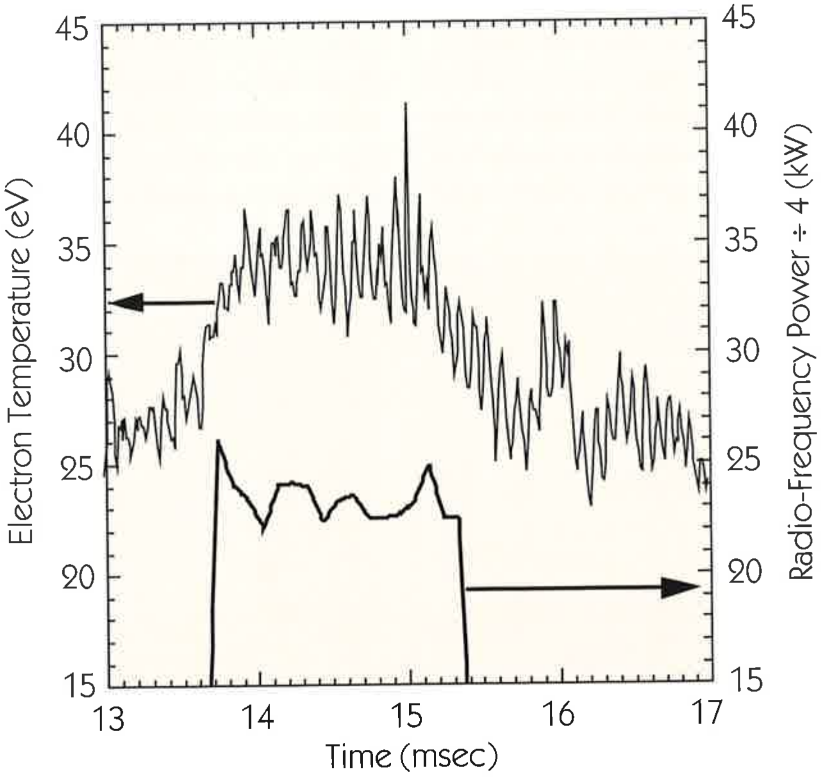


Figure 3. Time dependence of radio-frequency power and electron temperature during higher harmonic fast waves heating.

## Plasma Diagnostics

Confinement improvement in the ST depends on the successful coupling of the rf power to the plasma, and an understanding of the physical basis for its effectiveness as reflected in the temperature and density profiles and/or the magnitude of the fluctuation spectrum. Since techniques such as rf induction of sheared flow layers will result in radially localized reduction of transport (i.e., transport barriers), detailed profile measurements are needed to observe their local effects on the gradients and/or fluctuation levels.

A proof-of-principle test of tangential phase contrast imaging (PCI) for core fluctuation measurements was completed on CDX-U in FY97. Until now, PCI systems integrated over radial and poloidal structures due to their vertical views. This problem was eliminated, however, by the unique tangential geometry of the diagnostic on CDX-U (Figure 4). Image recovery and localization of spatial structures were demonstrated by the observation of a clear wavenumber cutoff in a very strong broadband signal, and large scale coherent features in the plasma core that were well-correlated with

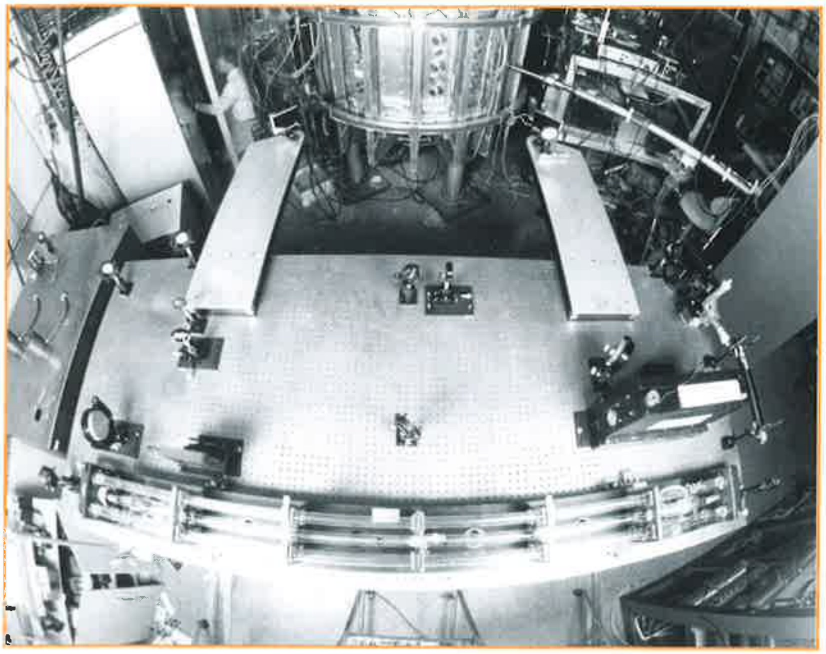


Figure 4. Layout of tangential phase-contrast-imaging diagnostic, showing the laser, focusing elements, and detector array on a movable optical table.

results using other diagnostic techniques. Improvements to the PCI that are under consideration include a more reliable laser and additional detectors for two-dimensional imaging of fluctuations.

For edge fluctuation measurements, standard filtered photodiode detectors will not be effective because their signals are dominated by the emission from the plasma core. To avoid this problem, arrays of multi-layer mirror (MLM) detectors are planned for NSTX. The X-ray energies are determined from the angle of the Bragg scattering off of the MLM, so the detectors avoid a direct view of the discharge.

A prototype detector for measuring the C V emission at 40.5 Å was successfully tested in FY97 on CDX-U by collaborators from Johns Hopkins University. A scan of the mirror angle around the C V line showed a spectral resolution of 1.3 Å, and the time evolution of the signal matched the data from a photodiode detector with a 30-90 Å filter (Figure 5). Poloidal MLM arrays will also be useful during the start-up phase, since plasma parameters can be determined from the ultrasoft X-rays emitted when the discharge is still relatively cool.

## Future Plans

Several improvements to the CDX-U facility are planned during FY98 to improve plasma performance. The toroidal field, vertical field, shaping field, and ohmic supplies will all be upgraded to permit longer pulse durations at higher plasma currents. The capacitor banks for the toroidal field, vertical field, and shaping coils will be replaced by power supplies, cabled from units that presently exist nearby for the Princeton Beta Experiment-Modification (PBX-M). These changes will not only extend the plasma duration, but are expected to enhance greatly the quality of the discharge "flattop" for transport studies.

With the modifications to the toroidal field supply, the field is expected to increase to 2.3 kG, with a "flattop" of 100 msec. The new power supplies for the vertical and shaping fields should be more than adequate for a doubling of the ohmic current, from 65 kA to 125 kA. The ohmic supply will still be based on capacitor banks, but the upgrades will allow the discharge duration to exceed 25 msec at the higher ohmic current.

The control of impurities is a critical issue for all magnetic confinement devices. For this purpose, low-Z plasma facing components and titanium gettering have been used in CDX-U. In addition, a Boron Low Velocity Edge Micropellet Injector is under development, and studies of its effectiveness are planned with diagnostics that include a filtered gated TV camera, bolometry, visible spectroscopy, and soft X-ray arrays.

The low toroidal fields and core plasma densities common to the ST preclude electron temperature measurements based on standard electron cyclotron emission techniques. Theory suggests, however, that to the electrostatic Electron Bernstein Wave, the CDX-U plasma looks like a blackbody emitter. Studies of the Electron Bernstein Wave should then allow proof-of-principle tests of both electron heating and electron temperature measurements, and the latter diagnostic application would augment the multi-point Thomson scattering system planned for CDX-U. Components from the Tokamak Fusion Test Reactor

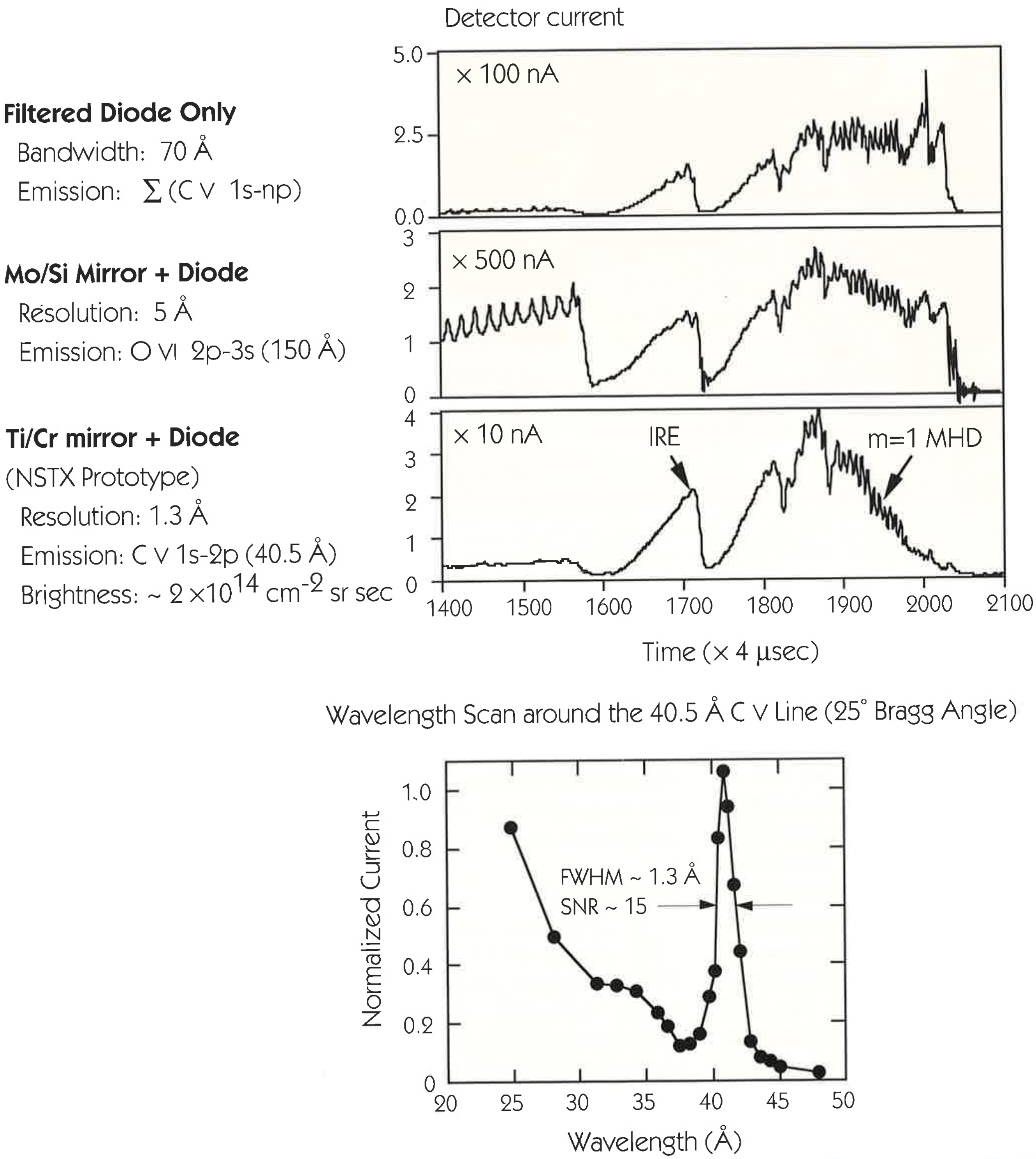


Figure 5. Measurements with a multi-layer mirror detector, showing good spectral resolution of the carbon-impurity line radiation and a time response comparable to standard photodiode detectors.

(TFTR) will be used to replace the existing single-point, multi-pass Thomson scattering diagnostic with a system capable of ten spatial measurements.

Additional high-power radio-frequency sources will be added to permit investigation of heating and non-inductive plasma startup in the ion cyclotron range of frequencies. Heating scenarios that involve the direct launch of Ion Bernstein Waves, mode conversion, and minority ion heating will also be studied.

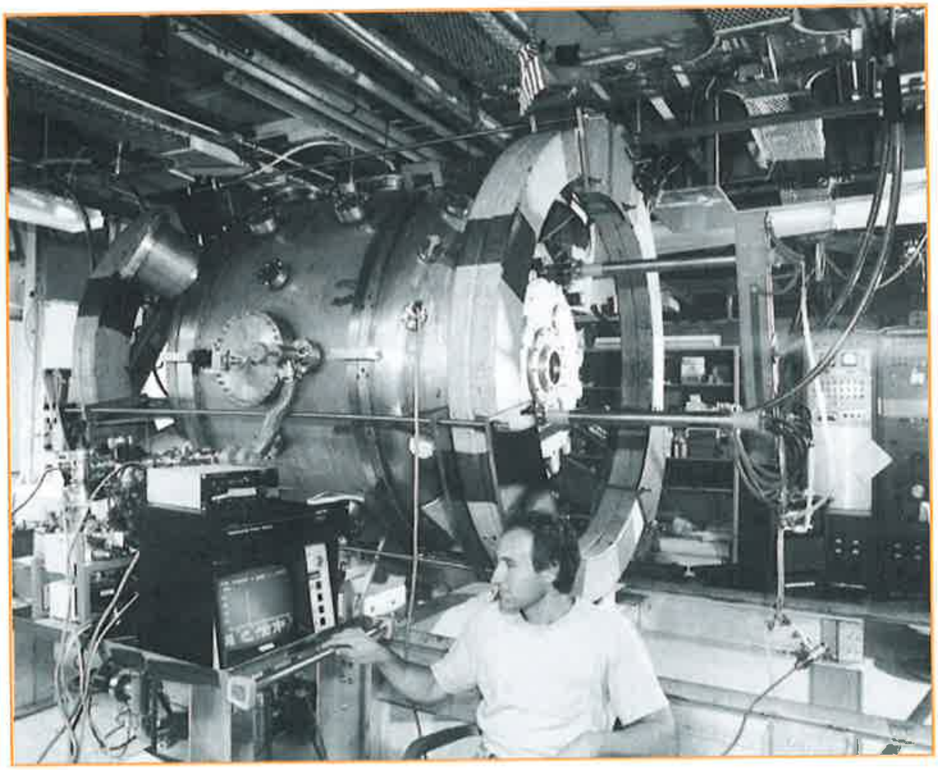
## Collaborations and Graduate Studies

The CDX-U project participated in ongoing collaborations with the A. F. Ioffe Physical-Technical Institute, St. Petersburg, Russian Federation, the Hebrew University, Israel, and the Johns Hopkins University, Baltimore, Maryland in rf physics and diagnostic development. In addition, CDX-U scientists worked actively with ST researchers from several institutions, including the National Institute for Fusion Science, Japan, and the Small Tight Aspect Ratio Tokamak (START) experiment at the Culham Laboratory in England.

The CDX-U device continued in its role as an excellent experimental plasma physics facility for graduate student training. Two graduate students from the Plasma Physics Program of the Princeton University Department of Astrophysical Sciences are continuing their doctoral research on CDX-U, and two first-year graduate students from the Princeton University Department of Physics began rf experiments during FY97. In addition, Ernest Lo defended his Ph.D. thesis in August, 1997. His thesis was entitled “Tangential Phase Contrast Imaging Diagnostic for Density Fluctuation Measurement on CDX-U.”

# MRX

## Magnetic Reconnection Experiment



Magnetic Reconnection Experiment

The Magnetic Reconnection Experiment (MRX) was built to study magnetic reconnection as a fundamental plasma process in a controlled laboratory environment. Magnetic reconnection — the topological breaking, annihilation, and reconnection of magnetic field lines — occurs in virtually all plasmas, both in the laboratory and in nature.

Despite its omnipresence, reconnection is not a well-understood phenomenon. In laboratory fusion plasmas, reconnection manifests itself as "sawtooth" oscillations in electron temperature and ultimately degrades plasma confinement. In nature, reconnection plays an important role in the dynamics of solar flares and in the origins of the aurora borealis. In recent years, the solar satellite Yohkoh has produced remarkable pictures of the Sun and has provided the best evidence yet that reconnection is involved in solar flare energy release. However, the rate of energy release is a mystery, unaccountable by current understanding of reconnection physics. The observed "fast reconnection" has made magnetic reconnection a very active area of research.

Experiments on MRX have provided crucial data with which the theoretical and observational research communities can compare their work. Already, cross-disciplinary interactions have led to fertile discussions and useful reassessments of the current understanding. Indeed, experimental research on MRX has triggered renewed interest in magnetic reconnection unseen for some decades.

The design and construction of MRX were completed entirely at the Princeton Plasma Physics Laboratory. Vacuum vessel hardware and data acquisition electronics from past experiments were used. The small size and rich plasma physics of MRX make it an ideal facility on which to study basic science and to train graduate students. Because of the strong impact of this experiment on many fields of research, MRX is jointly funded by the National Science Foundation, the National Aeronautics and Space Administration, the Office of Naval Research, and the United States Department of Energy.

## Research Objectives

The primary objective of experiments on MRX is the comprehensive analysis of magnetic reconnection which is crucial for understanding fusion plasmas, as well as solar and magnetospheric plasmas. The analysis focuses on the coupling between microscale features of the reconnection layer and global properties such as driving force, MHD (magnetohydrodynamic) flows, and the third component of the magnetic field.

In particular, MRX has the following research goals:

- Experimentally evaluate two-dimensional theoretical models.
- Determine the circumstances under which three-dimensional effects will dominate.
- Study global MHD issues including evolution of magnetic helicity.
- Identify the mechanisms by which magnetic energy is converted to plasma kinetic and thermal energy.
- Investigate the role of non-MHD physics in the reconnection layer.

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 lead directly to improved understanding of the physics of solar flares.

## Experimental Setup

Two plasma toroids with identical toroidal currents are formed using inductive electric fields generated from two sets of coil windings. The two plasma toroids are then merged together via their mutually attractive force and an applied external magnetic field. MRX was designed to achieve a variety of merging geometries and mag-

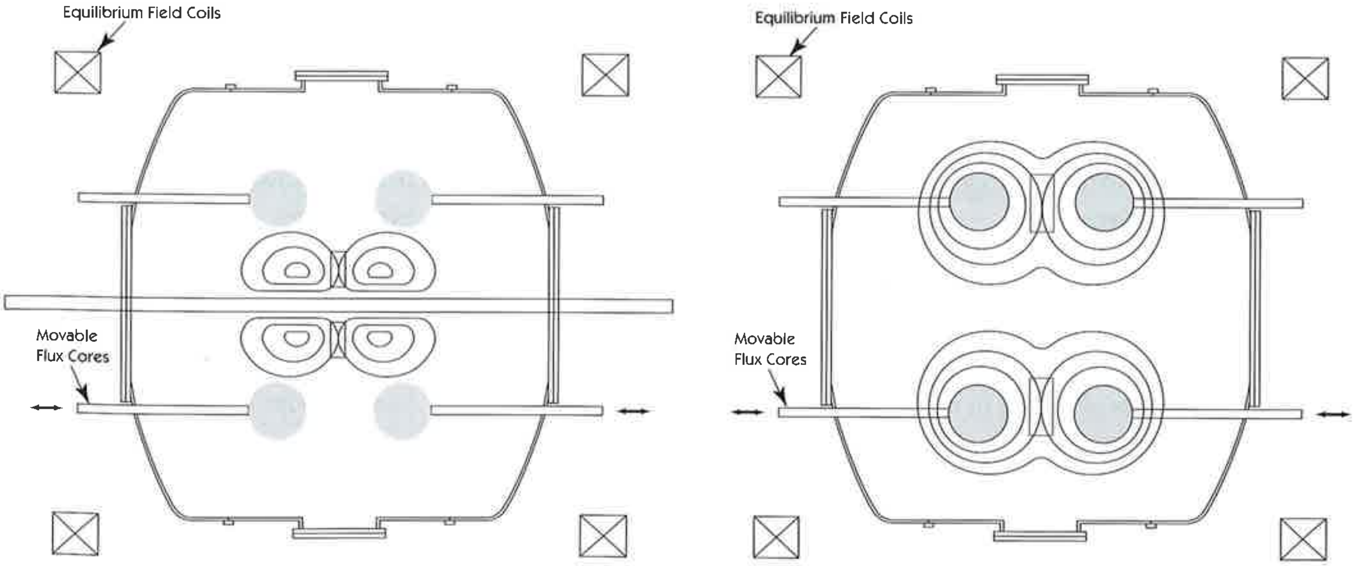


Figure 1. Cross-sectional view of MRX, illustrating the vacuum vessel, internal coils, and external coils. Plasma merging experiments using spheromaks (right) or annular plasmas (left) can be utilized to study local reconnection in the boxed regions.

netic field topologies as shown in Figure 1.

A set of carefully chosen diagnostics provides insight into the physics of magnetic reconnection and real-time monitoring of MRX plasmas. These include Langmuir probes (electron density and temperature), electrostatic energy analyzers and spectroscopy (ion temperature and flows), and arrays of magnetic probes (spatial profiles of local magnetic field vector). Installation of a laser-induced fluorescence diagnostic for nonperturbative measurements of local ion energy distribution is being considered.

## Results

In nature, as well as in most laboratory experiments, magnetic reconnection occurs in inherently three-dimensional geometries. However, theoretical models of magnetic reconnection are largely two-dimensional and therefore unable to capture the complete physics of a three-dimensional process. One of the first issues addressed in this experiment was the effect of the third magnetic field component on the reconnection speed and on the local features of the reconnection layer.

It was found that the presence of a strong toroidal field reduced the reconnection speed by a factor of three. As shown in Figure 2, a double-Y shape was observed in reconnection layers in which the toroidal field was very small or nonexistent (null-helicity), and an O-shaped region was observed in reconnection layers in which the toroidal field was substantial and on the order of the poloidal magnetic field (co-helicity). The current sheet thickness was verified with a high-resolution (5 mm) magnetic probe array and found in the null-helicity case to be as thin as 1 cm, which is approximately equal to the ion gyroradius and much less than the machine size.

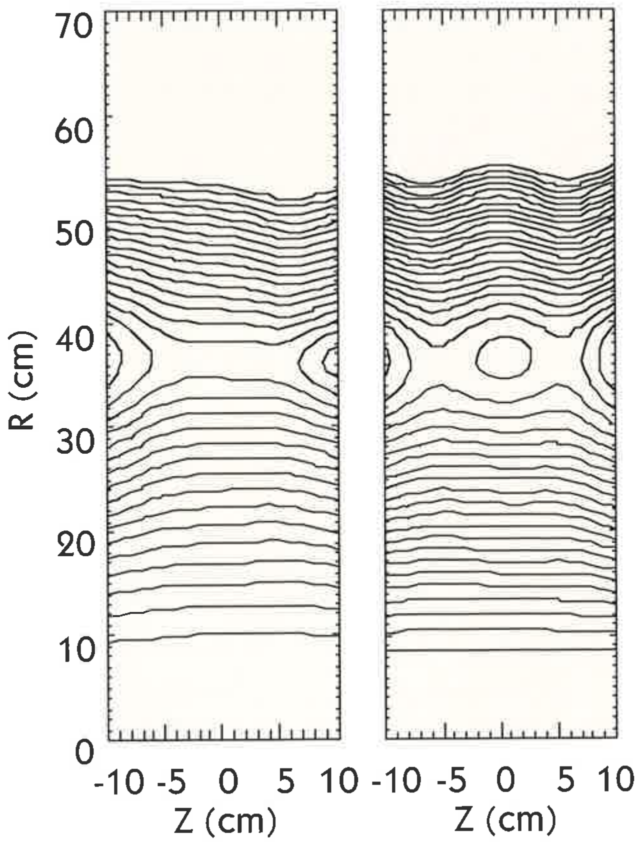


Figure 2. Experimental measurements of poloidal magnetic flux contours, indicating a "double-Y" shaped reconnection region for no toroidal field (left) and an "O-shaped" reconnection region for strong toroidal field (right).

These findings may play an important role in interpreting observational data from the solar surface and the magnetosphere.

The well-known Sweet-Parker model of magnetic reconnection predicts reconnection rates faster than that of resistive decay but much slower than those observed in solar flares. The model is a resistive magnetohydrodynamic model and assumes a two-dimensional, incompressible, and steady-state plasma. Despite these constraints, however, the model captures many of the essential local features of the magnetic reconnection layer. For forty years, the merits and shortcomings of this and other more elaborate models have been debated. Recently, the first laboratory experiments on the Sweet-Parker model were performed on MRX.

The experimental data indicated a reconnection speed consistent with a generalized Sweet-Parker model including the effects of plasma compressibility, finite pressure in the downstream region of the field lines, and "anomalous" plasma resistivity.

Compressibility allows more incoming plasma to accumulate in the current sheet, leading to a slight enhancement in reconnection speed over the classical Sweet-Parker speed. Conversely, finite downstream pressure hinders the outgoing plasma, leading to a reduction in plasma outflow speed and hence reconnection speed. The measured plasma resistivity was found to be enhanced over the classical Coulomb-collision value by up to a factor of ten; this enhancement is thought to play a crucial role in determining the reconnection rate.

Testing of the Sweet-Parker model in a laboratory experiment is an important first step in sorting out the essential physics behind "fast reconnection." However, much research must be performed before any definitive answers can be obtained.

## Future Work

Future work will address the source of the enhanced resistivity, including the role played by waves, instabilities, and turbulence. Concurrently, studies are planned to investigate the detailed mechanisms by which magnetic energy is converted to plasma kinetic and thermal energy. The results from these efforts should bring us closer to understanding magnetic reconnection, a fundamental process behind many spectacular natural displays such as the aurora borealis.

# Fusion Theory and Modeling

The fusion energy sciences mission of the Theory Department at the Princeton Plasma Physics Laboratory (PPPL) is to help provide the scientific foundations for establishing magnetic confinement as an attractive, technically feasible energy option. The Department generates the theoretical physics knowledge required for realistic extrapolation of present experimental results and suggests new approaches to improve performance. This involves the innovative development of better calculation capabilities, together with applications of the best theoretical tools to interpret and design experiments.

Important contributions to understanding the physics of plasma transport, MHD, and energetic particle behavior are reminders of the role theory can play in the fusion sciences program. These achievements underscore the fact that many of the advances in the field have resulted from an improved understanding of the basic mechanisms involved in toroidal confinement and not just from the development of empirical rules for scaling. Continuing improvements in operating regimes in magnetically confined plasmas and in diagnostic techniques should enable even more realistic comparisons of experimental results with theoretical models. As more reliable physics-based models emerge, it is expected that the pace of breakthroughs will be accelerated by more efficient harvesting of key results from experimental facilities and from identification of attractive new approaches and the associated designs for new facilities.

## Scientific Contributions

Endorsements and requests for enhanced collaborations in both tokamak and alternate concept research areas by the national and international fusion research community have been stimulated not only by the PPPL Theory Department's record for generating key seminal concepts, but also by its development and maintenance of the most comprehensive system of toroidal design and analysis codes. Examples of progress in the fusion program enabled by scientific results from the Department include:

- The powerful 3-D nonlinear MHD analysis capabilities in the M3D multi-level code package have been effectively utilized to test new ideas relevant to advanced tokamak scenarios (see Figure 1). The multi-level capabilities include resistive MHD, two-fluid, and hybrid (MHD background with gyrokinetic energetic particles) models.
- Progress has been made in the stellarator area during the past year with the identification of favorable neoclassical transport properties of highly symmetric configurations and with the provision of guidance on the level of allowable ripple. Configurations have been found which are stable at a beta of 7% with the wall at twice the plasma radius (effectively absent). Equilibrium studies of the MHH2 configuration have determined the dependence of the equilibrium beta limit on the pressure profile and indicate that for appropriate profiles the equilibrium beta limit can exceed 4%.
- A definitive paper in the axisymmetric MHD area was

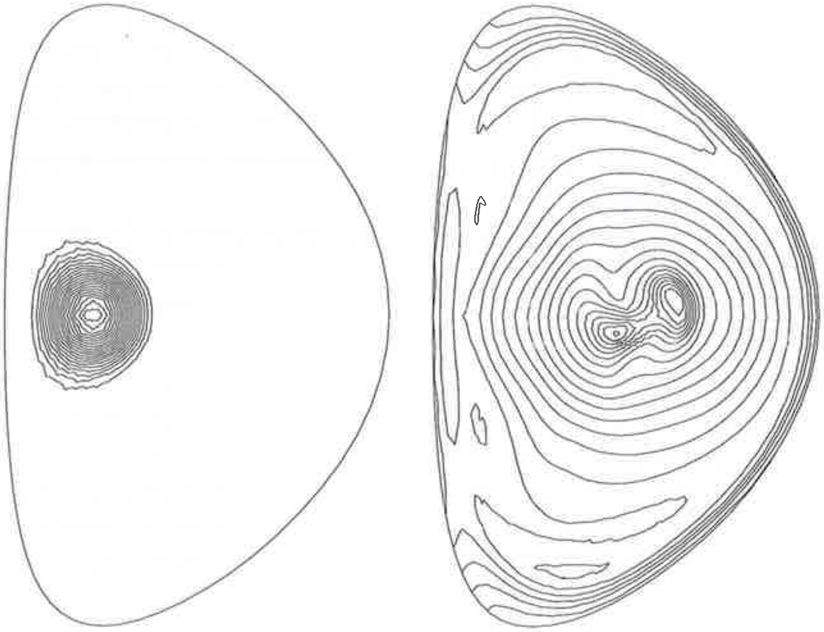


Figure 1. Numerical simulation of pellet injection using the M3D multi-level code package. The center of the dark mass in the left-hand figure represents a pellet injected on the inboard side of a tokamak plasma. The right-hand figure shows that the pellet is moving closer to the plasma center — due to a three-dimensional Shafranov-type shift which is supplemented by fast magnetic reconnection. This effect has explained the results of pellet-injection experiments: inboard-side injection is more favorable than outboard-side injection.

completed on vacuum calculations in an azimuthally symmetric geometry. Applications of these calculations included important collaborative design efforts on the role of external MHD modes and possible passive or active feedback stabilizing schemes (see Figure 2) for the proposed Korean Superconducting Tokamak Advanced Research (KSTAR) machine.

- Contributions in the area of disruption modeling were made with the completion of a simplified analytic halo current model which is supported by results from 3-D numerical simulations using the MH3D code. Initial applications are promising in that the observed dependence of the toroidal peaking on halo current fraction correlates well with trends from the International Thermonuclear Experimental Reactor (ITER) disruption database.
- Comprehensive linear microinstability calculations for high-n modes (via the FULL code) have been extended to include an improved model for sheared rotation and applied to representative cases from the TFTR (Tokamak Fusion Test Reactor). The results are consistent with, and help to justify, the heuristic criterion for complete stabilization: that the shearing rate be comparable to or larger than the linear growth rate.
- Realistic assessments of the neoclassical transport properties in magnetically confined plasmas have been enabled by the development of the 3-D gyrokinetic code GNC which properly represents the finite-orbit excursion of the ions.
- The state-of-the-art NOVA-K code, which analyzes stability properties of low- to medium-n Toroidicity-induced Alfvén Eigenmodes (TAE), has now been improved to include full drift-orbit width and finite Larmor radius effects. Collaborative applications to JT-60U have been very productive. For higher-n TAE relevant to large systems such as the ITER, a new stability code, HINST, has been developed. A quasi-linear (ORBIT-Q) and a full nonlinear kinetic-MHD (MH3D-K) simulation code that analyze energetic particle interaction with TAE's and associated particle transport have also been developed. Single-particle-orbit studies utilizing the ORBIT code have been productively applied in planning for research on the National Spherical Torus Experiment (NSTX) and for the analysis of TFTR deuterium-tritium experiments.
- Development of a hybrid fluid, Monte Carlo treatment of the plasma neutrals now permits efficient simulation of the full range of neutral transport regimes anticipated for reactor-relevant divertors. The coupling between DEGAS 2 and the fluid neutral transport model is a natural extension of the coupling with the fluid plasma codes, is designed to be adaptive, and is nearly optimal for both halves of the computation. DEGAS 2 simulations of H-alpha detectors in the Alcator C-Mod machine at the Massa-

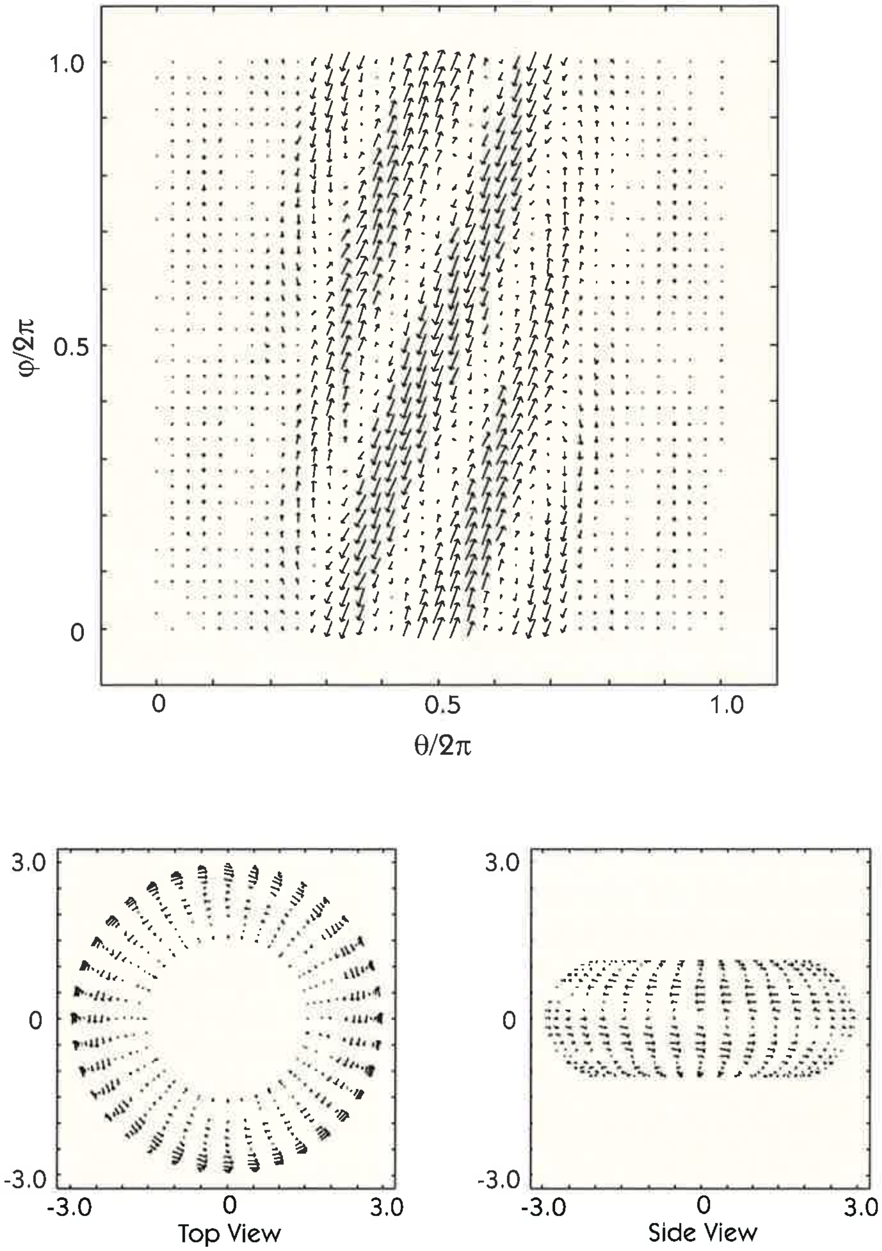


Figure 2. One crucial factor limiting tokamak performance is the external kink instability. Computer simulations like the one above show that the eddy currents induced by these external instabilities in a conducting shell are localized on the outboard size of the plasma; this indicates that passive or active stabilizing conductors need only be placed in this region. The top figure is an "unfolded" view of the shell in the toroidal-poloidal plane. The bottom figures are projected "top" and "side" views of the current pattern in the shell.

chusetts Institute of Technology (MIT) incorporated the effects of Doppler and Stark broadening on the spectrum and of reflection on the total H-alpha signals. Future work will incorporate polarization and Zeeman splitting into the spectrum simulations. The feasibility of using DEGAS 2 to deduce the ion temperature in recombining regions from the observed H-alpha spectrum will also be considered. The mechanisms for compiling and normalizing the output data from DEGAS 2 ("scoring") have been generalized and are managed entirely during preprocessing. An immediate consequence is that a single array can be used to transfer the DEGAS 2 data to the B2 and UEDGE plasma codes, providing a simple interface for a subroutine-based coupling.

## External Collaborations

Collaborations between the PPPL Theory Department and other national and international institutions, such as General Atomics (GA) in San Diego, the Japan Atomic Energy Research Institute in Japan, and the Institute for Fusion Studies at the University of Texas, as well as between individuals from university programs, such as MIT and the University of California-San Diego, have continued to be highly productive. This is evident from refereed journal publications, International Atomic Energy Agency and American Physical Society oral presentations, and experimental proposals, completed as well as planned, on devices such as the Doublet DIII-D at GA, the Joint European Torus in England, and JT-60U in Japan.

The PPPL Theory Department is participating in the ITER Project by helping to provide the tools and concepts for ITER research and development. For example, PPPL played a lead role in the Fusion Energy Sciences Advisory Committee assessment of the physics basis for ITER and PPPL theoreticians were members of the ITER expert teams. In addition, frequent requests are received for enhanced activity on the ITER project.

With the broader focus on innovative confinement concepts, stronger collaborative linkages are expected to be developed with the international stellarator community (e.g., the Large Helical Device in Japan and the Wendelstein 7-X in Germany) and with numerous national initiatives on stellarators, reversed-field pinches, and other innovative concepts.

## Future Impact

The potential is excellent for the PPPL Theory Department to impact the scientifically focused, restructured Office of Fusion Energy Sciences Program. "Site credits" include: (i) the Department's strong coupling to PPPL's experimental program with its record of past successes, such as TFTR, and scientifically exciting initiatives, including NSTX; (ii) the Department's integral relationship to Princeton's premier graduate academic program in plasma sciences; and (iii) the Department's array of computational and analytic talent.

Key topics of continuing and future focus include: (i) development of methods needed to interpret and possibly control or avoid MHD disruptions; (ii) cross validation of state-of-the-art gyrokinetic and gyrofluid capabilities for realistic turbulent transport simulations needed to provide understanding essential for reliable confinement projections; (iii) analysis of energetic particle dynamics and its relevance to alpha-particle physics issues in present and future deuterium-tritium plasmas.

In addition to providing the seminal ideas responsible for the gyrokinetic and gyrofluid initiatives which drive the national computational grand challenge Numerical Tokamak Project, the PPPL Theory Department has been an essential element in the much needed efforts to further improve the associated transport models. Plasma theory research at PPPL has also played a prominent role in developing tools for treating three-dimensional configurations such as stellarators and will enhance this activity in the near future.

In general, resources and concepts valuable not only to fusion but to other areas of physics and applied mathematics have been produced. Overall planning and execution of the research activities discussed here will be carried out in coordination with the Laboratory's Off-Site Research Program (see section on Off-Site Research in this report) with guidance from the newly formulated PPPL Science Focus Groups.

# Space Plasma Physics

The Earth's magnetosphere and the solar atmosphere have been the principal areas of research in space plasma physics at the Princeton Plasma Physics Laboratory (PPPL). The primary goal is to understand solar activity, such as the solar wind, corona mass ejection, and prominence eruption, and how these solar activities couple to the magnetosphere. Coupling between solar activity and magnetosphere determines how energy, momentum, and mass are transported into the magnetosphere. Such coupling problems typically involve disparate scales and, in order to adequately treat the coupling, a kinetic-MHD (magnetohydrodynamic) model has been developed which incorporates kinetic effects into the MHD model. The model has been successfully applied to study several fundamental magnetospheric physics problems.

This report focuses on two topics: (1) MHD waves and associated plasma transport at the magnetopause where plasma gradient scales are on the order of several ion gyroradii and (2) the formation of current sheets and prominences in the solar atmosphere.

## MHD Waves and Plasma Transport at the Magnetopause

The magnetopause is the boundary that prevents solar activity from penetrating directly into the Earth's magnetosphere. This boundary is characterized by substantial MHD activity which can lead to large plasma transport into the magnetosphere. The nature of MHD waves and associated transport have been studied by investigating quasilinear theory, as well as stochastic transport which results in large fluctuations. These results suggest that diffusive transport may be as important as magnetic reconnection for plasma entry into the magnetosphere.

Study of MHD wave activity in the magnetosheath has been based on a global mirror mode which takes into account profiles of plasma (flow, pressure and its anisotropy) and magnetic field, as well as wave-particle interaction. As the MHD waves propagate from the magnetosheath to the magnetopause, they mode convert into kinetic Alfvén waves which can explain the major features of the MHD wave observations.

For small wave fluctuation levels, the quasilinear diffusion mechanism is applicable and the diffusion coefficients have been obtained using the gyrokinetic formalism, including full Larmor radius effects. Our work on quasilinear transport has clarified the most important physical processes involved in plasma transport at the magnetopause.

Quasilinear diffusion can be due to (1) the parallel electric field, (2) transverse magnetic field fluctuations coupling to the particle magnetic drifts, and (3) compressional magnetic field fluctuations. Diffusion due to the parallel electric field results when the wavelength is the order of the Larmor radius. Diffusion due to magnetic drifts tends to be significant over most of the range of wavelengths. Diffusion due to compressional magnetic field can be larger than that due to the parallel electric field in high-$\beta$ plasmas.

For magnetopause parameters, diffusion due to magnetic drifts is at least an order of magnitude larger than diffusion due to the parallel electric field and compressional magnetic field fluctuations. This primarily results from the large magnetic field gradients at the magnetopause and is contrary to the previous thought that the parallel electric field is most relevant to the magnetopause. Based on the observed MHD wave amplitude, the diffusion coefficient is $D \approx 10^9$ $m^2$/sec, which is consistent with the measured rate of particle entry.

For large wave fluctuation levels, the stochastic diffusion mechanism becomes important. The stochastic particle motion occurs because of nonlinear coupling that results in overlapping of phase space particle orbit islands. For small wave amplitudes, particle motion is regular and remains on well-defined KAM surfaces in phase space. But, above a threshold value of $\delta B/B \approx 0.1$ (for southward IMF cases), particle motion becomes stochastic and particles rapidly diffuse throughout the phase space. Both diffusion and heating will occur and the diffusion can be as large $D \approx 10^{10}$ $m^2$/sec for typical wave amplitudes. For small magnetic shear such as in northward IMF cases, the threshold is significantly increased so that stochastic transport is not realized even for large fluctuation levels.

## Current Sheets and Solar Prominence Formation

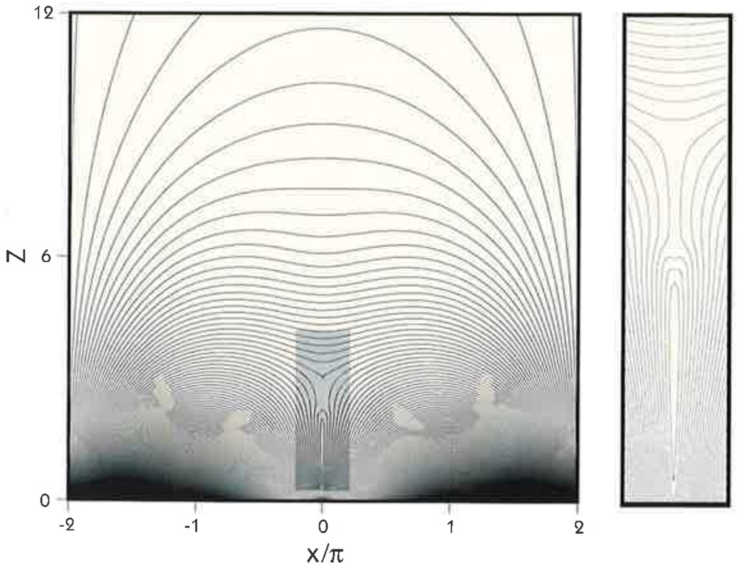
Mechanisms of current sheet formation have been studied. If magnetic field lines in opposite directions expand toward each other to squeeze out the field between them, they come into contact to form an abrupt field reversal (tangential discontinuity) which supports a current sheet. Field line expansion can be caused by the combined pressure gradient and gravity force, the magnetic field pressure gradient force, magnetic fields merging toward each other, or a combination of these effects. In a quadrupolar magnetic field geometry, magnetohydrostatic (MHS) equilibria without nullpoint can be deformed into equilibrium field configurations containing current sheets by changes in forces associated with thermodynamic properties or field line footpoint displacement. The shape of current sheets depends on the pressure distributions and footpoint displacement profiles.

Current sheets can be related to solar prominence in two aspects. First, the slab-like appearance and the high mass density of prominences require highly bent field lines in the prominence vicinity. Second, solar prominences are often observed between the opposing fields of two active regions, and the cancellation of magnetic patches of opposite polarities is regarded as one of the observational conditions in prominence-forming regions. This suggests that solar prominences are often formed in a current sheet. PPPL researchers have demonstrated that the evolution of current sheets can lead to prominence magnetic field configurations via resistive magnetic reconnection processes to support a higher plasma density at the reconnection site than in the surrounding region.

For a current sheet along a separatrix line between two bipolar arcades, the field configuration is deformed into a configuration with an X-point through resistive magnetic reconnection. An inverse polarity prominence can stably reside above the X-point. A new current sheet configuration with a sharp downward-pointing tip hanging at a distance above the bottom boundary has also been obtained. Resistive magnetic reconnection in this type of current sheet results in a Malville-type field configuration with a magnetic island wrapped in dipped field lines (see Figure). An inverse polarity prominence can stably reside within the magnetic island. Results suggest that the formation of magnetohydrostatic equilibria containing current sheets and their evolution into prominence magnetic field configurations must be a general process in the solar atmosphere.

## Acknowledgements

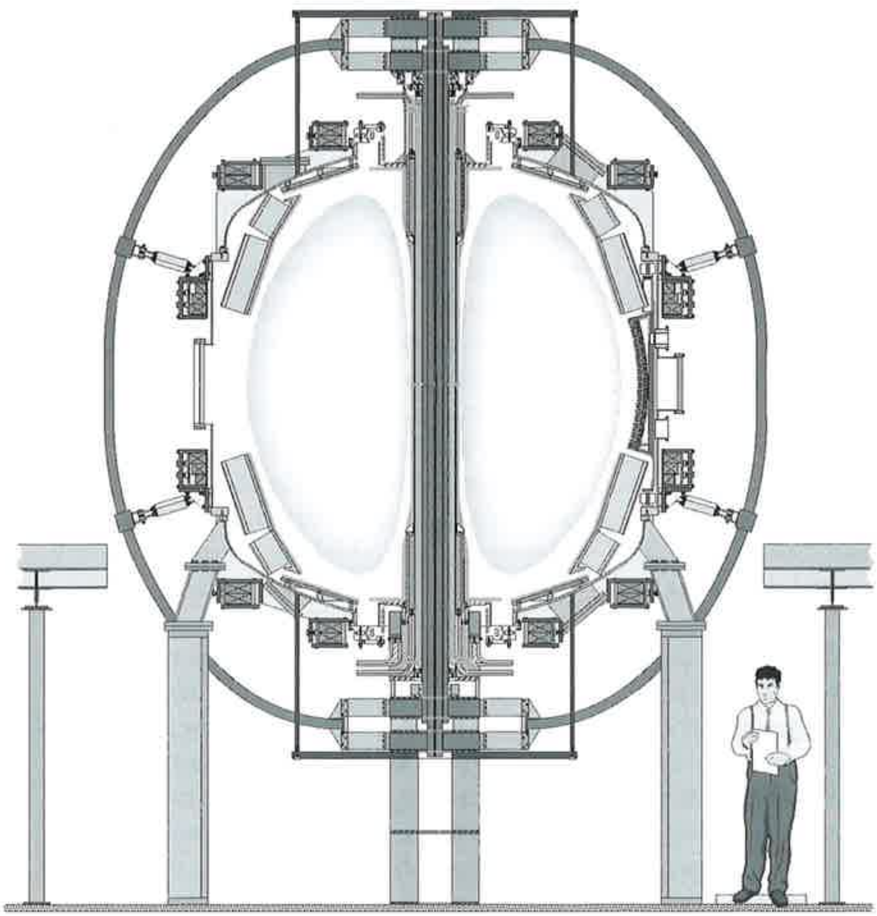
This research was supported by the U.S. Department of Energy and grants from the National Science Foundation.



The magnetic field configuration of a vertically elongated magnetic island formed in a thin current layer which resembles the prominence magnetic field model suggested by Malville. The $Z = 0$ horizontal axis represents the photosphere. The spatial coordinate is scaled to pressure scale height ($kT/g$, where $k$ is the ideal gas constant, $T$ is the plasma temperature, and $g$ is the gravitational constant). The figure on the right is a magnification of the shaded area containing the magnetic island.

# NSTX

## National Spherical Torus Experiment



Cross-sectional schematic of the National Spherical Torus Experiment.

The National Spherical Torus Experiment (NSTX) is a new device designed to prove the physics principles of a spherical torus (ST) plasma. The NSTX is under construction at the Princeton Plasma Physics Laboratory (PPPL), with first plasma scheduled for April, 1999.

The cross-section of the NSTX device is shown in the schematic above. Spherical tori produce plasmas that are shaped differently from 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 approach could play an important role in the development of smaller and more economical fusion reactors.

The NSTX device is being built jointly by Princeton Plasma Physics Laboratory, Oak Ridge

National Laboratory (ORNL), the University of Washington at Seattle, and Columbia University. PPPL has lead responsibility for the NSTX Project and coordinates the design and construction effort. ORNL provides the Program Director for NSTX, physics support in plasma modeling, and the engineering of plasma facing components. The University of Washington provides the conceptual design of the coaxial helicity injector, and Columbia University provides physics support for high-beta plasma stabilization. In addition, PPPL in partnership with ORNL is constructing the high harmonic fast wave system. The NSTX project is taking advantage of the equipment and infrastructure already available at PPPL, saving time and money.

During FY97, the NSTX design team completed a series of reviews of critical path components. Incremental changes in project cost and schedule for locating NSTX at D-site instead of C-site, as originally planned, were also reviewed. A top view of the NSTX in its Test Cell at D-site is shown in Figure 1. The NSTX Project Definition Statement was approved by the U.S. Department of Energy (DOE) Office of Fusion Energy Sciences in March, 1997. The procurement and fabrication of critical path items, such as the center-stack components, were well underway. The poloidal-field coils, taken from PPPL's old S-1 device, will be used for NSTX.

## NSTX Mission

The mission of NSTX is to prove the scientific principles of an ST plasma including:

- noninductive start-up, current sustainment, and profile control;
- global confinement and local transport physics;
- pressure limits and self-driven currents;
- scrape-off-layer and divertor physics; and
- stability and resilience to disruptions.

NSTX researchers will investigate plasma regimes that promise small fusion cores for near-term applications such as volume neutron sources and long-term applications such as electric power production. These plasma regimes are characterized by:

- simultaneously high toroidal beta (25-45%), self-driven current fraction (40-80%),

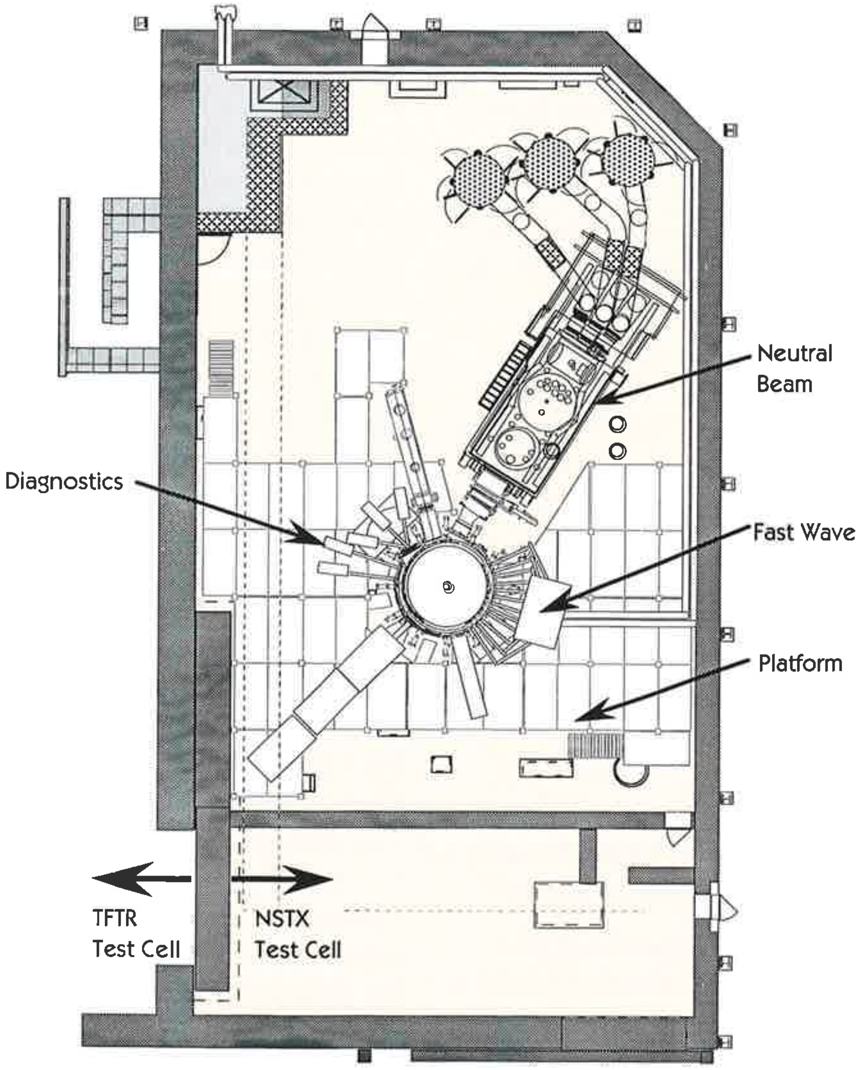


Figure 1. The NSTX device in the new D-Site Test Cell, formerly the TFTR Hot Cell.

and confinement in steady state;

- noninductive start-up of full current not relying on induction from the ohmic solenoid;
- efficient noninductive drive for the needed increment in plasma current; and
- dispersed particle and power exhausts on high heat flux components facing the plasma.

Successful proof of these desired properties will make possible cost-effective designs achieving several times the plasma current and toroidal field of conventional tokamaks without increasing plasma size. These designs would enable smaller, less expensive, fusion power reactors.

## NSTX Program Activities

The NSTX Program Advisory Committee, formed by the PPPL Director, is composed of senior fusion scientists from U.S. and foreign fusion laboratories. The Committee reviews the progress of the NSTX Research Program and advises the PPPL Director on:

- NSTX physics design requirements where they affect the experimental research;
- major proposals for new research initiatives on NSTX which are to be proposed to DOE;
- the overall NSTX experimental research plan, including key priorities and milestones consistent with the DOE-approved work scope;
- adjustments to program priorities, taking into account the mission of NSTX and the overall direction of the U.S. and world fusion programs.

The Program Advisory Committee met November 21-22, 1996; May 15-16, 1997; and September 17-18, 1997. The group endorsed the general objectives and overall process proposed for the formation of the NSTX national research program and team participation. The Committee offered many useful suggestions for improvement.

The first annual (by fiscal year) NSTX Research Forum was held February 5-7, 1997. Eighty scientists from 16 fusion institutions participated, with about half of the participants from PPPL. This was the first step in efforts to share the excitement and "ownership" of the research program being planned for NSTX. The presentations and discussions at the Forum were broad and informative, including the Plenary Information Session as well as the Working Group Sessions. Summaries of these sessions are available on the internet at http://www-local.pppl.gov/nstxhome/nstx/meetings/. These documents provide up-to-date information on the broad and exciting elements of scientific investigation of the high-temperature ST plasmas planned for the NSTX facility. This information will be of interest to fusion scientists considering collaborative research on NSTX.

## NSTX Physics Activities

NSTX physicists are working with project engineers to further define and refine the physics requirements for device design and construction. Recent work has shown that high loop voltages (over 6 volts) are available during plasma initiation, taking into account additional volt-seconds from the poloidal-field coils. This voltage makes it possible to withstand finite stray fields for durations long enough for the plasma to form in an inductive-only fashion. Simulations of coil currents needed for plasma control during coaxial helicity injector start-up were also carried out, indicating only modest requirements.

The stability of plasma profiles during the fast current ramp-up period was assessed, and the plasmas were determined to be stable to low and high-n modes at all times, except for the time at the end of the current ramp, where the plasma was unstable to n=3 modes. With only minor adjustments to the pressure profile (specifically, a flattening of the profile in the center), stability could be achieved.

Columbia University collaborators have been working with PPPL personnel to develop the EFIT code as a tool for calculating NSTX equilibria for subsequent stability analysis. Results of this work have shown the sensitivity of mode stability to the curvature of the outer boundary.

This helps refine operating scenarios to optimize NSTX performance. EFIT will be used to assess operational space, assuming a wider range of pressure and current profiles than examined previously.

Two-dimensional modeling of the NSTX edge and divertor plasma was carried out by ORNL personnel using the b2.5 code to estimate the range of peak heat fluxes that might be observed in the worst-case scenarios. The peak heat fluxes are quite sensitive to the amount of divertor radiation, and, to a lesser extent, the recycling coefficient. The worst-case heat flux estimate indicates the need for cooling both the inboard and outboard divertor plates.

Radio-frequency (rf) modeling of NSTX plasmas is being carried out primarily by the ORNL group as part of the rf antenna design task, using the full wave code PICES. Additionally, scientists at the University of California at San Diego are using the ray-tracing code CURRAY. An rf code benchmarking exercise using standard NSTX equilibria was initiated with an aim towards identifying the rf code that will be integrated into the various discharge analysis tools presently being developed.

In preparation for initial operations, simulations of ohmic-heating-only discharge scenarios were carried out using the Tokamak Simulation Code to determine possible current flattop durations for fully double-swung ohmic heating. The duration of the current flattop depends on both the current level and the plasma confinement (the plasma temperature). Figure 2 shows the range of possible current flattop duration for a range of these assumptions, where the confinement time is based on that given by the Lackner-Gottardi-Connor low-confinement mode scaling. While 1-MA targets are achievable without auxiliary heating, the current flattop duration is negligible. At lower target currents, however, significant current flattop durations are realizable. Furthermore, current flattop durations of up to one-half second are possible at 1 MA with auxiliary heating.

## NSTX Project Activities

Project activities significantly increased in FY97. The efforts in first half of the year focused on the design and fabrication of the center stack and shifted to other torus components during the second half.

The Final Design Review of the center stack was held in February. Contracts were awarded for the conductor and insulation material for the center-stack magnets and assembly and testing of the inner toroidal-field bundle and ohmic-heating coils. All of the center-stack conductor and insulation has been delivered. The inner toroidal-field copper bars

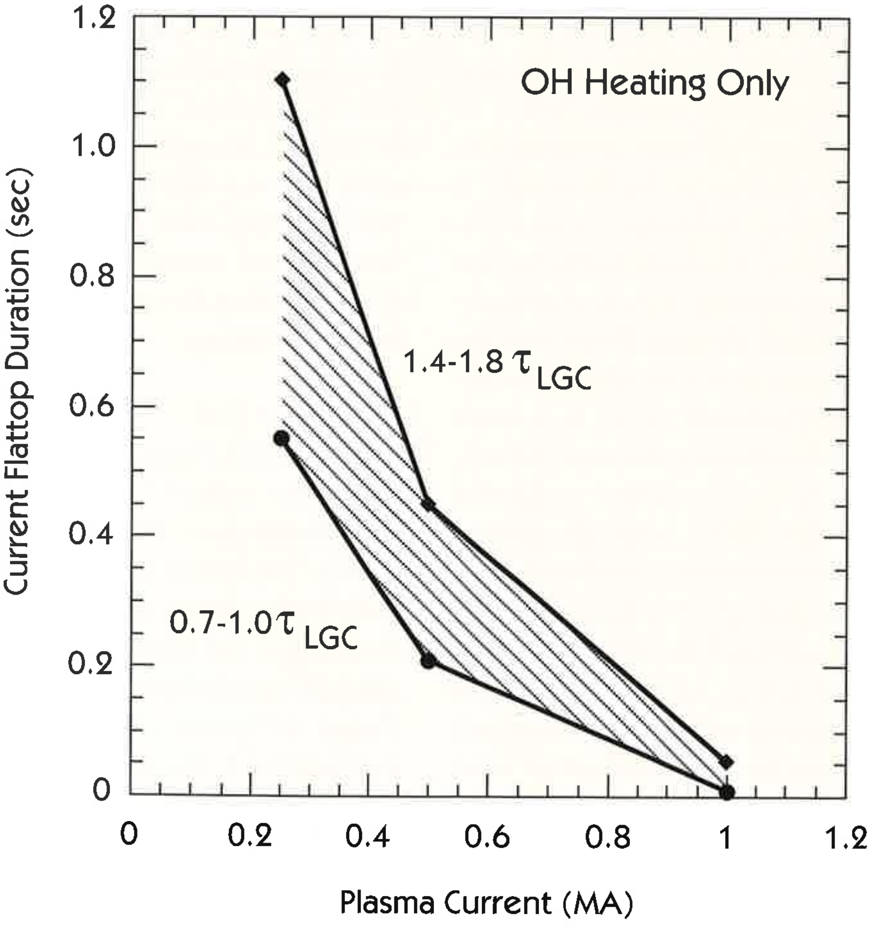


Figure 2. Current flattop duration for double-swung ohmic-heating-only NSTX plasmas.

were machined at PPPL and sent to the contractor for assembly and testing. The completed toroidal-field bundle is scheduled for delivery in February, 1998. The contractor for the ohmic-heating coils is setting up tooling in preparation for coil manufacturing during February, 1998. Other center-stack components such as the casing, poloidal-field coils (PF#1), thermal insulation, magnetic diagnostics, hub assembly (a mechanical restraining structure in the toroidal-field joints), flags (radial extension pieces for the inner toroidal-field bundle), and flanges are being fabricated on schedule.

In April, 1997, design efforts shifted to the outer toroidal-field and poloidal-field coils, ceramic insulators, vacuum vessel, and plasma facing components. The final vacuum vessel configuration was decided at the May NSTX Program Advisory Committee meeting. The high harmonic fast wave antenna system configuration was changed from two six-element antennas (placed on opposite sides of torus) to a single twelve-element antenna. According to the calculations performed by the ORNL team, the twelve-element antenna has a better wave spectrum which is needed for current drive. This new configuration has an added advantage of requiring only three sectors (out of twelve total) instead of four. The extra sector can be used, for example, for diagnostics. Additional tangential ports and divertor viewing ports were added to the vacuum vessel based on input from the February NSTX Research Forum. Two neutral-beam injection ports and ports for poloidal charge-exchange recombination spectroscopy were also added. In July, a final design review was held at PPPL during which the ORNL team presented the plasma facing component design. Pull out tests on the carbon-fiber-composite material for the center stack indicated that the mechanical strength is more than adequate to withstand halo-current loads. The procurement processes for those components have started. The outer toroidal-field coil copper and insulation material has been purchased and a manufacturing contract has been awarded. The vacuum vessel cylindrical section drawings have been completed and the section is being procured. The poloidal-field coils 2, 3, and 4 from PPPL's old S-1 device will be reused for NSTX. They have been disassembled and transported to the RESA building for modifications and refurbishing.

## NSTX Test Cell

The NSTX Project will make use of the nation's largest magnetic fusion asset, PPPL's D-site facility. The D-Site Hot Cell was completely cleared by the Tokamak Fusion Test Reactor staff and officially transferred to the NSTX Project in October 1997, becoming the NSTX Test Cell. This location offers a number of important advantages when compared to the C-site option, previously considered. These include better power systems, the availability of a neutral-beam injection system, a well-shielded test cell, and a spacious control room. By the end of FY97, the NSTX platform was being installed in the NSTX Test Cell.

## Upgrade Diagnostics

The NSTX Research Forum and the Program Advisory Committee have strongly recommended the early use of plasma profile diagnostics.

The highest priority diagnostic is the multi-pulse Thomson scattering system which measures both the plasma temperature and density as functions of position and time. Due to low toroidal-field and high density, conventional electron cyclotron emission will not work for NSTX. A multi-pulse Thomson scattering system feasibility study was initiated. Rather than reuse a single-time-point ruby laser system as proposed in the project baseline, a modular multi-pulse Nd:YAG-based laser system will be available within the first year of operation. This system can be enhanced to provide increased spatial and temporal resolution as resources allow.

Because of the importance and special challenges of a current density diagnostic for NSTX, a special study group met in July, 1997 at PPPL. Promising ideas including Faraday rotation, heavy ion beam probe, improved motional Stark effect techniques, and a soft X-ray pinhole camera were presented. The study group's summary was distributed. Some of the most promising current density diagnostics were recommended for funding in FY98. The Program Advisory Committee recommended the Day-1 implementation of plasma start-up diagnostics such as ultra-soft X-ray tomography and a fast visible camera. A study group for the fluctuation diagnostic will meet in FY98.

With the arrival of manufactured components in February, 1998, the center-stack assembly will begin in the RESA building at PPPL. Assembly of the NSTX device in the Test Cell is scheduled to begin in the summer of 1998.

# ITER

## International Thermonuclear Experimental Reactor

International Thermonuclear Experimental Reactor

In FY97, the International Thermonuclear Experimental Reactor (ITER) project focused on completion of the Detailed Design Report and preparation of the Final Design Report, as well as documenting the ITER physics basis. The Princeton Plasma Physics Laboratory (PPPL) continued its role in ITER physics and engineering work with PPPL staff assignments to the Joint Central Team (now three physicists in San Diego; one engineer in Garching, Germany; and one engineer in Naka, Japan), increased support to the U.S. Home Team Design activities (both physics and engineering), and increased participation and coordination of ITER physics R&D. 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 U.S. Home Team Task Area Leaders in physics design.

The ITER Project reached the "five-year point" in its six-year Engineering Design Activities phase in July, 1997. Design tasks were focused on delivery of the Final Design Report in November, 1997. This report will be reviewed by the Technical Advisory Committee in

January, 1998, and by the four ITER Parties (European Union, Japan, the Russian Federation, and the United States) in 1998, leading to consideration by the ITER Council in July, 1998.

PPPL work as part of the U.S. Home Team focused on physics design, diagnostics design, and engineering design.

## PPPL Physics Design Activities

Discharge simulations and plasma control simulations are two primary areas that have been addressed with PPPL's Tokamak Simulation Code. The discharge simulations included a full simulation of the ignited reference discharge from current rampup through current rampdown. These simulations determined that the poloidal-field (PF) coils are adequate for achieving the scenario: that is, the coils stay within their prescribed limits and the plasma position, shape, and current remain within their allowables. The flattop burn is actually longer than the required 1,000 sec by about 200 sec, allowing for some recovery of volt-seconds. The plasma reaches all design parameters, indicating a fully ignited state in the presence of a sawtooth instability, accumulated helium, 2% beryllium impurity, and radiation losses. The bootstrap current contributed 20% of the total plasma current. In both the current rampup and rampdown phases, the plasma remains within the stable operating zone of the $\ell_i$-$q_{95}$ space. It was also found that volt-seconds could be recovered by shortening the current rampup phase with little impact on the plasma evolution or the PF coil power consumption.

Studies of heating during the plasma current rampup phase with powers ranging from 40 to 100 MW and with various assumptions on the confinement [low (L) or high (H) mode] and the density trajectory were done. Since auxiliary power would be required during the current rampup when the PF coil power is typically its highest, the plasma current trajectory was modified to accommodate this heating power. Cases assuming L-mode used 23 volt-seconds less and those assuming H-mode used 46 volt-seconds less than the reference discharge. H-mode cases with sufficient density increase during the current rampup could produce significant alpha heating. The various heating scenarios generated different trajectories for $\ell_i$-$q_{95}$, beta-poloidal, sawtooth radius, and the bootstrap current, although no difficulties were apparent. These scenarios also generated different trajectories for the PF coil currents, all of which remained within their maximum allowable currents, except for PF8 in the highest heating cases. These differences are driven by the balancing of ohmic and equilibrium currents, which depend on the flux state and how fast it advances during the current rampup.

An examination of soft plasma termination was done to determine the shortest time required to shutdown the plasma without inducing a disruption, until the current was low enough. This involves both the burn termination and current rampdown phases. It was found that the burn termination could be shortened by taking credit for shorter particle confinement times after the plasma exited the H-mode, leading to a minimum burn termination time of 50 sec, half the reference value. The current rampdown phase was shortened by ramping the PF coils faster, which was limited by the stability in the $\ell_i$-$q_{95}$ space, vertical stability, the final plasma current before disruption, control of the plasma shape, and the PF coil power. These lead to a minimum current rampdown time of 100 sec, half the reference value. This determined a minimum soft plasma termination time of about 150 sec. Shorter times for plasma shutdown would necessarily involve disruptive behavior.

A full simulation of the (Reversed Shear) Steady-State Operational Mode from plasma current rampup through flattop was developed. This involved an inductive current rampup to 6 MA with low heating; a transition to 100 MW of heating to produce 2 MA lower-hybrid current drive and 4 MA bootstrap current and to begin the transition to a hollow current profile; and a transition to 12 MA plasma current from increased density and the formation of an internal transport barrier with 2 MA of lower-hybrid current drive and 10 MA of bootstrap current. The alpha power reaches 350 MW, and the plasma is driven with a Q $(P_{fus}/P_{aux})$ of 17.5. The simulation showed that the plasma could be produced with PF coil power not exceeding 150 MW combined with a total auxiliary power of 100 MW, and that the PF coils were well within their allowables. In addition, the plasma position, shape, and current could be controlled during the strong changes in the plasma parameters ($\ell_i$, beta-poloidal).

Simulations of the plasma position, shape, and current control were done for minor disruption-type disturbances, such as beta-poloidal changing from 0.9 to 0.7 and $\ell_i$ changing from 0.9 to 0.8. Modern optimal controllers utilizing linearized plasma models were shown to be successful for the ignited reference plasma, maintaining the gap deviations within 15 cm of nominal, the total PF coil power below 100 MW, and the settling time under 25 sec. Control of the Reversed Shear Steady-State plasma was also done, with a modern optimal controller and a minor disruption disturbance. The deviations in the gaps can be as high as 30 cm, since the plasma is strongly deformable. This is due to a very low $\ell_i$ and high beta-poloidal. In fact, the strong coupling between the plasma boundary shape and $\ell_i$ caused $\ell_i$ to oscillate in the early phases of the control simulation, which caused the large deviations in the gaps to oscillate. The PF coil power was shown to be on the high end of acceptability, and all PF coils remained within their allowables.

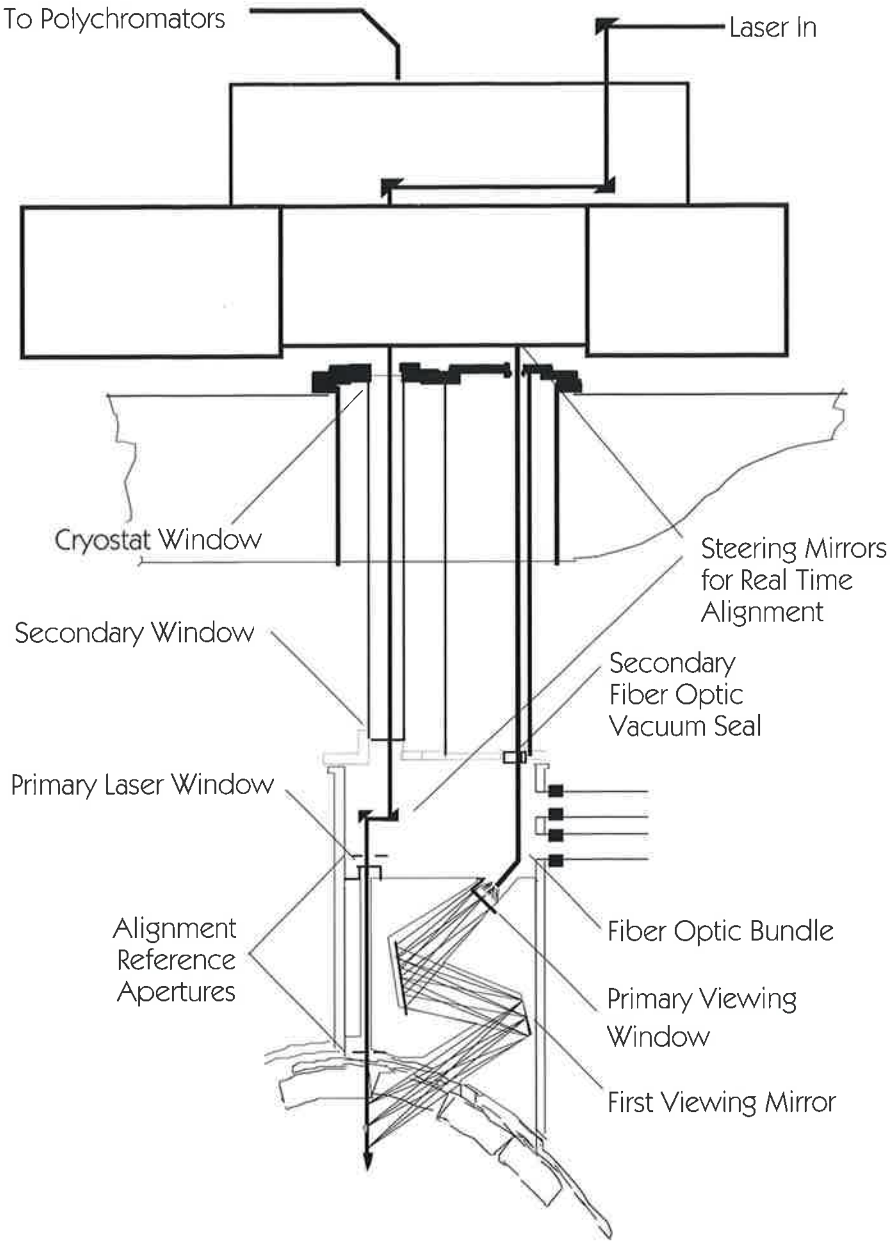


Figure 1. Concept design of the ITER edge Thomson scattering system showing the top port arrangement.

## PPPL Diagnostics Design Activities

ITER diagnostics design and R&D in the U.S. are being carried out at a number of institutions under the leadership of the Task Area Leader from PPPL. The designs have progressed significantly and resulted in papers presented at a Workshop on Diagnostics for Experimental Fusion Reactors held in Varenna in September 1997. The descriptions of the designs presented there were followed up by formal reports to the ITER Joint Central Team for the appropriate level of design. The PPPL contribution consisted of extending the design level achieved by the end of FY96 to (i) a conceptual design of a system for measuring escaping alpha-particles, (ii) preliminary design of a Thomson scattering system for edge density and temperature measurements, shown in Figure 1, (iii) preliminary design of an array for measurement of the visible bremsstrahlung emission from the plasma, (iv) preliminary design, with Fusion Physics and Technology, of a motional Stark effect spectrometer system for measuring the current density profile, and (v) engineering design of a microwave reflectometer for measurement of the density profile to determine the plasma position. With Los Alamos National Laboratory, PPPL also provided the preliminary designs of the (vi) neutron-flux monitoring system and of the (vii) neutron activation system for determining the integrated neutron fluence.

## PPPL Engineering Design Activities

PPPL's engineering support for ITER focused mostly on electromagnetic analyses of the in-vessel components. These analyses derive the forces on the in-vessel components due the current flows driven by the plasma behavior. The in-vessel components include the blanket/shield modules, the backplate which is the structure on which the modules are mounted, and the divertor cassettes. The plasma behavior was determined in a collaboration with Oak Ridge National Laboratory using the Tokamak Simulation Code developed by PPPL. Current distributions due to plasma motions are determined by using a PPPL-developed code called SPARK or a commercial code "EMAS" by ANSOFT. The forces are then used in finite element analysis codes to calculate the stresses and deflections due to these currents crossing the magnetic fields in which they are immersed. The design development is an iterative process, with the engineering details such as material type or thickness being refined until acceptable stresses and/or deflections are obtained.

PPPL also provided engineering expertise in a number of other areas. The Laboratory was a major contributor to the segmented solenoid study that concluded in the first quarter of FY97. The vacuum vessel field-welded joints were analyzed, taking into consideration fabrication tolerances and design code considerations. A feasibility study of ferromagnetic inserts for ripple reduction was performed. Two-dimensional and three-dimensional finite element analyses were performed to assess the thermal stresses resulting from thermal processing of the blanket modules. PPPL engineers contributed to the magnet design criteria. A cooling scheme for the metrology laser sensor was designed and analyzed. Reference discharge simulations were completed using the Tokamak Simulations Code. Reverse shear discharge simulations were completed. Laboratory engineers designed the power supply control system and played a significant role in the writing of the power System's Design Description Document.

# Stellarators

Stellarators, a family of plasma confinement concepts characterized by three-dimensional magnetic fields, are the most developed magnetic fusion concept after the tokamak. The concept has advanced greatly since its invention by the Princeton Plasma Physics Laboratory's (PPPL) founding Director, Lyman Spitzer, Jr., in the 1950s. Now, two large superconducting stellarator experiments in the billion-dollar class — the Large Helical Device (LHD) in Japan and the Wendelstein 7-X (W7-X) in Germany — are under construction, with the LHD scheduled to begin operation in 1998. The world-wide interest in the stellarator concept stems from its potential for use as a steady-state fusion reactor featuring interruption-free plasma operation, low recirculating power, and good plasma performance. However, projections based on current stellarator knowledge indicate these reactors will be relatively large.

Scientists at PPPL, in collaboration with colleagues from the U.S. and abroad, are studying design concepts that would make stellarators more compact. In 1997, they completed the development of a capability that computes compact-stellarator plasma configurations that are optimized to have low plasma transport and high plasma pressure limits. This was made possible through some innovative stellarator design strategies, some of which were developed at PPPL. The prospects for significantly improving stellarator reactor designs have been greatly enhanced as a result. Experimental tests are now needed to confirm the predicted favorable properties of the new configurations. A medium-scale, "proof-of-principle" device, based on a promising stellarator plasma concept, would meet the facility requirements for these experiments. In 1997, the Laboratory began a national concept design study to develop the plasma configuration, machine concept, and cost and schedule targets for such an experiment, which could be sited at the Princeton Plasma Physics Laboratory.

## Compact-Stellarator Plasma Design Innovations

A major challenge in the design of three-dimensional magnetic-field configurations is to reduce the energetic alpha-particle losses due to magnetic-field ripple. In recent years, stellarator theorists have developed some innovative solutions to this problem. One is to make use of quasi-symmetry, in which a magnetic-field structure that is three-dimensional in physical space possesses an underlying symmetry as seen by energetic particles in the system. This property makes it possible to have particle drift trajectories that are just as good as those in exact symmetry, e.g., in tokamaks, and hence have low alpha-particle losses and low neoclassical transport.

In quasi-axisymmetric devices, the plasma's self-generated bootstrap current is comparable to that in a tokamak and flows in the direction to add to the helical twist, or rotational transform, of the magnetic-field structure. Rotational transform is favorable for plasma energy confinement in the stellarator. To the extent that some of the rotational transform is provided by the bootstrap current, the design of the stellarator coils is eased, allowing them to be less twisted and farther from the plasma than in other designs. The bootstrap current allows the toroidal plasma to have a lower aspect ratio (ratio of major radius to minor radius), making it more compact. It is also predicted to suppress the unstable growth of magnetic islands, which could rapidly destroy the plasma configuration and disrupt operation, if the shear in the rotational transform is arranged to be in the appropriate direction.

Another recent innovation in configuration design, developed at PPPL, is the development of a strategy to ensure stability against ballooning modes at high beta. Stellarators typically have ballooning beta limits lower than that of tokamaks (an exception is the German W7-X device, now under construction). However, it was found that high ballooning beta limits can be obtained in quasi-axisymmetric stellarators by introducing a strong axisymmetric component of the shaping, as is done in advanced tokamak configurations. Configurations with these properties are constructed by combining high-bootstrap advanced-tokamak plasma configurations (e.g., ARIES II) with quasi-axisymmetric helical fields to produce stellarator-tokamak hybrids. An example of the plasma configuration that results is shown in Figure 1.

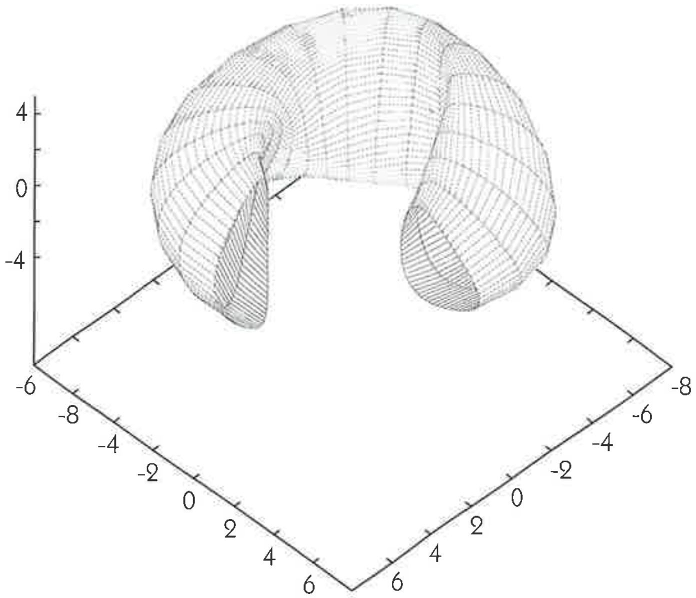


Figure 1. Plasma configuration for quasi-axisymmetric stellarator in which 25% of the rotational transform is provided by external coils.

A further challenge is to eliminate a design feature that in advanced tokamaks represents a major complication — the need for a conducting wall close to the plasma for stabilizing external kink modes, i.e., helical deformations of the plasma surface that can be unstable at high beta. It would be most advantageous, if tokamak-like beta values could be achieved in a stellarator without such a wall. A suggested solution is to introduce magnetic "shear," a steepening in the rotational transform profile near the edge of the plasma. Using the newly developed optimization capabilities, ballooning-stable high-beta configurations with this characteristic were generated; subsequent analysis confirmed that they were stable to external kink modes at a beta of 7% without a close-fitting wall. If further analyses confirm that favorable transport properties also can be realized, this will be a very exciting advance.

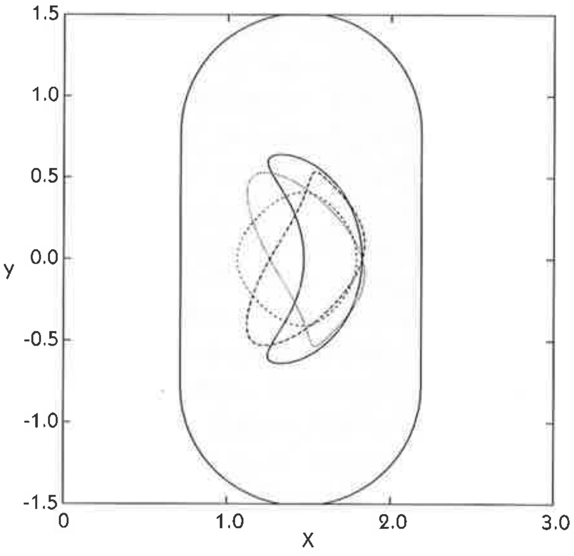


Figure 2. Quasi-axisymmetric plasma superimposed on the Princeton Beta Experiment-Modification (PBX-M) tokamak vacuum vessel, with space reserved for coils. Modification of the PBX-M may provide a low-cost stellarator experiment.

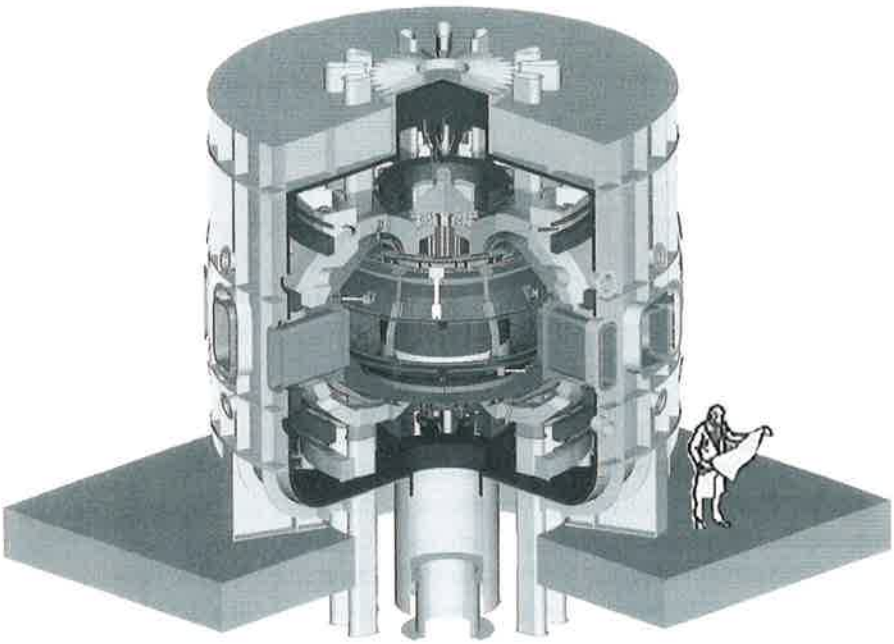
These innovations combine to open up a new path toward compact stellarator reactors with high beta and good confinement. In comparison with tokamaks they offer the advantages that they are potentially disruption-free and provide better control over the magnetic configuration properties important for high-beta stability. The use of externally produced transform has the advantage relative to tokamaks that it reduces or eliminates the requirement for current drive, with its attendant recirculating power in a reactor.

## The Next Step: Experimental Tests

A cost-effective experimental test of compact stellarator plasma concepts may be possible using a modification of the existing Princeton Beta Experiment-Modification (PBX-M) tokamak facility. Figure 2 shows how a quasi-axisymmetric stellarator plasma could fit in the PBX-M vacuum vessel, leaving space available for internal coils to provide the required helical fields. The existing external magnet system and vacuum vessel would serve as the basic structure for the new machine. Operation of such a facility, which would support a national experimental program centered at PPPL, could begin as early as 2003.

# KSTAR

## Korea Superconducting Tokamak Advanced Research Project



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

Since mid-1996, a team of United States scientists has been providing support for the design of the Korea Superconducting Tokamak Advanced Research (KSTAR) fusion experiment to be constructed in Taejon, South Korea. Members of the group, led by the Princeton Plasma Physics Laboratory (PPPL), include personnel from General Atomics, the Lawrence Livermore National Laboratory, the Northrop-Grumman Corporation, the Massachusetts Institute of Technology, and the Oak Ridge National Laboratory. The work is being performed under a subcontract with the Korean Basic Sciences Institute.

KSTAR's mission is to develop a steady-state advanced superconducting tokamak to establish the scientific and technological bases for an attractive fusion reactor as a future energy source. The primary research objectives are to:

- Extend stability and performance boundaries of tokamak operation through active control of plasma profiles and transport.
- Explore methods to achieve steady-state operation for tokamak fusion reactors using noninductive current drive.
- Integrate optimized plasma performance and continuous operation as a step toward an attractive tokamak fusion reactor.

U.S. interest and support for the KSTAR project stems from the fact that the basic mission and specific research objectives for KSTAR provide the foundations for an advanced tokamak facility in the United States.

The KSTAR tokamak will features: fully superconducting magnets, long-pulse operation, flexible pressure and current profile control, flexible plasma shape and position control, and advanced plasma profile and control diagnostics.

KSTAR will play an important role in world-wide fusion research. Its contributions will include:

- Extending advanced tokamak research to high-performance and steady-state operating regimes;
- Developing techniques for successful steady-state physics operation of the International Thermonuclear Experimental Reactor (ITER);
- Providing advanced tokamak physics which can be compared with that of superconducting stellarators and spherical tokamaks;
- Providing experience in large-scale superconducting magnet design, manufacture, and operation;
- Providing experience in high-power neutral-beam, microwave and radio-frequency technologies;
- Providing experience in state-of-the-art plasma diagnostics and controls and advanced computational methods.

KSTAR is a long-pulse (300 sec), superconducting tokamak which will be constructed in a new facility at the Korea Basic Science Institute and is scheduled for operation in 2003.

The machine configuration includes sixteen superconducting toroidal-field coils and thirteen superconducting poloidal-field coils, symmetrically located about the plasma midplane. The seven inner poloidal-field coils form the central solenoid assembly. A cryostat encloses all of the superconducting coils. The cryostat and vacuum vessel form the vacuum boundary for the superconducting toroidal-field and poloidal-field coils. KSTAR is not being designed for deuterium-tritium operation. Deuterium operation will be limited, eliminating the need for remote maintenance. The KSTAR machine parameters are presented in the accompanying table.

During FY97, the U.S. team was responsible for a major part of the tokamak design, including the training and mentoring of Korean scientists and engineers. These Korean personnel are forming the core of a Korean design and construction group that will carry the primary responsibility for the next phase of the project.

During 1997, U.S. scientists participated in two highly successful international KSTAR meetings: the Physics Validation Review in June 1997 and the Tokamak Systems Engineering Review in early December 1997, both held in Taejon, South Korea. The team for the Physics Validation Review found, "that the KSTAR machine rightly focuses on areas which are crucial for development of fusion reactors." The Tokamak Systems Engineering Review team was equally positive, finding, "the design presented provides an adequate basis for proceeding with a more detailed engineering design. The design is sound in that it has defined adequate spatial boundaries for the major tokamak system components, while satisfying engineering design criteria appropriate for this stage of design." In addition to these two major reviews, two other important project workshops were held: the Design Definition Workshop, held at PPPL in February 1997, and the Engineering Workshop held in Taejon following the completion of the Physics Validation Review.

An Ancillary Systems Engineering Review will be held in the summer of 1998. The U.S. team will play a supporting role for this review, assisting in the development of the project cost and schedule estimates and examining the documentation developed by the Korean team for the Review.

**KSTAR Major Parameters.**

| Plasma Parameter | Base | Upgrade |
|---|---|---|
| Toriodal Field ($B_t$) | 3.5 T | — |
| Plasma Current ($I_p$) | 2.0 MA | — |
| Major Radius ($R_o$) | 1.8 m | — |
| Minor Radius (a) | 0.5 m | — |
| Elongation ($\kappa$) | 2.0 | — |
| Triangularity ($\delta$) | 0.8 | — |
| Poloidal Divertor Nulls | 2 | — |
| Pulse Length | 20 sec | 300 sec |
| Plasma Heating | | |
| Neutral Beam | 8 MW | 24 MW |
| Ion Cyclotron | 6 MW | 12 MW |
| Lower Hybrid | 1.5 MW | 4.5 MW |
| Electron Cyclotron | 0.5 MW | — |
| Deuterium Operation | 20,000 sec/year | — |
| Number of Pulses | 50,000 | — |

# Off-Site Research

The Princeton Plasma Physics Laboratory's (PPPL) off-site collaborations have been targeted at addressing the highest-impact scientific issues by an integrated program of experimental and theoretical work, utilizing the remote facilities as resources for multi-device studies. PPPL uses its access to the leading remote facilities to propose and conduct coordinated experiments to acquire data over a range of plasma sizes and configurations. PPPL utilizes integrated data analysis and theory codes to process the combined data to increase understanding beyond that available on a single facility.

The PPPL collaborative off-site tokamak research program takes as its primary focus the development of attractive reactor-prototypical physics operating regimes. Complementarily, the collaborative programs on spherical tori and stellrators focus on improved understanding of the physics of those configurations, to provide a knowledge base for developing attractive plasma configurations.

## Alcator C-MOD Collaborations

The Alcator C-MOD tokamak at the Massachusetts Institute of Technology (MIT) is the only high-magnetic-field compact tokamak in the U.S. The C-MOD program is devoted to the study of the physics of high-density, high-magnetic-field fusion devices. In recent years, the effort has concentrated on divertor physics and experiments in support of the International Thermonuclear Experimental Reactor (ITER) program, especially the scaling of confinement and high-confinement mode (H-mode) behavior.

PPPL is collaborating with MIT to extend and exploit the physics opportunities presented by C-MOD. In FY97, principal areas of activity included support for the radio-frequency (rf) heating and divertor diagnostics. Unlike most other tokamaks, ion-cyclotron radio-rrequency (ICRF) heating is the sole auxiliary heating method used on C-MOD.

A major effort in the rf area was the transfer to MIT of two high-power (2 MW) variable-frequency (40-80 MHz) rf amplifiers. Engineering personnel from PPPL disassembled units previously used on the Tokamak Fusion Test Reactor (TFTR) and assisted in the installation and check-out of the units at MIT. The units were subsequently operated on C-MOD in the Spring of 1997. In addition, PPPL engineering staff provided assistance to MIT on the optimization and operation of their original two rf amplifiers.

To exploit the higher power levels available on C-MOD, an additional ICRF antenna is being constructed by PPPL for installation on C-MOD in the Spring of 1998. During FY97, the design of this antenna was completed and construction begun.

Understanding the physics of the divertor is a major goal of the C-MOD program, both for full exploitation of C-MOD's capabilities and for the crucial role a divertor plays in a tokamak fusion reactor, such as ITER. Princeton Plasma Physics Laboratory personnel worked on two divertor diagnostics in 1997 — Fabry-Perot measurements of recycling hydrogen and X-point Thomson scattering to measure the electron temperature in the divertor region. The Fabry-Perot interferometer was transferred from TFTR while the Thomson scattering device was a new system. The X-point system is expected to become fully operational in FY98.

### Doublet-III-D Collaborations

PPPL staff participated in the Doublet-III-D (DIII-D) tokamak program at General Atomics (GA) in research, operations, technical support, and upgrades.

PPPL scientists participated in an evaluation of proposed ICRF transmission line reconfigurations on DIII-D. Each of these proposed configurations is a "robust" system in the sense that large transients in antenna loading do not result in significant amounts of reflected power at the transmitter. After evaluating the configurations, it was found that a change in the arc detection system may make the configuration nearly optimum.

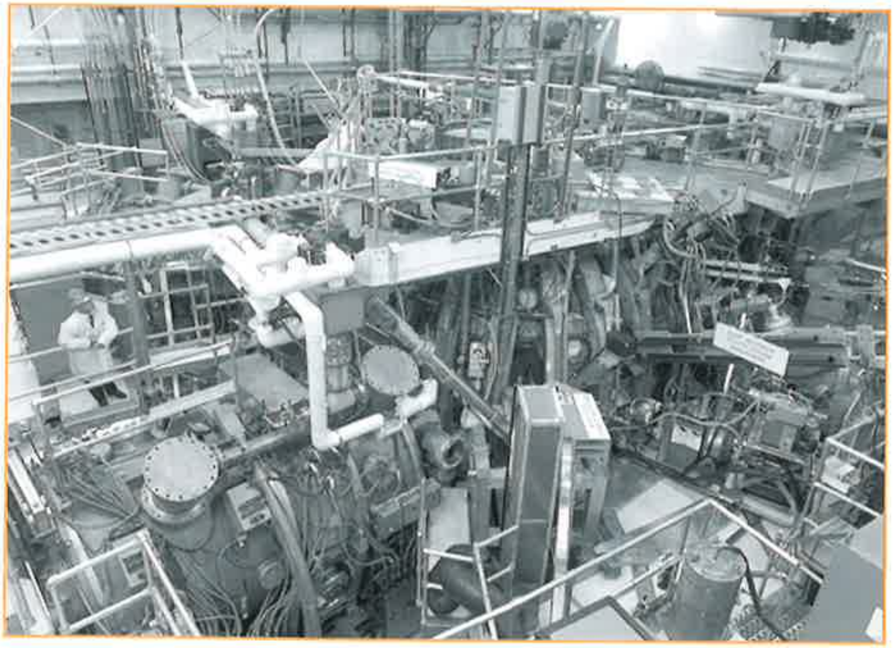
Because of the renewed interest in arc detection, PPPL staff have investigated non-voltage standing wave ratio based methods. Second harmonic signals could have been used as a reliable arc detection indicator on TFTR as they were found only during arcs, but earlier tests indicated that this approach might not be as reliable on DIII-D because of false signals in the presence of edge localized modes. New measurements of both second harmonic and low-frequency noise that could be generated by an arc were made; it was discovered that second harmonic signals did indicate arcs on the antenna during vacuum conditioning, but no second harmonic signal was observed during arcs in the pressurized transmission line. The low-frequency signals were observed in both cases (5-15 MHz band), however, similar amplitude signals were also measured during plasma operation. Narrower band filters have been placed on voltage probes closer to the antenna to continue these studies.

Parts have been machined for the Asea Brown Boveri/EIMAC tube adapter. The parts will be delivered to PPPL in early FY98, where they will be fit checked to an EIMAC tube. Then, they will be sent out to be plated. After the water circuits are fabricated, the kits will be ready for GA. Parts have been ordered and received to finish the grid regulator upgrade for the 30-60 MHz FMIT (an arc source originally built for the Fusion Materials Irradiation Test facility). These parts will be shipped to GA for installation in early FY98.

PPPL continues to provide support for DIII-D data analysis codes. The 4D code was upgraded for improved printing. A new version of the Doppler shift widget was installed and the EFIT code widget's ability to read files was upgraded, along with other improvements. PPPL also continues to provide support for the Shot Logger Program, including instruction, problem solving, and development work on the Time Series Analysis code.

The SPARROW code was imported from PPPL for the visualization and time series analysis of magnetohydrodymanic (MHD) instabilities and the study of sawtooth or modulated electron-cyclotron heating pulses using electron-cyclotron emission, soft X-ray or Mirnov data. The code has been converted to run on the UNIX-based Hewlett Packard computers and to access DIII-D raw data files. SPARROW has been upgraded to access raw beam emission spectroscopy data, and DIII-D time-series analysis has been upgraded with a peak tracker and the facility for graphing 3-D perturbation profiles. SPARROW can now be used on the X-terminals in the DIII-D control room.

The SPARROW code was used to analyze a variety of electron-cyclotron emission and soft X-ray data from modulated electron-cyclotron

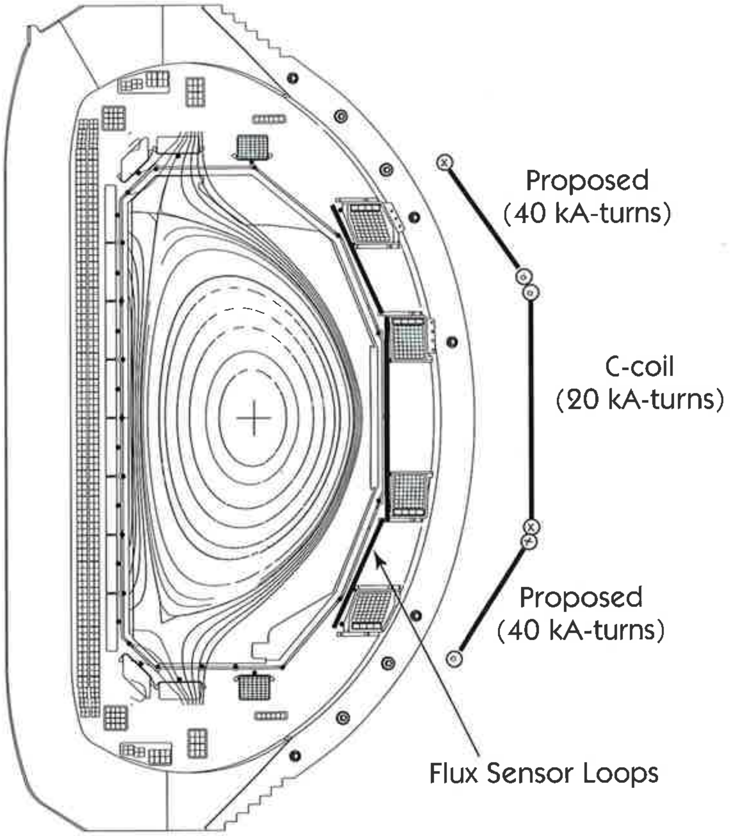


The Doublet III-D facility at General Atomics in California. PPPL scientists collaborate in research, operations, technical support, and design and construction of upgrades for the tokamak.

heating discharges for power deposition and heat transport coefficients. The data suggests that the power deposition is not strongly localized.

SPARROW was also used to start cataloging beta-limit disruption precursors. The preliminary conclusion is that L-mode (low-confinement mode) edge negative central shear beta-limit disruptions have similar precursors to those seen in TFTR enhanced-reverse-shear beta-limit disruptions.

PPPL continues to provide engineering support for the DIII-D nonaxisymmetric feedback coil project. A variety of options for feedback coil power supplies have been investigated and design of the saddle coil sensor loops to complement the "C" coil has begun.



In FY97, PPPL continued to provide engineering support for the DIII-D nonaxisymmetric feedback coil project. The above shows a design for additional proposed control coils and flux sensor loops.

## International Collaborations

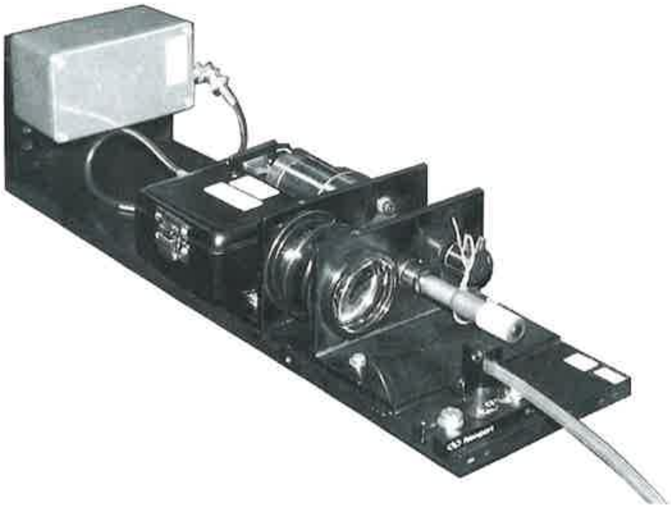
The international component of PPPL's collaboration program grew and changed in FY97, with a strong growth expected in FY98. The ending of experiments on TFTR occurred as the Joint European Torus (JET) in England was preparing for its series of full deuterium-tritium experiments. It became very clear that the tokamaks with the most high-power physics capability, JET and JT-60U (in Japan), were abroad. Managers of these devices welcomed the opportunity to have PPPL staff work on their physics programs.

Money and manpower availability limited participation in smaller tokamak programs in Europe. However, PPPL is now building the National Spherical Torus Experiment (NSTX) whose physics basis has been greatly strengthened by results from the Small Tight Aspect Ratio Tokamak (START) device in England. Therefore, PPPL began collaboration on START experiments at the end of the fiscal year. PPPL is assisting in theory and diagnostic development for the Large Helical Device (LHD), a Japanese stellarator which will begin operation in early 1998. Princeton's involvement comes as the result of the developing interest in building an innovative compact stellarator at PPPL.

At the end of the year, the U.S. Department of Energy appointed a Working Group on International Collaborations which will hopefully result in clear goals for international collaborations and a cohesive program involving people from various U.S. facilities.

In the area of burning plasma and fast-ion physics, the major information comes from experiments on JET. JET's series of full deuterium-tritium experiments lasted longer than planned and was beginning to achieve high-power performance at the end of the fiscal year. PPPL physicists, using TFTR's 14-MeV neutron generator, contributed significantly to the calibration of JET neutron diagnostics and helped prepare them for the experimental run. JET's neutron activation system is similar to TFTR's and key to assuring that the calibration of other detectors is maintained. The system was operated through the experimental run period.

PPPL physicists studied JET's fast-ion and alpha-particle-induced instabilities (TAE modes), both theoretically and experimentally. Laboratory research staff also participated in the first determination of TAE instabilities caused by the negative-ion neutral beam on JT-60U.



One unit of the motional Stark effect array diagnostic system for measuring the poloidal magnetic field inside the JET plasma.

The plasma conditions were deliberately set, making use of PPPL theoretical projections and experience in driving and damping such modes in TFTR. During FY97, JT-60U's high-energy negative-ion neutral beam underwent commissioning, and PPPL staff worked with JT-60U scientists to understand the ion optics to insure specified performance.

The recent exciting results that indicate substantially improved plasma performance in reversed shear discharges, detailed measurements of transport barriers, and the influence of E × B shear on TFTR led to PPPL's interest in supporting the core confinement programs of JET and JT-60U, including a motional Stark effect system for measuring the poloidal magnetic field inside the plasma for JET and a correlation reflectometer for the measurement of density fluctuations in the plasma core for JT-60U. [PPPL has also assisted Tore Supra (in France) in preparing their new motional Stark effect system.] These diagnostics will come on-line in FY98, but there has already been participation in physics studies of JT-60U's high-beta operation. The interpretation of performance has been greatly helped by the use of the transport code, TRANSP, developed at PPPL and being applied now to JET plasmas as well. The most important aspect in the development of the code this year has been the incorporation of modules to handle rf-accelerated ions, an activity in which PPPL has been assisted by the TEXTOR group in Germany.

A novel X-ray crystal spectrometer system has been used on the TEXTOR device; other diagnostics have been developed as part of PPPL participation on experiments. PPPL staff have built interface hardware for the electron-cyclotron emission diagnostics for the LHD. One physicist is making measurements of escaping fast ions on the Compact Helical System (CHS) stellarator in Japan, while developing designs for similar detectors for LHD. There has been a continued collaboration on MHD codes and application with the LHD team.

There has been some PPPL participation in experiments and considerable analysis of physics issues for spherical tokamaks with the START team in England. It is hoped that this collaboration will evolve as both the larger devices, NSTX and Mega Amp Spherical Tokamak or MAST (at Culham), become operational.

An important aspect of making these collaborations more effective has been the setting up of a modest off-site control room at PPPL with computers and video-link systems to relate with the operating devices and their experimental teams. While this is presently most effective for collaborations within the U.S., it is intended to provide experience relevant to a future ITER-like international device.

Discussions were initiated with the tritium group of the Japan Atomic Energy Research Institute. PPPL is offering to provide them with expertise required for work in the deuterium-tritium operational environment. This collaboration is expected to start in FY98.

# Collaborations

## Laboratories

A.F. Ioffe Physical-Technical Institute, St. Petersburg, Russian Federation
Argonne National Laboratory, Argonne, IL
Associated Western Universities, UT
Association Euratom-CEA, Cadarache, France
Association Euratom-CS, Lausanne, Switzerland
Associazione Euratom-CNR, Padova, Italy
Associazione Euratom-ENEA, Frascati, Italy
Brookhaven National Laboratory, Upton, Long Island, NY
Ecole Polytechnique Federale de Lausanne, Lausanne, Switzerland
Ecole Royal Militaire, Brussels, Belgium
Environmental Measurements Laboratory, U.S. DOE, New York, NY
Electrotechnical Laboratory, Tsukuba, Japan
Fermi National Accelerator Laboratory, Batavia, IL
Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID
Institute for Plasma Research, Ghandinagar, India
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 Atomic Energy Research Institute, Taejon, 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
Max Planck Institut für Plasmaphysik, Greifswald, Germany
National Institute for Fusion Science, Toki, Japan
National Institute for Science and Technology, Washington, DC
New Jersey Department of Environmental Protection, Trenton, NJ
Oak Ridge National Laboratory, Oak Ridge, TN
Pacific Northwest National Laboratory, Richland, WA
Russian Research Centre, Kurchatov Institute, Moscow, Russian Federation
Sandia National Laboratories, Albuquerque, NM
Sandia National Laboratories, Livermore, CA
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
UKAEA Technology Laboratory, Harwell, United Kingdom
Ukrainian Institute for Nuclear Research, Kiev, Ukraine

U.S. Department of Agriculture, Eastern Regional Research Center, Philadelphia, PA
Westinghouse Savannah River Site, Aiken, SC

## Industries

BASF, Charlotte, NC
BELCORE, Morristown, NJ
Biofine, Waltham, MA
Bristol-Myers Squibb, Lawrenceville, NJ
Canadian Fusion Fuels Technology Project, Canada
Charged Injection Corporation, Monmouth Jct., NJ
CompX, Inc., Del Mar, CA
Cookson Fibers, Bristol, PA
DuPont Chemical Corporation, Wilmington, DE
Fusion Physics and Technology, Inc., Torrance, CA
General Atomics, San Diego, CA
Hoechst Celanese, Charlotte, NC
Lodestar, Boulder, CO
Lucent Technologies, Murray Hill, NJ
Northrop Grumman Aerospace and Electronics Corporation, Bethpage, NY
Orincon Corp., San Diego, CA
Princeton Scientific Instruments, Inc., Princeton, NJ
Plasma Technology, Inc., Santa Fe, NM
Radiation Science, Inc., Belmont, MA
Russia Mission Research Corporation, Newington, VA
SAIC, San Diego, CA
Union Camp Corporation, Lawrenceville, NJ
Wellman, Charlotte, NC
Westinghouse Corporation, Pittsburgh, PA
WNET TV, Newark, NJ
Xerox Corporation, N. Tarrytown, NY

## Universities and Educational Organizations

American Physical Society, College Park, MD
Auburn University, Auburn, AL
The Australian National University, Canberra, Australia
Caltech, Pasadena, CA
Carnegie Science Center, PA
Center for Technological Education Holon, Holon, Israel
The College of New Jersey, Trenton, NJ
Colorado School of Mines, Golden, CO
Columbia University, New York, NY
The Contemporary Physics Education Project, Palo Alto, CA
Cornell University, Ithaca, NY
Drexel University, Philadelphia, PA
The Federal Laboratory Consortium
Florida State University, National High Magnetic Field Laboratory, Tallahassee, FL
Georgia Institute of Technology, Atlanta, GA
Hebrew University, Jerusalem, Israel
Idaho State University, Moscow, ID
Institute of Applied Physics, Academy of Sciences, Nizhny Novgorod, Russian Federation
Institute for Fusion Science, Austin, TX
Iowa State University, Ames, IA
Johns Hopkins University, Baltimore, MD
Korea Advanced Institute of Science and Technology, Taejeon, Republic of Korea
Lehigh University, Bethlehem, PA
Liberty Science Center, Elizabeth, NJ
Massachusetts Institute of Technology, Cambridge, MA
Mid-Atlantic Eisenhower Consortium, U.S. Department of Education, Philadelphia, PA
Nagoya University, Nagoya, Japan
National Association of Specialized Secondary Schools for Science and Mathematics, Washington, DC
New York University, New York, NY
Oak Ridge Institute for Science and Engineering, Oak Ridge, TN
Pennington High School, Pennington, NJ
Plainsboro Public Library , Plainsboro, NJ
Pohang University of Science and Technology, Pohang, Republic of Korea
Prairie View A&M University, Prairie View, TX
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
Trenton Schools System, Trenton, NJ
University of California, Davis, CA
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 Paris, Paris, France
University of Rochester, Rochester, NY
University of Texas, Austin, TX
University of Tokyo, Japan
University of Washington, Seattle, WA
University of Wisconsin, Madison, WI

# Engineering and Technical Infrastructure

The Engineering and Technical Infrastructure Department is responsible for managing the Princeton Plasma Physics Laboratory's (PPPL) engineering resources. The Department is organized functionally and includes the Mechanical Engineering Division; the Electrical Engineering Division; the Computer Engineering Division; and the Fabrication, Operation and Maintenance Division. In addition to providing engineering resources and support to the Laboratory's research endeavors, the Department is responsible for the technological infrastructure that supports the experiments, as well as the caretaking of PPPL's D-Site and [future] decontamination and decommissioning of the Tokamak Fusion Test Reactor (TFTR).

## Tokamak Fusion Test Reactor

In April 1997, the TFTR completed its final operating period bringing to close a highly successful phase of research in plasma science. The TFTR produced more than 65,000 high-power plasmas during its nearly 15-year lifetime, acquiring and archiving about 4 terabytes of data for scientific analysis. At maximum levels of instrumentation, more than 200 megabytes of data were acquired in a 12-minute period for a single pulse. More than 1,000 deuterium-tritium experimental discharges and more than 23,000 deuterium-deuterium discharges were carried out in the last four years of operation, producing record breaking plasmas of more than 10 MW of fusion power. During this time, TFTR technical systems routinely operated at or beyond the original design criteria, maintaining an impressive machine availability of greater than 85%. On the final night of operations, a plasma with a record 7.7 MJ of stored energy was attained.

The TFTR systems safely processed more than 950 kCi of tritium within the constraints of a 50 kCi site limit and a 25 kCi machine limit. The Tritium Purification System processed more than 50 kCi of recovered tritium at greater than 98% purity, sending it back to the Tritium Storage and Delivery System U-Beds for reuse in TFTR experiments.

For the final operating campaign, an antenna designed to direct launch ion-Bernstein waves for control of the plasma density profile was installed and fed by two of the existing radio-frequency sources redesigned to operate at both 76 and 50.7 MHz at power levels of up to 3 MW. Two new four-strap antennas were installed to provide the capability of launching toroidally directed waves for current drive and for studying the possibility of "channeling" alpha-particle energy to the fuel ions in deuterium-tritium plasmas. A Poloidal Rotation Diagnostic was installed and the existing Motional Stark Effect Diagnostic was upgraded with enhanced in-vessel optics to improve the signal-to-background ratio. The DOLLOP (Deposition of Lithium by Laser Outside the Plasma) was installed to provide, a method of aggressively depositing lithium on the limiter.

Upon conclusion of the experimental program, TFTR equipment was shutdown and safed in preparation for caretaking and/or removal.

## National Spherical Torus Experiment

Engineering analyses, manufacturing R&D, and design drafting of the key hardware components of the National Spherical Torus Experiment (NSTX) were performed in preparation for the final design reviews. These components included the magnet systems, vacuum vessel, and plasma-facing components. The reviews were completed on schedule, permitting the placement of long lead-time contracts for the magnets, copper, and the insulation materials. The first receipt of copper and insulation was in midsummer 1997. Delivery of the center stack magnets and the beginning of assembly operations are scheduled for the first quarter of calendar year 1998.

### Korean Superconducting Tokamak Advanced Research

The U.S. Home Team engineering activities for the Korean Superconducting Tokamak Advanced Research (KSTAR) Project centered around experimental device configuration, engineering of superconducting magnets, and plasma facing components and vacuum vessel design. This work provided input to a Design Point Definition Workshop held at PPPL in February 1997 at which time the mission, research objectives, machine parameters, and machine configuration were fixed. A Physics Validation Review was held in June to establish the physics design and general requirements; these were then translated into engineering requirements in a General Requirements Document.

### International Thermonuclear Experimental Reactor

The Department contributed to the International Thermonuclear Experimental Reactor (ITER) segmented solenoid study which concluded in the first quarter of FY97. Electromagnetic analyses were performed in support of the first wall and divertor designs using both the PPPL-developed SPARK program and commercial finite element codes. The vacuum vessel field welded joints were analyzed, taking into consideration fabrication tolerances and design code considerations. A feasibility study of ferromagnetic inserts for ripple reduction was performed. A cooling scheme for the metrology laser sensor was designed and analyzed. Reference discharge simulations were completed using the Tokamak Simulations Code. Reversed shear discharge simulations were completed and modern controller simulations were performed.

### Advanced Projects

PPPL participated in the development of a design point for a stellarator. An in-house computer code for generating quasi-axisymmetric configurations was developed, and optimization and stability codes were employed. These codes were used to evaluate configurations that have a high stability beta limit and a desirable rotational transform profile. Quasi-axisymmetric configurations have been developed with varying amounts of external rotational transform that show the ballooning mode stable to beta values in excess of 5%.

### Computer-Aided Design and Drafting

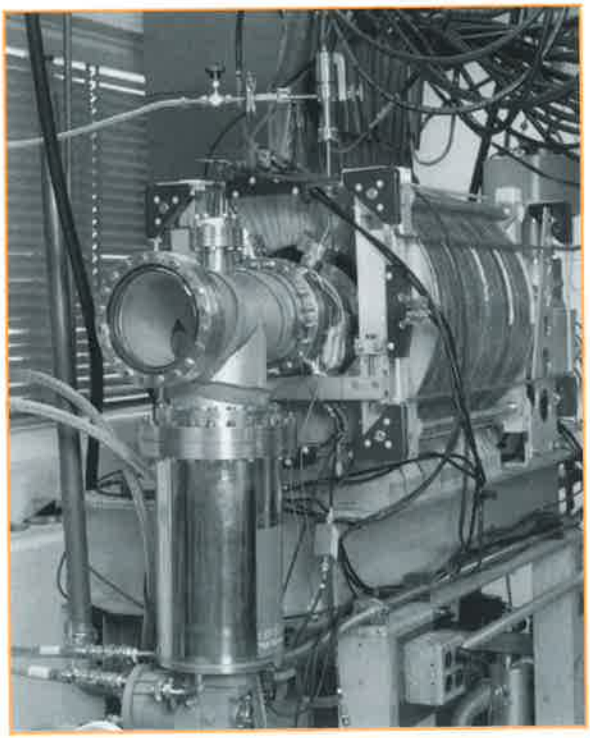
Five workstations utilizing Digital Equipment Corporation's 500-MHz Alpha processors and high-end video cards running under Windows NT, as well as three packages of Parametric Technology's "Pro Engineer" software, were installed. These provide a common computer-aided design platform with many of our collaborators and improve our ability to do concurrent engineering which will increase the efficiency of the design and analysis process.

### Collaborations

In an effort to enhance PPPL remote collaboration capabilities, a Remote Collaboration Center was configured with several x-terminals and workstations and fixed graphics units for displaying data from remote experiments. The room is capable of videoconferencing using several types of network-based tools (MBONE, Cu-SeeMe, Quicktime conferencing), as well as an ISDN-based system. The room has been used to follow the Doublet III-D, Alcator Mod-C, and Japanese Tokamak-60U experiments. To provide researchers with better quality access to remote meetings, MBONE capability was made available on most PPPL networks.

The Remote Collaborations Center at PPPL. The clocks in the upper right-hand corner of the photo are set for time of day in Japan and San Diego, California, respectively—sites of remote collaborations with the Japanese Tokamak-60U and Doublet III-D experiments.

# Nonneutral Plasmas



Electron Diffusion Gauge Experiment

A nonneutral plasma is a many-body collection of charged particles in which there is not overall charge neutrality. Such systems are characterized by intense self-electric fields and, in high-current configurations, by intense self-magnetic fields. Nonneutral plasmas, like electrically neutral plasmas, exhibit a broad range of collective properties, such as plasma waves, instabilities, and Debye shielding. Moreover, the intense self fields in a nonneutral plasma can have a large influence on detailed plasma equilibrium, stability, and confinement properties, as well as on the nonlinear dynamics of the system.

The many practical applications of nonneutral plasmas include: improved atomic clocks; the development of positron and antiproton ion sources; coherent electromagnetic radiation generation by energetic electrons interacting with applied magnetic field structures, including free electron lasers, cyclotron masers, and magnetrons; intense nonneutral electron and ion flow in high-voltage diodes; investigation of nonlinear collective processes and chaotic particle dynamics in high intensity charged particle beams propagating in periodic-focusing accelerators, such as those envisioned for heavy ion fusion, tritium production, and spallation neutron sources; and the measurement of background neutral pressure and electron collision cross sections with neutral atoms and molecules.

Experimental research on nonneutral plasmas at the Princeton Plasma Physics Laboratory is carried out in a Malmberg-Penning trap. The experimental apparatus in shown in Figure 1. The pure electron plasma is contained in cylindrical geometry, with a uniform, static axial magnetic field providing radial confinement, and applied potentials on the electrically isolated end cylinders providing axial confinement. The source of electrons is a directly heated spiral of tungsten wire. By varying the bias on the filament,the size and density of the plasma can be controlled. The plasma column rotates because the radial electric field due to space-charge effects gives an $\mathbf{E} \times \mathbf{B}$ drift in the azimuthal direction.

Single-species nonneutral plasmas have very robust confinement properties because the conservation of total canonical angular momentum provides a powerful constraint condition on the allowed radial positions of the particles. If no external torques act on the plasma, the plasma cannot expand radially to the wall. Internal interactions among the particles will then drive the plasma toward a confined thermal equilibrium state.

However, a background neutral gas will exert a torque on the rotating electron plasma thus allowing the plasma to expand radially. This forms the basis of current thesis research by a Princeton graduate student who is investigating the use of pure electron plasma as a pressure-sensing medium due to electron-neutral collisional transport and collective excitations. Typical experimental data is illustrated in Figure 2 where the increase in mean-square radius $<r^2>$ of the plasma column is plotted versus time t for confining magnetic field B = 108 G and electron line density $N_e = 2.8 \times 10^7$ $cm^{-1}$, and a background neutral pressure of $5 \times 10^{-9}$ Torr.

## Acknowledgments

This research was supported by an Office of Naval Research grant.

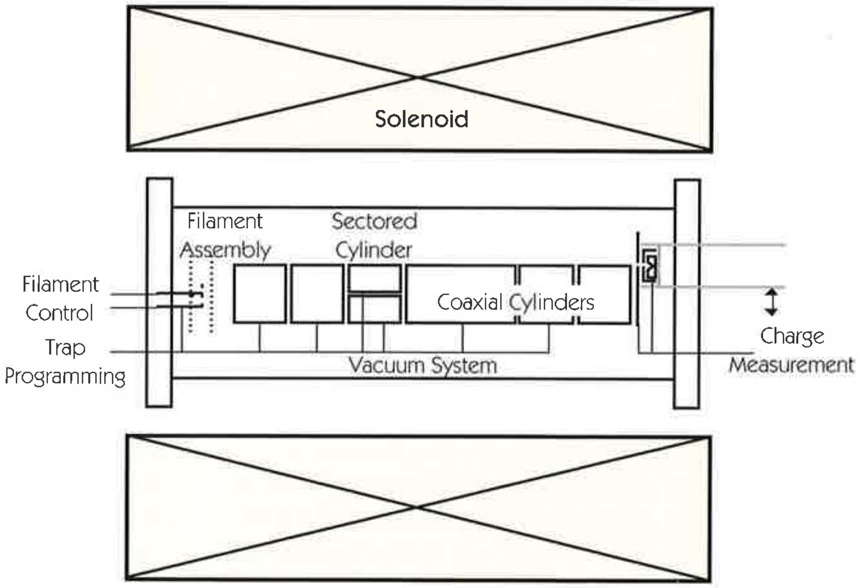


Figure 1. Schematic of the apparatus used in nonneutral plasma experiments. Typical experimental parameters are background pressure P ~ $10^{-9}$ Torr, magnetic field B ~ 100-600 G, plasma density n ~ $10^7$ $cm^{-3}$, and plasma temperature T ~ 1-5 eV.

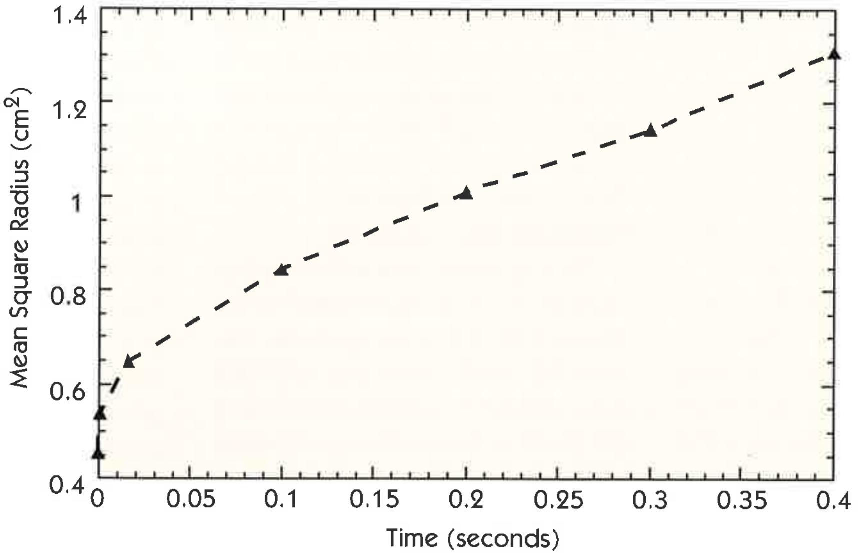


Figure 2. Typical experimental data illustrating the increase in mean-square radius $<r^2>$ of the plasma column versus time due to electron collisions with background neutral gas atoms.

# Technology Transfer

To insure the transfer of technology to the private sector, the Princeton Plasma Physics Laboratory (PPPL) continually seeks industrial and academic partners for research and development projects. These collaborations, primarily Cooperative Research and Development Agreements or CRADAs, involve applications of technologies relating to fusion and plasma sciences and their supporting disciplines.

CRADAs enable Laboratory researchers and their partners to work on projects of mutual interest. Costs and results may be shared by the participants. Since PPPL is funded by the U.S. Department of Energy, the Laboratory may only enter into CRADAs relating to DOE-funded research.

In addition to CRADAs, other technology transfer mechanisms are available to PPPL researchers, including Work-for-Others, Employee Exchanges, and Licensing of Inventions and Technologies. In Work-for-Others, industry pays for work performed at PPPL, while in the Employee Exchanges, researchers from industry assume a work assignment at the Laboratory or PPPL staff work in the industrial setting.

The following projects were underway during FY97.

## The American Textile Partnership — AMTEX

The American Textile Partnership (AMTEX) is a multi-laboratory Master CRADA that spans the entire U.S. textile industry. AMTEX has a number of subtasks, including the On-line Process Control Project (OPCon). PPPL is collaborating with Dupont, BASF, Camac Cookson, Wellman, and Hoechst-Celanese, through the Princeton Textile Research Institute, to develop a noncontact diagnostic instrument for use by U.S. synthetic fiber manufacturers to assure that their fibers conform to the required specifications. Noncontact measurements must be made on the production line, in real time. PPPL had completed the second year of this effort with demonstration measurements made at the facilities of several industrial partners, when the program was suspended because of funding limitations. In FY97, PPPL restarted the project. During FY98, a commercial prototype of the On-line Process Control System will be constructed.

## Modeling of Plasma Chemical Synthesis

This CRADA, with Drexel University's Center for the Plasma Processing of Materials (Philadelphia, PA) and Plasma Technology, Inc., a small business in Santa Fe, NM, addressed the technical feasibility of using an induction-coupled plasma torch to synthesize ozone at atmospheric pressure. Ozone concentrations up to about 250 ppm were produced using a thermal plasma reactor system based on an induction-coupled plasma torch operating at 2.5 MHz and approximately 11 kVA, with an argon/oxygen mixture as the plasma-forming gas. The ozone concentration in the reaction chamber was measured by Fourier transform infrared spectroscopy for a variety of experimental configurations. A gaseous oxygen quench formed the ozone by rapid mixing of molecular oxygen with atomic oxygen produced by the plasma. The geometry of the quench gas flow, the quench flow velocity, and the quench flow rate play dominant roles in determining the ozone concentration. It was shown that the ozone concentration is sensitive to the radio-frequency power, but insensitive to the torch gas flow rates.

These observations are interpreted within the framework of a simple model for ozone production synthesis.

### Radiation Sciences, Inc.

The objective of this Small Business Innovative Research CRADA was to develop the technology for bending large crystals for use in double focusing X-ray spectrometers and similar instruments requiring high spectral and spatial resolution simultaneously. To do this, PPPL researchers and Radiation Sciences personnel built a prototype of a new class of radiation resistant X-ray spectrometers for use on fusion experiments having high plasma temperatures and large fluxes of neutrons.

The first phase of the program used engineering analysis techniques, including finite element analysis of the crystal stresses, to ascertain that the scientific requirements of the spectrometer could be achieved. In the second phase, an accurately scaled down "breadboard" crystal bending fixture was constructed to bend the crystal. The optical properties of the crystal surface using visible-light interferometric techniques were evaluated. In FY98, this will be followed by measuring the focusing properties of the bent crystal at X-ray wavelengths. If Radiation Sciences wins a Phase II Small Business Innovative Research grant, the plan is to build a full-scale crystal X-ray spectrometer using a quartz crystal.

### Korean Basic Sciences Institute

In FY97, PPPL entered into a licensing agreement with the Korean Basic Sciences Institute for the use of the SPARK engineering analysis code, developed by PPPL for use on tokamak design. In return for the use of the code, the Korean Basic Sciences Institute supported the development of increased capabilities and enhancements of the code. PPPL technology is licensed through Princeton University's Office of Research and Project Administration.

### Work-For-Others Projects

The following Work-For-Others project was underway in FY97.

*Scaling Laws for Hall Thrusters:* This project, performed for the Air Force Office of Scientific Research, involves the development of a theoretical basis for the operation of plasma thrusters which could be used to stabilize and orient rockets and for long distance propulsion.

The following Work-For-Others projects are larger programs warranting their own sections in the Annual Highlights Report.

The *Magnetic Reconnection Experiment* (MRX) is a basic plasma physics research facility used to study the physics of magnetic reconnection—the topological breaking and reconnection of magnetic field lines in plasmas. Scientists 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. The results of these experiments will have relevance to solar physics, astrophysics, magnetospheric physics, and fusion energy research. This project receives support from the National Science Foundation, the National Aeronautics and Space Administration, the Office of Naval Research, as well as the U.S. DOE.

For the *Korean Superconducting Tokamak Advanced Research* project (KSTAR), PPPL is coordinating a U.S. team to support the design of the KSTAR device. KSTAR is the flagship project of the Korean National Fusion Program that was launched officially in January, 1996. The KSTAR device will be built at the National Fusion R&D Center at the Korean Basic Science Institute in Taejon, Republic of Korea.

For *Space Plasma Physics* research, PPPL has two grants from the National Science Foundation. The study of Kinetic Effects on MHD Phenomena in the Magnetosphere deals with theory and data analysis related to kinetic effects on MHD phenomena in the magnetosphere. When MHD activities are strongly affected by particle kinetic effects, they are referred to as kinetic-MHD phenomena. These studies are being performed with realistic anisotropic plasma pressure, magnetospheric equilibria, and realistic particle distribution functions. Simulation Study of the Formation of Solar Prominences and the Eruption of Solar Magnetic Fields includes the study of the physical processes associated with solar prominences and eruption of solar magnetic fields on the basis of computer simulations and mathematical theories.

In the study of *Nonneutral Plasmas*, the Experimental and Theoretical Studies of Nonneutral Plasmas project, funded by the Office of Naval Research, researches critical problem areas related to the equilibrium, stability, and nonlinear properties of nonneutral plasmas.

# Graduate Education

Fiscal year 1997 graduate students in The Program in Plasma Physics, Department of Astrophysical Sciences, Princeton University.

The Princeton Plasma Physics Laboratory (PPPL) 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 181 graduates since 1959, the Program has had a significant impact on the field of plasma physics, providing many of today's leaders in the field of 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 FY97, there were 42 graduate students in residence in the Program in Plasma Physics, holding among them one Department of Energy Magnetic Fusion Science Fellowship, one Princeton/Hertz Fellowship, two National Science Foundation Fellowships, one Department of Defense National Defense Science and Engineering Graduate Fellowship, one National Aeronautics and Space Administration Graduate Student Researchers Program Fellowship, and one Princeton University Honorific Fellowship.

## Students Admitted to the Plasma Physics Program in Fiscal Year 1997.

| Student | Undergraduate Institution | Major Field |
|---|---|---|
| Daniel Clark | Dartmouth College | Physics and Engineering Science |
| Ronald Stowell | California Institute of Technology | Physics and Applied Math |
| Susan Sujono | Massachusetts Institute of Technology | Physics |
| Sorin Zaharia | University of Bucharest | Physics |

Four new students were admitted in FY97, one from Indonesia, one from Romania, and two from the U.S. Four students graduated in FY97. Two received postdoctoral positions, one at the University of California at Los Angeles and the other at the Los Alamos National Laboratory. One of these graduates won a prestigious postdoctoral research fellowship from the Department of Energy. Two graduates took positions in private industry, one at Communications and Power Industries in California and the other at Sanwa Securities in New York.

Three awards were given out this year, one to Mr. Yang Chen, a fifth-year graduate student, who 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. Dmitri Uzdensky, also a fifth-year graduate student, won the Princeton University Charlotte Elizabeth Proctor Honorific Fellowship for scholarly excellence, and Mr. Hong Qin, a fifth year student, won a Wolfram Corporation Mathematica Visiting Scholar Grant.

First-year graduate students in the Program in Plasma Physics in 1997. From left-to-right are Sorin Zaharia, Ronald Stowell, Daniel Clark. Susan Sujono also a member of the first-year class is not pictured.

### Recipients of Doctoral Degrees in Fiscal Year 1997.

**Stephen R. Cauffman**

Thesis: Ion Cyclotron Emission from Fusion Plasmas
Advisor: Richard Majeski
Employment: Communications and Power Industries, CA

**Benjamin D.G. Chandran**

Thesis: Nonlinear Turbulent Dynamos and the Origin of the Galactic Magnetic Field
Advisor: Russell Kulsrud
Employment: University of California, Los Angeles, CA

**Hans W. Herrmann**

Thesis: Anomalous Loss of DT Alpha Particles in the TFTR
Advisor: Stewart Zweben
Employment: Los Alamos National Laboratory, NM

**Yi Zhao**

Thesis: Interaction between Energetic Particles and Sawtooth Instabilities in Tokamak Plasmas
Advisor: Roscoe White
Employment: Sanwa Securities, NY

Hong Qin (left), a fifth-year graduate student, received a Wolfram Corporation Mathematica Visiting Scholar Grant; Dmitri Uzdensky (middle), fifth-year graduate student, was awarded the Princeton University Charlotte Elizabeth Proctor Graduate School Honorific Fellowship; and Yang Chen, also a fifth-year graduate student received the Princeton University Ray Grimm Memorial Prize in Computational Physics.

# Science Education

Coached by PPPL Engineer Alex Nagy, fifteen students from Hopewell Valley Central High designed, built, and tested a robot (shown above) to enter in the Johnson & Johnson Mid-Atlantic Regional FIRST Competition. FIRST — For Inspiration and Recognition of Science and Technology — is a national engineering contest that immerses high school stduents in the world of engineering. Working after school and on weekends, the project took about 100 hours to complete. PPPL's Science Education Program sponsored the team in the competition.

The Princeton Plasma Physics Laboratory's (PPPL) Science Education Program continued to build on its past successes during fiscal year 1997. In addition to continuing the Program's 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

The PPPL Science Education Program continued the Princeton Research Enrichment Program (PREP), a residential scientific enrichment experience for talented high school students started in 1996. 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 PREP include career explorations in science and engineering, scientific enrichment using real-world problems to teach scientific content, and hands-on research as part of a team of scientists, engineers, and technicians. PREP is part of PPPL's enhanced outreach efforts.

In 1997, PREP focused on students in the Union City (New Jersey) Summer Scholars Program. Seven students were selected to participate, including one student from Trenton Central High School. (See the Table below for a listing of the participants and their projects.) The PPPL Science Education Program and individual mentors received a City Citation by the Mayor and Board of Commissioners of Union City for their contributions and support of the Summer Scholars Program.

PPPL also participated in the Liberty Science Center's Partners in Science Program. The program provides scientific internships to high school students. One student, Mark Ferraris of West Orange High School, worked at PPPL during the summer with Charles Neumeyer.

PPPL continued its commitment to provide volunteer internships to students attending local area high schools. In 1997, volunteer internships were awarded to students attending the Hun School of Princeton and Hopewell Valley Central High School.

1997 marked the first year the Science Education Office at PPPL sponsored a team to participate in FIRST (For Inspiration and Recognition of Science and Technology), a national creative engineering contest. The program gives students the opportunity to discover the important connection between the classroom and real world applications. The 1997 team, comprised of Hopewell Valley Central High School students and PPPL engineers, designed, constructed, and tested a championship robot. The Team competed in the Johnson & Johnson Regional Competition held at Rutgers University.

## Community Partnership Development

PPPL Science Education is collaborating with colleges and universities as well as community and industry-based programs, such as the National Science Research Council, the Invention Factory, Bristol Myers Squibb, the Science Alliance, Bridges to the Future, and others in science education reform efforts.

In 1997, PPPL received an award from the New Jersey Association of Partners in Education and the New Jersey Association of School Administrators. The award acknowledges the the Laboratory's outstanding efforts in the area of School Partnership Programs through the project "Building Bridges to the Future."

Through programs such as the Sigma-Xi Science Advisors program, PPPL scientists are continuing to work with teachers and students to enrich science curriculum and engage students in inquiry-based science experiments.

## Fusion Outreach Efforts

The Science Education Program was responsible for planning the 1997 Science Teachers Day and the Plasma Sciences Expo activities held in conjunction with the annual meeting of the American Physical Society's Division of Plasma Physics. In addition to workshops and presentations, several PPPL scientists took the opportunity to share their work and ideas with teachers and students.

## Interactive Plasma Physics Educational Experience

The Interactive Plasma Physics Educational Experience (IPPEX) (http://ippex.pppl.gov/ippex/) was designed by a PPPL team from the Physics, Computer, and Science Education divisions to provide internet-based physics curriculum modules for middle and high school students on the World Wide Web.

**Participants and Assignments in the 1997 Princeton Research Enrichment Program.**

| Name | High School | Mentor | Project |
|---|---|---|---|
| Juan Calles | Emerson High School | Andrew Post-Zwicker | Global Climate Modeling Development |
| Jazlyn Carvajal | Emerson High School | Carl Szathmary | Tritium Testing at REML |
| Eliezer Gervacio | Emerson High School | George Labik | Magnetic Reconnection Experiment |
| Sachin Patel | Emerson High School | Charles Gentile | Data Analysis on TFTR Tritium Usage and Design of the Tritium Monitor |
| Adrinne Vassell | Trenton Central High School | Robert Ellis | Thermal Analysis of ITER Metrology Probe Mast |
| Adalberto Vazquez | Union Hill High School | Carol Phillips/<br>Patti Wieser | Editorial and Information Services |
| Da Jin Wang | Union Hill High School | Andrew Post-Zwicker | IPPEX Development |

## Participants in the 1997 National Undergraduate Fellowship Program in Plasma Physics and Fusion Engineering.

| Name | School | Research Location | Mentor |
|---|---|---|---|
| Mary B. Dias | Hamilton College | University of Wisconsin | Professor Daniel J. Den Hartog |
| James A. Gill | Swarthmore College | Massachusetts Institute of Technology | Professor Jeffrey Freidberg |
| Atul Gupta | City College of the City University of New York | Lawrence Livermore National Laboratory | Dr. Fred V. Hartemann |
| Nathanial Hicks | Washington State University | General Atomics | Dr. Robert Pinsker |
| Christopher Holland | Johns Hopkins University | General Atomics | Dr. Rajesh Manji |
| Kenji Kadota | Ohio State University | General Atomics | Professor C. Craig Petty |
| Yeong S. Loh | Harvard University | General Atomics | Professor Todd Evans |
| Theng H. Lok | University of Texas at Austin | Princeton Plasma Physics Laboratory | Dr. Masaaki Yamada |
| Mihail M. Milkov | Angelo State University | University of California at Los Angeles | Dr. Francis F. Chen |
| David J. Strozzi | Princeton University | University of Texas at Austin | Dr. Wendell Horton |
| Kolo Wamba | Columbia University | Caltech | Professor Paul M. Bellan |
| Kim-Ee Yeoh | Hamilton College | Massachusetts Institute of Technology | Professor Peter J. Catto |
| Vitaliy Ziskin | SUNY at Stony Brook | Princeton Plasma Physics Laboratory | Dr. Hantao Ji |

In the fall of 1997, IPPEX was cited for its excellence on five web sites, including those of New Scientist magazine and the Exploratorium museum.

The "Virtual Tokamak," an IPPEX section created by PPPL's Daren Stotler, was chosen as one of the top 25 percent web applets by JARS, the JAVA Review Service. WWW Associates, an Internet development company, voted IPPEX one of the top ten science sites on the web. Finally, the Yahooligans Directory on the Internet cited IPPEX as its only "cool" physics site under "Top Science and Oddities: Physics."

In addition to being noted at various web sites, IPPEX was featured in the WNET (Channel 13, New York) program, "The Internet in Action—Real Time and Remote Visits," where tenth graders at the Bronx High School of Science used it in their physics classes.

## National Teacher Enhancement Project

Fiscal year 1997 marked the final year of the three-year teacher institute funded by the National Science Foundation and the U.S. Department of Energy. The institute is designed for science and mathematics teachers of grades 6-8 and features an integrated mathematics, science, and technology curriculum, as well as assessment techniques and leadership skills.

The third year concentrated on energy and its effects on the environment. Teachers were introduced to systems dynamics for use in the classroom. They used the mini-Climate Assessment Model to investigate different global energy consumption scenarios and their environmental implications. To better understand fossil fuels, teachers studied historical geology and fossil formation, and visited a coal mine in Scranton, Pennsylvania.

As a result of research experience gained in the project, teachers are better able to design experiments, analyze data, and draw meaningful conclusions, and are engaging their students in these activities more effectively and more frequently. Participants are demonstrating increased leadership in their schools and districts by conducting workshops for other teachers, serving on district curriculum committees, organizing science-related events for students and parents, and serving as a science resources for other teachers and administrators.

## PPPL-Trenton Partnership

The Trenton Partnership was begun in November 1990, when it became apparent that a "band-aid" approach to working with students in the 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 fiscal year 1997, the focus of the Partnership was on the implementation of inquiry-based curriculum using science kits in grades K-8. By the end of 1997, more than 500 teachers had been trained in the use of the kits. Through the efforts of PPPL, funding was secured from Bristol Myers Squibb to maintain and refurbish the kits.

Other regional and community stakeholders have become involved in the effort to improve math and science performance in the District. In addition to Bristol Myers Squibb, the participating organizations are Princeton University, The College of New Jersey, Mercer County Community College, the Invention Factory Science Center, Sigma Xi Science Advisors Program, the Bridges to the Future Partnership, The Education Fund of Trenton, Inc., Community Partners for Trenton Youth, Princeton Center for Leadership Training, and the IASA (Improving America's Schools Act) Advisory Council of the Trenton Public Schools.

Through the Partnership, the work of these organizations has evolved into a web of coherent, mutually supportive efforts with a common vision that provide significant leveraging of resources.

## Undergraduate Research Programs

The U.S. Department of Energy Office of Fusion Energy's Sciences National Undergraduate Fellowship Program in Plasma Physics and Fusion Engineering was held again during the summer of 1997. The program offered additional topics and new lecturers in its highly regarded week-long introductory course in plasma physics. This year's program hosted thirteen undergraduates from twelve different colleges and universities throughout the United States (see Table page 52).

PPPL also hosted seven students from Historically Black Colleges and Universities, Women's Colleges, and Hispanic Serving institutions as part of an undergraduate research opportunity program started in 1995.

Undergraduate students from both programs had an 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 Pittsburgh, Pennsylvania in November, 1997.

Science on Saturday, a thirteen-year-old lecture series geared towards high school students but open to all, drew more than 2,400 participants in FY97. Held Saturday mornings January through March, guest speakers included scientists, mathematicians, and other professionals from central New Jersey. In FY97, the lectures covered a wide range of topics, including "Knots, Tangles, and Bangles," "Making Diamonds from Thin Air: Learning New Ways to Do Things," and "Chemistry in the Crime Lab."

# Individual Honors

**Wilbert Barlow**
Civility Month Honoree
Princeton University

**Peter Bonanos**
Distinguished Engineering Fellow
Princeton Plasma Physics Laboratory

**Mary Ann Brown**
Spirit of Caring Award
United Way

**Charles Bush**
Civility Month Honoree
Princeton University

**Yang Chen**
Ray Grimm Memorial Prize
in Computational Physics
Princeton University

**John Clark**
Civility Month Honoree
Princeton University

**Steve Green**
Civility Month Honoree
Princeton University

**Linda Harmon**
Civility Month Honoree
Princeton University

**Richard Hawryluk**
Kaul Foundation Prize
for Excellence in Plasma Physics
and Technology Development
Princeton Plasma Physics Laboratory

**Charles Kessel**
Certificate of Merit
U.S. International Thermonuclear
Experimental Reactor Home Team

**Fred Levinton**
Award for Excellence
in Plasma Physics Research
American Physical Society

**Joellyn Lumberger**
Civility Month Honoree
Princeton University

**Lewis Meixler**
Representative of the Year
Federal Laboratory Consortium

**Harry Mynick**
Fellow
American Physical Society
Division of Plasma Physics

**Martin Peng**
Fellow
American Physical Society
Division of Plasma Physics

**Carl Potensky**
Hammer Award
Vice President Al Gore

**Hong Qin**
Mathematica Visiting Scholar Grant
The Mathematica Corporation

**Westley Reese**
Civility Month Honoree
Princeton University

**Gregory Rewoldt**
Fellow
American Physical Society
Division of Computational Physics

**Chris Ritter**
Civility Month Honoree
Princeton University

**Robert Tucker**
Civility Month Honoree
Princeton University

**Dmitri Uzdensky**
Charlotte Elizabeth Procter Fellowship
Princeton University

**Michael Williams**
Executive of the Year
Professional Secretaries International
Mercer County Chapter

**Lynne Yager**
Civility Month Honoree
Princeton University

**Masaaki Yamada**
Distinguished Research Fellow
Princeton Plasma Physics Laboratory

*U.S. Department of Energy Princeton Group Manager Jerry Faul (right) congratulates Carl Potensky on receiving the prestigious Hammer Award.*

## 1997 PPPL Employee Recogntion Award Recipients

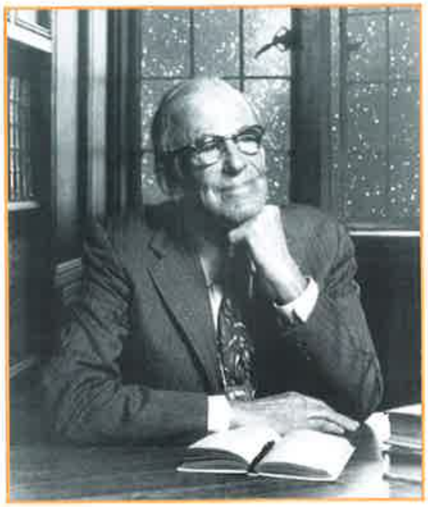
*Honored by their co-workers for their "personal qualities and professional achievements," sixty-six PPPL employees, including thirty-two tour guides, received Employee Recognition Awards in 1997. The recipients are, from left (front row), Sue Pontani, John Dong, Henry Carnevale, Glenn Pearson, Stewart Zweben, Dick Majeski, Alex Ilic, Mel Gensamer, Bill Jackson, Bobbie Forcier, Jeanne Salerno, and John DeLooper; (second row) Harry Towner, Irving Zatz, Bill Blanchard, Tom Kozub, Larry Dudek, Jim Kamperschroer, Keith Rule, John Luckie, Richard Wieland, Kevin McGuire, Stefano Bernabei, Bill Davis, Ben LeBlanc, Patti Wieser, Phil Heitzenroeder, Bob Kaita, Hantao Ji, and Stephen Paul; (back row) Steve Elwood, Scott Larson, Steve Williams, Charles Ancher, Al von Halle, Skip Schoen, Larry Sutton, Tom McGeachen, and Susan Murphy-LaMarche. Not pictured are George Ascione, John Bavlish, Norton Bretz, Raymond Camp, Dave Ciotti, Vern Clift, Mark Cropper, Nero Fortune, Charles Gentile, Steven Green, Carol Hirschman, Steve Kemp, Donald Long, Mark Oldaker, Erik Perry, Steve Raftopoulos, Ed Rogers, Greg Schmidt, Carl Scimeca, Steve Scott, Charles Sims, Richard "Pete" Szaro, Timothy Vavricka, Michael Williams, Joe Winston, Ken Young, and Nazia Zakir.*

# The Year in Pictures

*Robert J. Goldston, Professor of Astrophysical Sciences at Princeton University and Associate Director for Research at PPPL, became the Laboratory's fifth Director on July 1, 1997.*

*Richard Hawryluk, who led the record-breaking experiments on the TFTR Project, was named Deputy Director of the Laboratory in August.*

*William M. Tang, Head of the internationally renowned Theoretical Department at PPPL, was appointed Chief Scientist of the Laboratory in August.*



*Laboratory founder Lyman Spitzer, a giant in theoretical astrophysics and plasma physics, died on March 31, just a few days before the final TFTR experiments were conducted.*

On April 4, experiments on the Laboratory's flagship experimental fusion machine, the Tokamak Fusion Test Reactor (TFTR), concluded. TFTR received wide recognition when it set a world record of 10.7 megawatts of controlled fusion power in 1994 and, in 1995, reached a world-record plasma temperature of 510 million degrees Celsius. Staffers, reporters, and family and friends gathered around computer monitors to watch the results of the final experiments.

Pamela Lucas was named PPPL Diversity Officer, a newly established position created by former Director Ronald C. Davidson. Lucas oversees the Lab's diversity efforts and leads the newly formed Diversity Working Group at PPPL.

The Science on Saturday lecture series was a hit, drawing more than 2,400 people to PPPL for talks that ranged from earthquakes and science in the crime lab to diamond making and optoelectronics. Princeton University Professor John Conway discusses "Knots, Tangles, and Bangles" as part of the series.

The Laboratory honored thirty-three inventors for Fiscal Year 1996 during the Fifteenth Annual Patent Recognition Dinner at Princeton University's Prospect House. Those attending the dinner and receiving awards were, from left, (front row) Frank Tulipano, Schweickhard von Goeler, Manfred Bitter, Richard Majeski, and Szymon Suckewer; (back row) Joseph Bartolick, Charles Ancher, Ronald Bell, John Schmidt, Nathaniel Fisch, Gennady Shvets, Robert Woolley, and Sam Cohen.

# Patent Activities for Fiscal Year 1997

## Patents Issued:

*Apparatus and Process for Producing High Density Axially Extended Plasmas*
— J.E. Stevens and J.L. Cecchi

## Patents Applied For:

*Traveling Spark Ignition (TSI) System*
— S. Suckewer and E.J. Durbin

## Invention Disclosures:

*Spectroscopic Method to Measure Electric Fields in a Plasma*
— M.C. Zarnstorff

*Apparatus and Method for Non-optical Imaging and Structure Determination of Random Variable Targets (Brillonin Doublet Correlations: A New Method for Structure Determination and Non-optical Imaging of Random Variable Targets)*
— R. Nazikian

*The Conducting Shell Stellarator*
— G.V. Sheffield

*Live Parallels*
— J. DeSandro, J. Wioneck, J. Vannozzi, and W. Zimmer

*Magnetic Field Sensors (probes) using Thick-film Printed-circuit (PC) Technology*
— H. Takahashi

*Efficient Tritium Removal by Heating with Continuous Wave Lasers*
— C.H. Skinner

*Magnetic Nozzle to Promote Plasma Recombination*
— S.A. Cohen, J. Park, T. Munsat

*Pulse Shaping in Short-pulse FFL Oscillators using Multiple Resonators*
— G. Shvets and J.S. Wuztele

*A Molecular Sieve Binder for Tritiated Water which Prevents Hydrogen Gas Formation*
— R.T. Walters

*SPARK Version 2.0*
— D. Weissenburger and J. Bialek

*Method and Apparatus to Produce and Maintain a Thick, Flowing, Liquid Lithium First Wall for Toroidal Magnetic Confinement DT Fusion Reactors*
— R.D. Woolley

*Method and Apparatus to Directly Produce Electrical Power within the Lithium Blanket Region of a Magnetically Confined, Deuterium-Tritium (D-T) Fueled Thermonuclear Fusion Reactor*
— R.D. Woolley

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# Organization, Staffing, and Budget

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## PPPL Staffing Summary by Fiscal Year

| | FY93 | FY94 | FY95 | FY96 | FY97 |
|---|---|---|---|---|---|
| Faculty | 7 | 7 | 7 | 7 | 6 |
| Physicists | 100 | 97 | 91 | 89 | 88 |
| Engineers | 171 | 156 | 118 | 105 | 76 |
| Technicians | 351 | 306 | 215 | 198 | 137 |
| Administrative | 131 | 121 | 91 | 81 | 66 |
| Office and Clerical Support | 69 | 57 | 37 | 28 | 19 |
| Total | 829 | 744 | 559 | 508 | 392 |

## PPPL Financial Summary by Fiscal Year
## (Thousands of Dollars)

| | FY93 | FY94 | FY95 | FY96 | FY97 |
|---|---|---|---|---|---|
| **Operating Costs** | | | | | |
| Fusion Energy Sciences | | | | | |
| TFTR Physics | $13,870 | $17,331 | $14,207 | 13,004 | 13,607 |
| TFTR Operations | 43,858 | 50,646 | 46,938 | 33,792 | 13,497 |
| TFTR DT Systems | 21,246 | 1,041 | — | — | — |
| TFTR Shutdown/Caretaking | 716 | 4,503 | 2,047 | 8 | 12,368 |
| Subtotal TFTR | $79,690 | $73,521 | $63,192 | $46,804 | $39,472 |
| NSTX | — | — | — | 1,163 | 1,441 |
| TPX | 14,691 | 15,550 | 43,145 | (1,255) | (1,062) |
| Advanced Projects | — | — | — | 1,073 | 702 |
| Theory and Computation | 3,202 | 3,142 | 3,295 | 2,683 | 2,929 |
| ITER | 1,691 | 2,146 | 2,138 | 2,981 | 3,546 |
| Off-site Collaborations | 519 | 430 | 2,279 | 1,253 | 4,028 |
| PBX-M | 8,535 | 3,913 | 4,138 | 9 | — |
| CDX-U | 585 | 677 | 758 | 699 | 479 |
| Science Education Programs | 238 | 271 | 429 | 301 | 440 |
| Other Fusion | 393 | 519 | 1,710 | 1,232 | 1,469 |
| Change in Inventories* | (96) | (1,915) | (76) | (90) | (35) |
| Total Fusion Energy Sciences | $109,448 | $98,254 | $121,008 | $56,853 | $53,409 |
| Environmental Restoration and Waste Mgt | 3,434 | 4,811 | 5,728 | 3,581 | 4,066 |
| Computational and Technology Research | 50 | 66 | 300 | 391 | 157 |
| University and Science Education | 334 | 406 | 331 | 279 | 92 |
| Energy Management Studies | 115 | 65 | 124 | 136 | 13 |
| Total DOE Operating | $113,381 | $103,602 | $127,491 | $61,240 | $57,737 |
| Work for Others | | | | | |
| Korea Basic Science Institute | — | — | — | 186 | 1,837 |
| All Other | 1,370 | 490 | 797 | 693 | 1,199 |
| Total Operating Costs | $114,751 | $104,092 | $128,288 | $62,119 | $60,773 |
| **Capital Equipment Costs** | | | | | |
| TFTR | $1,954 | $373 | $469 | $546 | $241 |
| NSTX Fabrication | — | — | — | — | 3,412 |
| All Other Fusion | 904 | 390 | 458 | 71 | 32 |
| Environmental Restoration and Waste Mgt | 73 | 67 | 127 | 125 | 75 |
| Total Capital Equipment Costs | $2,931 | $830 | $1,054 | $742 | $3,760 |
| **Construction Costs** | | | | | |
| General Plant Projects - Fusion | $2,398 | $1,875 | $2,066 | $2,158 | $473 |
| General Plant Projects - ERWM | — | 310 | 163 | — | — |
| Safety and Fire Protection Improvements | 1,936 | 1,014 | 817 | 332 | 34 |
| Radioactive Waste Handling Facility | — | — | 1,066 | 560 | 1 |
| Energy Management Projects | (6) | 11 | 71 | 66 | 255 |
| Total Construction Costs | $4,328 | $3,210 | $4,183 | $3,116 | $763 |
| TOTAL PPPL | $122,010 | $108,132 | $133,525 | $65,977 | $65,296 |

*Change of the inventory levels on hand at the end of the fiscal year compared to the previous fiscal year.

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**July 1998**

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