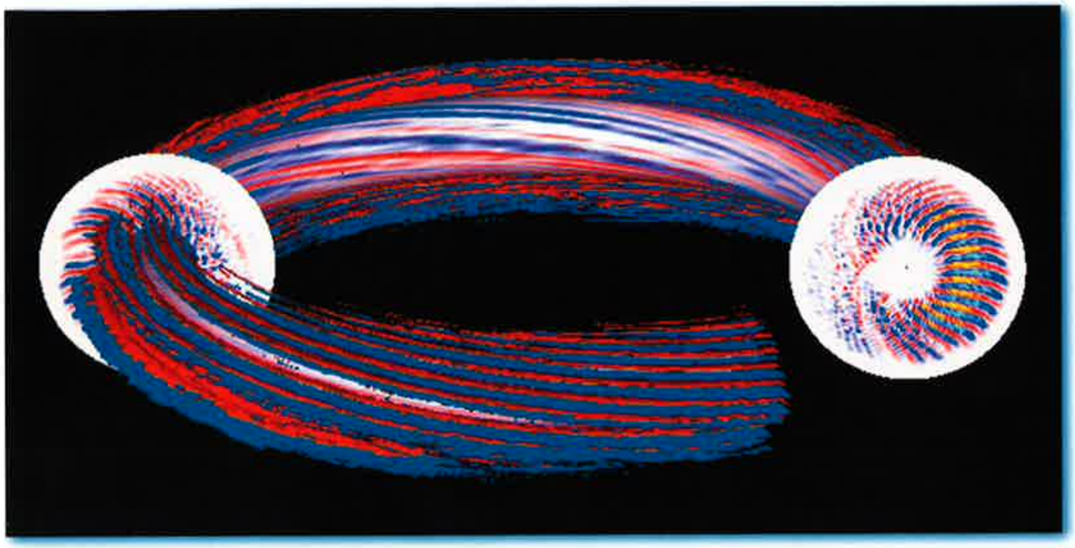
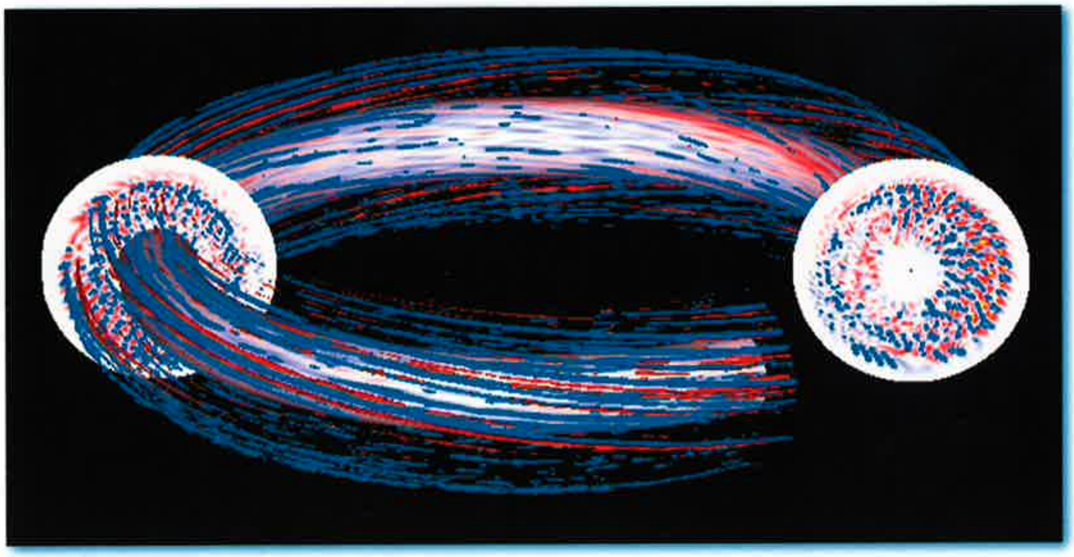
# 1998
# Annual
# Highlights





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 and approaching operation.

PPPL is managed by Princeton University under contract with the U.S. Department of Energy. The fiscal year 1998 budget was approximately $58 million. The number of full-time regular employees at the end of the fiscal year was about 390, not including approximately 50 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 advanced computational simulations, 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 the development of a noncontact diagnostic instrument for use by U.S. synthetic fiber manufacturers 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

Fusion research in the U.S. will be revolutionized by greatly enhanced simulation and modeling capabilities afforded by massively parallel processing. The results depicted on the cover were made possible using the full capabilities of the massively parallel CRAY T3E Supercomputer at the National Energy Research Scientific Computing Center at the Lawrence Berkeley National Laboratory. In these gyrokinetic particle-in-cell simulations of plasma turbulence in a tokamak, fluctuating finger-like density contours (shown in the upper panel) which promote heat and particle loss are destroyed (see lower panel) by the shearing action of self-generated zonal flows.

This publication highlights activities at the Princeton Plasma Physics Laboratory for fiscal year 1998 — 1 October 1997 through 30 September 1998.

# 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.

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# From the Director

The key themes of our research at the U.S. Department of Energy's Princeton Plasma Physics Laboratory (PPPL) are Understanding, Innovation, and Collaboration. We strive to *understand* the physics of plasmas and then to develop key *innovations* based on that understanding. Our vision is indeed to develop the new ideas that will make fusion a practical energy source for the next Millenium. But we are also interested in understanding and innovation in all areas of plasma science and related technologies. Success in our endeavors requires strong *collaboration* among researchers, among elements of the Laboratory, and among research institutions both in the U.S. and abroad. We are proud of our accomplishments in all of these areas. The design of the innovative National Spherical Torus Experiment (NSTX) would not have been possible without the discovery and exploration of the self-generated "bootstrap" current on the Tokamak Fusion Test Reactor (TFTR). Many of the innovative features of the National Compact Stellarator Experiment (NCSX), under design by PPPL and a large collaborative team, particularly from the Oak Ridge National Laboratory, rest on understanding developed from tokamak research, such as the identification of neoclassical tearing modes on TFTR. We are also proud of our growing collaborative off-site experimental efforts, and of the strong national collaborative teams assembled to perform research on NSTX. We are particularly indebted to our colleagues in the international stellarator community for their collaboration on NCSX.

***Robert J. Goldston***

The purpose of the Annual Highlights Report is to present a brief overview of the Laboratory's research and programmatic accomplishments during Fiscal Year 1998 (October 1, 1997 through September 30, 1998). Fiscal Year 1998 was a time of transition for PPPL. The highly successful TFTR was shut down in Fiscal Year 1997, and NSTX was not scheduled to begin operation until Fiscal Year 1999. Major efforts to support this transition included a strong focus on analyzing and publishing large amounts of the data from TFTR, and on optimizing the final design and construction of NSTX. The NSTX construction effort is on budget and ahead of schedule. National and international collaboration will play a larger role in the future at PPPL, and Fiscal Year 1998 saw a great strengthening of collaborative efforts, particularly at the DIII-D tokamak at General Atomics in San Diego, CA; at the Alcator C-MOD tokamak at MIT in Cambridge, MA; at the Joint European Torus (JET) in England; and at the JT-60U tokamak in Japan. Another major initiative involved the strengthening of the Computational Plasma Physics Group, supporting both our theoretical and experimental teams with advanced computational techniques. Dramatic successes were scored in the design of a new compact stellarator concept, building on new understanding in both the tokamak and stellarator arenas, and potentially leading to a system combining the high power density of an advanced tokamak with the rigid stability and low recirculating power of a stellarator. Very important results were achieved with PPPL's smaller operating experiments, particularly the Magnetic Reconnection Experiment (MRX) and the Current Drive Experiment-Upgrade (CDX-U). Important contributions were made to the design of the Korea Superconducting Tokamak Advanced Research (KSTAR) device, and to the design of the International Thermonuclear Experimental Reactor (ITER). Finally, very important progress was made in a number of areas of applications research.

Some highlights of this year's research include:

- Discovery of a very steep electron temperature gradient near the shear reversal point in Enhanced Reversed Shear modes in TFTR, indicating a very narrow and strong transport barrier.
- Confirmation of the effectiveness of High Harmonic Fast Wave (HHFW) heating on CDX-U. HHFW is the planned radio-frequency heating technique for NSTX.
- Confirmation in MRX of the applicability of an extended Sweet-Parker model to magnetic reconnection, a key fundamental phenomenon of basic plasma physics.
- The application of massively parallel supercomputers to vastly accelerate computations of plasma turbulence.
- Development of a new model of geomagnetic substorms based on the kinetic ballooning mode, first developed for understanding kinetic effects in fusion plasmas.
- Rapid progress in the construction of NSTX, including improvements to the poloidal coil system design and delivery of key components.
- A breakthrough in the design of compact stellarators, in which quasi-axisymmetric configurations were discovered with simultaneous kink, ballooning and neoclassical tearing stability.
- Important contributions to the ITER and KSTAR projects, both in the areas of physics analysis and engineering design.
- Initiation of major collaborative efforts at DIII-D, C-MOD, JET and JT-60U.
- Confirmation of the diffusive loss of a pure-electron plasma due to electron-neutral collisions.
- Major progress in the development of laser scattering as an on-line diagnostic for the manufacture of fibers for the textile industry.
- Improved understanding of techniques for ozone manufacture, using plasmas.
- Support of the U.S. Department of Agriculture in research using radio-frequency waves for cold-pasteurization of liquids.

We are proud of our close association with Princeton University and its Department of Astrophysical Sciences. The Graduate Program in Plasma Physics is certainly among the strongest in the nation, continuing to produce the future leaders, we believe, in plasma science. Ties are also growing with the Princeton Department of Computer Science, in addition to our traditional close relationship with the Mechanical and Aerospace Engineering Department, as well as the Princeton Center for Energy and Environmental Studies.

Fiscal Year 1998 was a year of transition, marked by a series of important successes and great optimism for the future. We believe that the key understanding we have harvested from TFTR, combined with future insights from both on-site and off-site experiments, and from theory and advanced computation, will lead to the innovations that will make fusion a leading energy source for humankind.

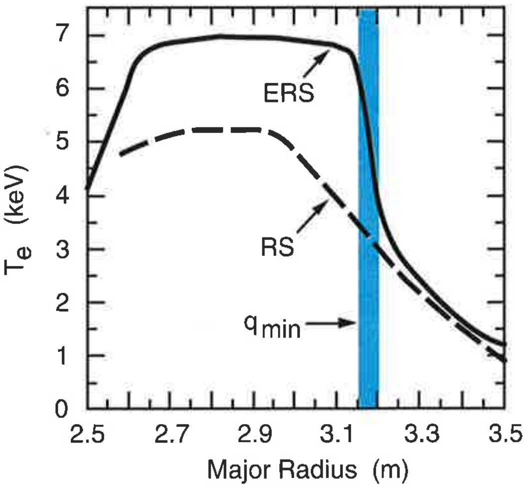
# Tokamak Fusion Test Reactor

Experimental operations were conducted on the Tokamak Fusion Test Reactor (TFTR) through April 4, 1997. The 14 years of experimentation in TFTR included more than three years of research in the science of deuterium-tritium plasmas. The tokamak is now in a safe shutdown condition awaiting eventual dismantling and removal. Ancillary systems, including power supplies, neutral-beam injectors, ion cyclotron radio-frequency generators, and diagnostic equipment, are being transferred for reuse on the National Spherical Torus Experiment (NSTX). Although operation of TFTR has ceased, an active research program was conducted in FY98 to analyze and publish the vast quantity of data accumulated over the final years of its operation, particularly during its operation with deuterium-tritium plasmas.

## TFTR Data Analysis

The analysis of TFTR data in FY98 revealed several new characteristics of plasmas in both the supershot and enhanced reversed shear (ERS) regimes. Electron temperature profile measurements using a plasma position jog technique were analyzed. In these experiments, the plasma was moved past the fixed channels of the electron cyclotron emission grating polychromator. Analyses revealed that in ERS plasmas, the electron temperature gradient is much larger in the vicinity of the shear reversal surface, but also much lower inside the reversed shear region than previously thought. This structure was not apparent in similar reversed-shear discharges which did not exhibit an ERS transition. Profiles of the electron temperature in such plasmas are compared in the figure below. This suggests that a radially localized barrier exists for the electron thermal transport in ERS plasmas but that the electron transport actually increases near the axis in these plasmas.

The poloidal rotation in TFTR L-mode (low-mode), supershot, and reversed-shear plasmas was found to be quite different from the predictions of neoclassical theory. The measurements in supershots and L-mode plasmas provide quan-



***Radial profiles of the electron temperature in an ERS and an reverse shear (RS) plasma measured by the plasma jog technique after correction for the channel-to-channel calibration uncertainties of the electron cyclotron emission grating polychromator diagnostic. The extreme temperature gradient in the ERS plasma in the vicinity of 3.2-m major radius suggests a radially localized thermal transport barrier near the shear-reversal ($q_{min}$) surface.***

titative support for a theory linking the improved ion confinement of these regimes to the suppression of the turbulent transport associated with toroidal ion-temperature gradient modes by sheared plasma flow. The possibility of inducing the necessary sheared flow in the plasma by external means was confirmed by the results from experiments with ion-Bernstein waves, either launched directly or produced by mode-conversion from ion cyclotron radio-frequency (ICRF) fast waves in mixed-ion plasmas. The power levels in the TFTR experiments were, however, too low to produce radical changes in the plasma confinement.

Analysis of TFTR discharges with ICRF heating coupled through the H-minority fundamental resonance has revealed the excitation of a new group of modes in the Alfvén frequency range. Unlike the familiar toroidal Alfvén eigenmodes whose frequencies vary slowly with local plasma parameters, the frequencies of these modes chirp rapidly down as their location moves radially outwards following their initial appearance in the plasma core. These modes, tentatively identified as energetic particle modes and which exist in the normal toroidicity-induced gaps in the Alfvén continuum, appear to be responsible for the loss of energetic ions and a reduction in the heating efficiency as the ICRF power is increased above the threshold for their excitation.

Physicists supported by the TFTR Data Analysis Division in FY98 have presented research papers at several national and international meetings. Colloquia on TFTR results have been delivered at the Max-Planck-Institut für Plasmaphysik, Greifswald, Germany; the Australian National University, Canberra, Australia; and the JET Laboratory, Abingdon, United Kingdom.

A strength of the TFTR program over many years has been its interaction with collaborators from many institutions in the U.S. and abroad. Collaborative programs were continued in FY98 with colleagues from 17 institutions (see table).

In addition to many specialized research papers about TFTR results published in FY98 (approximately 80 papers were published or submitted), several comprehensive reviews of TFTR research have been and continue to be prepared for publication in the archival scientific literature. The topics of these reviews include: confinement regimes, transport, MHD stability, fusion performance, ion cyclotron radio-frequency heating, alpha-particles, toroidal Alfvén eigenmodes physics, and tritium technology.

***TFTR Data Analysis Collaboration Colleagues in FY98.***

| Collaborators | Home Institution |
|---|---|
| S. Sabbagh, F. Paoletti | Columbia University |
| W. Houlberg, C. Bush, G. Hanson, J. Hogan | Oak Ridge National Laboratory |
| Y. Hirooka, S. Luckhardt | University of California, San Diego |
| G. Wurden | Los Alamos National Laboratory |
| R. Fisher | General Atomics |
| F. Levinton | Fusion Physics and Technology |
| A. Kumar | University of California, Los Angeles |
| J. Myra, D. D'Ippolito | Lodestar |
| D. Smithe | Mission Research, New Mexico |
| R. Fonck, J-S. Kim, J. Scharer | University of Wisconsin |
| D. Ruzic | University of Illinois |
| H. Berk, B. Breizman | Institute for Fusion Studies, University of Texas, Austin |
| A. Kritz | Lehigh University |
| I. Semenov, S. Mirnov, N. Gorelenkov, A. Krasilnikov | Triniti, Russia |
| P. Savrukhin | Kurchatov, Russia |
| V. Yavorskij | Kiev Institute for Nuclear Research, Ukraine |
| M. Petrov | Ioffe, Russia |

# Current Drive Experiment-Upgrade

The principal research objective of the Current Drive Experiment-Upgrade (CDX-U) is to study the uses of radio-frequency (rf) power in a spherical torus (ST). The ST is a promising alternative approach to the economical production of fusion power, which offers potential advantages in compactness and simplicity when compared to conventional tokamaks. The novel features of the ST — high plasma pressure relative to the confining magnetic field, low toroidal field, and high plasma current relative to conventional tokamaks of similar size — force a reexamination of the rf heating, current drive, profile and particle control techniques that have been developed for the tokamak program. CDX-U, the world's first rf-heated ST, provides a testbed for the application of established rf techniques to the ST, and for the exploration of new rf regimes unique to the ST. The CDX-U research program includes investigations into:

- High Harmonic Fast Wave (HHFW) heating. This approach to heating and current drive will be the initial technique used for heating and current drive on the National Spherical Torus Experiment (NSTX). Extensive tests of HHFW heating have been performed on CDX-U.
- Electron Bernstein Wave (EBW) heating. This technique promises to extend electron cyclotron heating to the ST, and will be tested on CDX-U.
- Mode Conversion Heating and Current Drive. Heating and current drive through excitation of an Ion Bernstein Wave (IBW) via mode conversion was demonstrated on the Tokamak Fusion Test Reactor and has been extensively examined on Alcator C-Mod at the Massachusetts Institute of Technology and other tokamaks. Extension of this technique to the ST will be explored on CDX-U.
- Noninductive Start-up of an ST. The compact nature of the ST will make conventional ohmic operation impossible in a reactor, hence the necessity for noninductive initiation of the plasma discharge. Discharge initiation by a combination of rf techniques will be explored on CDX-U.

## Facility Description

A schematic of CDX-U indicating the magnetic field coils and vacuum vessel cross section, is shown in Figure 1. During FY98, the facility underwent an extensive program of upgrades and modifications to allow more comprehensive experiments and continued safe operation. Existing, unused power supplies originally installed at the Laboratory for the Princeton Beta Experiment-Modification (PBX-M) were cabled to the CDX-U

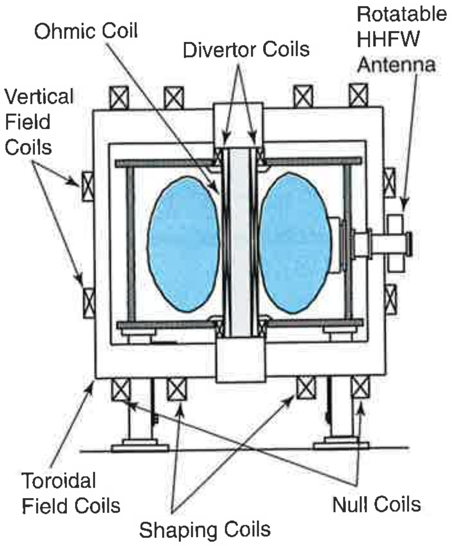


***Figure 1. Schematic cross section of CDX-U showing the field coils and rotatable high harmonic fast wave radio-frequency (HHFW) antenna.***

poloidal and toroidal field coils. The remaining CDX-U capacitor bank supplies, which power the ohmic solenoid and a new poloidal field coil coil, designed to improve plasma initiation, were also upgraded. As a result, the toroidal field will increase from 1.4 kG to 2.3 kG with a flattop of 100 msec. The new power supplies for the vertical and shaping fields will permit discharges with plasma current up to 150 kA, while the discharge duration will be extended to greater than 25 msec. All power supplies (with the exception of the two capacitor banks) will be preprogrammed and controlled by digital-to-analog waveform generators. The plasma geometry remains unchanged with major radius R = 34 cm, a minor radius a = 22 cm, and an aspect ratio $A = R/a \geq 1.4$.

Other improvements to CDX-U include the introduction of solid boron carbide rail limiters as plasma contacting components, improvements to the vacuum system, implementation of a boronization system, and additional access to the plasma for diagnostics. A major new diagnostic, the multipoint Thomson scattering system, was added. A control and data acquisition room, separate from the CDX-U area, was prepared to ensure operator safety. A new rf source was constructed, doubling the power available for HHFW to more than 200 kW. New antennas are being designed for excitation of the mode converted IBW. Finally, a 40-kW, 14-GHz microwave system has been loaned to the Laboratory by the University of Wisconsin Pegasus group to permit an investigation into EBW heating.

## Radio-Frequency Heating Experiments

The low-aspect-ratio ST plasma 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 in conventional tokamaks. In this case, rf waves launched at high harmonics of the ion cyclotron frequencey are effectively absorbed by the electron population with $\beta$ values of about 5% or greater. This property makes the HHFW a good candidate for electron heating and current drive in the ST. As a result, HHFW will be the first auxiliary heating and current-drive scheme applied to NSTX.

The first phase of experiments involving HHFW heating was completed in CDX-U in FY97, with subsequent analysis of the data continuing into FY98. Up to 100 kW of HHFW power was coupled into ohmically heated target discharges, using a novel rotatable antenna (Figure 2). Detailed measurements of fast-wave-induced density fluctuations using far-forward scattering techniques demonstrated wave coupling to the core plasma. Langmuir triple probe measurements taken at normalized minor radii $r/a > 0.6$ indicated that the electron temperature increased by about 30% in the outer region of the

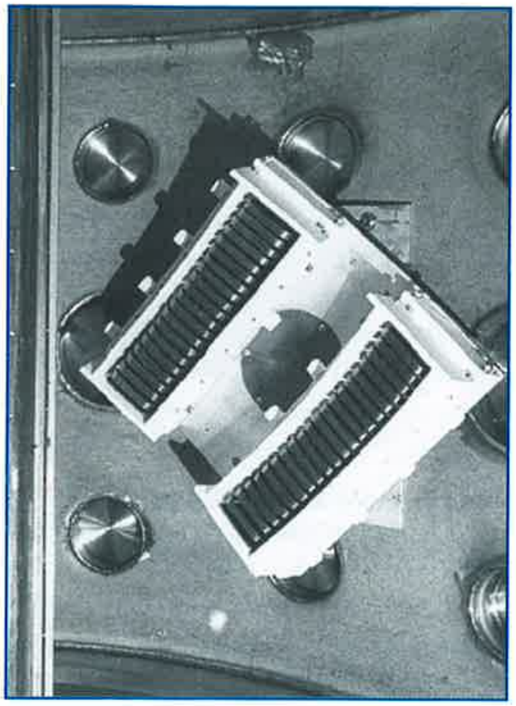


***Figure 2. Antenna for radio-frequency plasma heating rotated 45 degrees.***

plasma during rf injection. In most discharges, core electron heating was found to be modest. More recently, a careful examination of spectroscopic data, coupled with simulation of the plasma response using the MIST (Multiple Impurity Species Transport) code, indicated that in a few discharges, the core electron temperature increased by up to 50% during rf injection. The modeled increase in the electron temperature is shown in Figure 3. Modifications of the magnetohydrodynamic (MHD) activity consistent with the estimated core electron heating (≈30% increase in the electron diamagnetic frequency near the q = 1 radius) are also observed.

A proposed explanation for the infrequent core heating, consistent with the experimental observations and numerical estimates, is that the CDX-U plasma is in most cases slightly above the threshold of an accumulation instability for low-Z impurities. This neoclassical instability has recently been described in the context of high-Z impurities in large tokamaks by Tokar's model, which predicts a power deposition threshold for "breaking through" the saturated stage of the instability and allowing the core temperature to increase. Applying the model with the estimated CDX-U oxygen concentration, it is indeed found that increasing the core temperature would require auxiliary power deposition comparable to the ohmic input (≈150 kW). Since rf input power of approximately 100 kW, satisfies this condition marginally, the Tokar model may explain the intermittent observation of core electron 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.

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 multilayer mirror (MLM) detectors are planned for NSTX. The X-ray energies are determined from the angle of Bragg scattering off of the MLM, so the detectors avoid a direct view of the discharge. A prototype detector for measuring the Carbon-V emission at 40.5 Å was successfully tested earlier on CDX-U by collaborators from Johns Hopkins University. Based on this demonstration, MLM arrays are being constructed for NSTX and CDX-U.

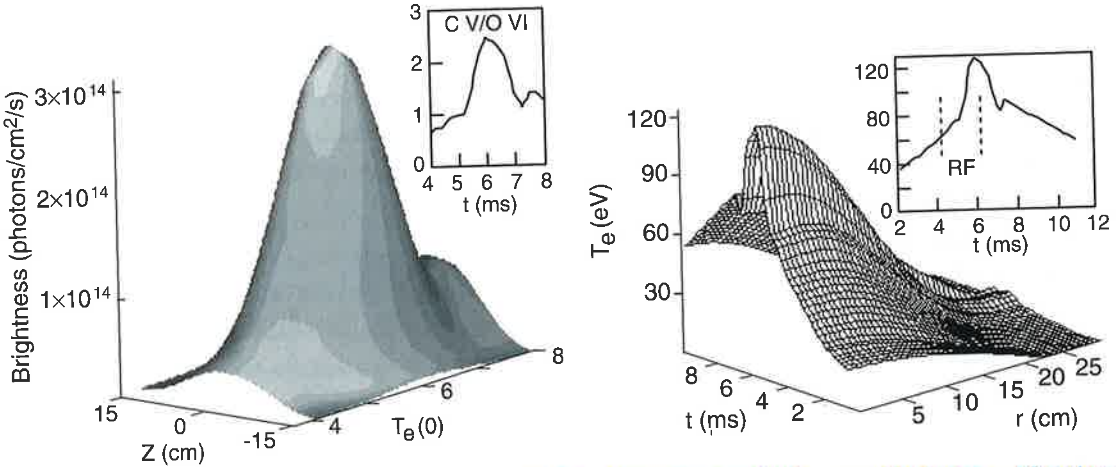


***Figure 3. Spectroscopic signals and estimated temperature evolution for discharge evidencing strong core heating during high harmonic fast wave injection: left is C V emission profiles and C V/O VI intensity ratio and right is $T_e(r,t)$ profiles.***

The CDX-U multilayer mirror array will be employed to investigate transport using injected boron atoms. Preliminary boron injection experiments with a Boron Low-Velocity-Edge Micropellet Injector have been performed, and further examination of its effectiveness for impurity control and as a tool for impurity transport are planned.

By the end of FY98, work neared completion on a new 12-point Thomson scattering system for CDX-U. This system will yield single-shot density and temperature profile information for rf heating and transport studies. The system will also provide calibration for a new electron cyclotron emission technique being developed on CDX-U for eventual application to NSTX.

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 for the electrostatic EBW, the CDX-U plasma looks like a blackbody emitter. A system to detect EBW emission from the CDX-U plasma was constructed during FY98 and will be tested during FY99. If EBW emission proves to be an effective diagnostic for electron temperature, then this system will provide electron temperature profiles throughout the discharge, with good time resolution. Present plans are to follow the tests on CDX-U with implementation on NSTX.

An obvious extension of the EBW emission experiment is to invert the emitter and collector and use the EBW to provide electron cyclotron heating at the plasma core, where the densities are too high to permit conventional electron cyclotron heating.

CDX-U also employs an array of standard diagnostics, including magnetic pickups for fluctuation and equilibrium diagnostics, a movable 2-mm microwave interferometer, numerous soft X-ray and optical diagnostics, Langmuir and rf magnetic probes, a Rogowski coil for measurement of the plasma current, a fast neutral pressure gauge, and a fast framing camera for high-time-resolution optical plasma imaging.

## Future Plans

Upgrades and modifications to CDX-U will be completed early in CY99. Operations will begin with new HHFW heating experiments at higher power (>200 kW) in denser, hotter plasmas than were previously possible in CDX-U. Characterization of the EBW emission from the CDX-U plasma will be followed by EBW heating experiments at modest (40 kW) power levels, at the second harmonic of the core electron cyclotron frequency (14 GHz). Noninductive start-up experiments will utilize both the 14-GHz microwave system and the 200-kW HHFW system to build up plasma density and temperature. Following these experiments, a new low-frequency antenna system will be installed to permit heating, current drive, and startup studies using the mode-converted IBW. The new low-frequency antenna system will also permit investigations of rotamak current drive in the ST, in a collaboration with Flinders University in Australia.

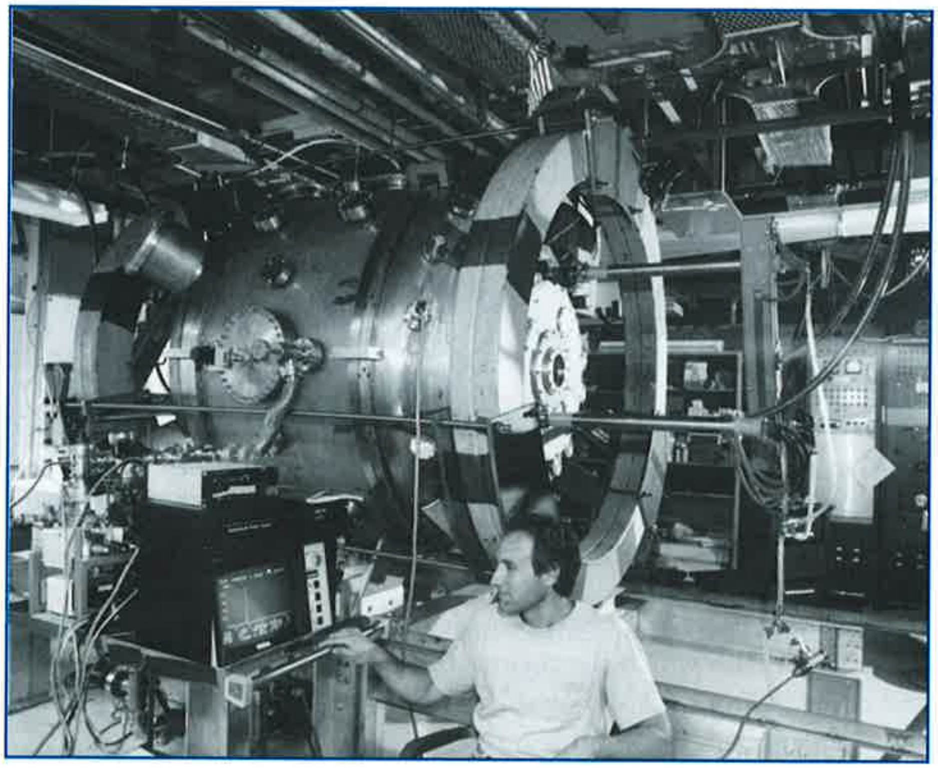
## Collaborations and Graduate Studies

The CDX-U group and the spectroscopy group at Johns-Hopkins University, Baltimore, Maryland, have maintained a long-running collaboration in the area of diagnostic development for the ST. In addition, the CDX-U group maintains ongoing collaborations with the University of Wisconsin, Madison, the University of Tokyo, Japan, Flinders University, Australia, the A.F. Ioffe Physical-Technical Institute, St. Petersburg, Russian Federation, and the Hebrew University, Israel. In addition, CDX-U scientists have worked actively with ST researchers from the Small Tight Aspect Ratio Experiment at Culham Laboratory in England.

During the summer of 1998, researchers and graduate students from Fisk University and Florida A&M University installed an argon-ion laser on CDX-U. The goal is to use laser-induced fluorescence to study plasma fluctuations, and measurements are planned when CDX-U resumes operations in CY99.

A primary role of CDX-U at PPPL has always been to serve as a training ground for graduate students in experimental plasma physics. In June 1998, Jonathan Menard defended his Ph.D. thesis entitled “High Harmonic Fast Wave Coupling and Heating Experiments in the CDX-U Spherical Tokamak.” Tobin Munsat is expected to defend his thesis in early CY2000. Four additional graduate students from the Princeton University Departments of Astrophysical Sciences and Physics are currently pursuing research projects on CDX-U. Undergraduate and high school students also worked with CDX-U as part of summer science honors programs.

# Magnetic Reconnection Experiment



*The Magnetic Reconnection Experiment.*

The Magnetic Reconnection Experiment (MRX), shown above, 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, shown in Figure 1, 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.

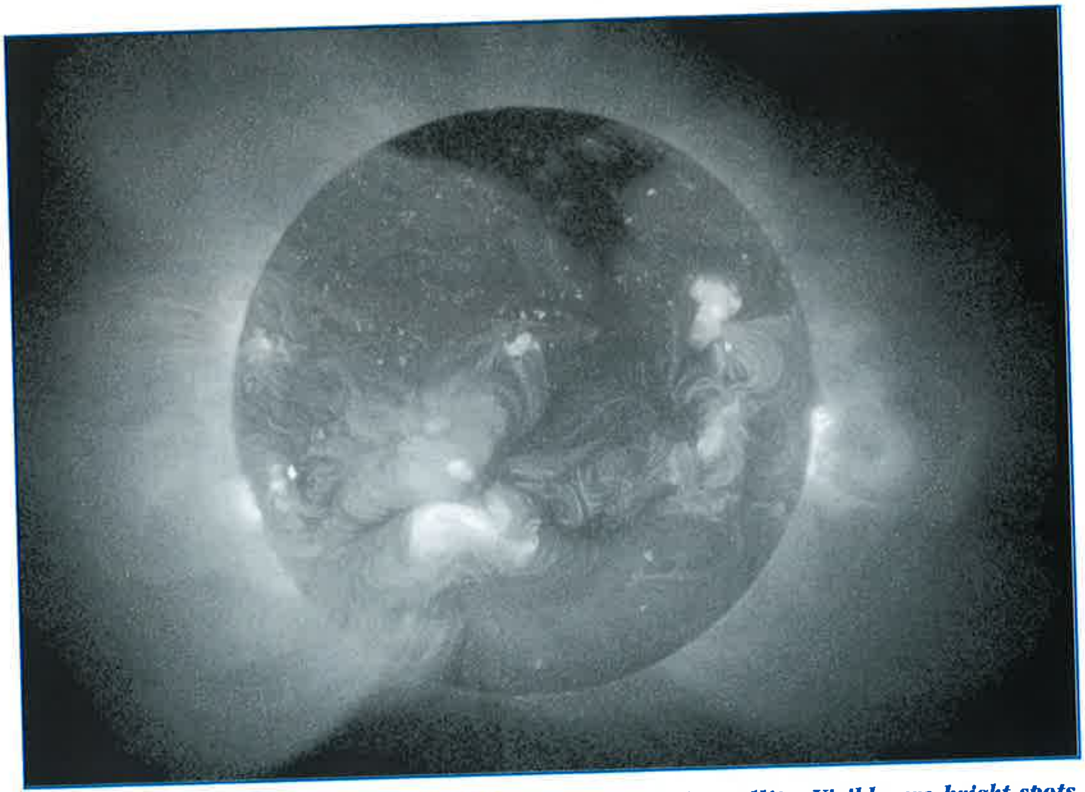


***Figure 1. Soft X-ray picture of the Sun taken by the Yohkoh satellite. Visible are bright spots, called "active regions" which are believed to be associated with strong magnetic activity including magnetic reconnection.***

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 a renewed interest in magnetic reconnection unseen for decades.

The design and construction of MRX were completed entirely at the Princeton Plasma Physics Laboratory (PPPL). 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, National Aeronautics and Space Administration, the Office of Naval Research, and the Department of Energy.

## Research Objectives

The primary objective of experiments on MRX is the comprehensive analysis of magnetic reconnection both locally and globally in solar and magnetospheric relevant 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 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 flow and thermal energies.
- 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 corona 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.

The Magnetic Reconnection Experiment was designed to achieve a variety of merging geometries and magnetic field topologies. Two types of reconnection have been studied: null-helicity and co-helicity. In the former, there is no toroidal magnetic field in the reconnection layer, and in the latter, there is a sizable toroidal field. Qualitative differences in the reconnection layer arise depending on the presence of the toroidal field. A photo of an MRX plasma discharge appears in Figure 2.

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 planned.

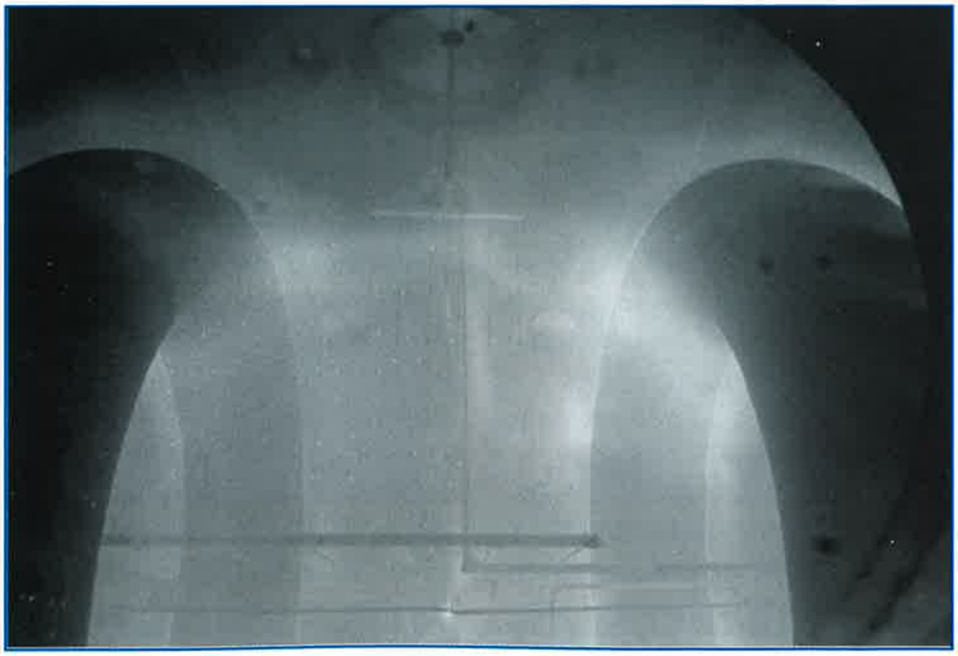


*Figure 2. A plasma discharge in the Magnetic Reconnection Experiment.*

## Results

**The Sweet-Parker Model.** The well-known Sweet-Parker model of magnetic reconnection predicts reconnection rates faster than that of resistive diffusion, but much slower than those observed in solar flares. The model is a resistive MHD 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. The first laboratory experiments on the Sweet-Parker model were performed on MRX.

Null-helicity experimental data indicated a reconnection speed consistent with a generalized Sweet-Parker model, which includes the effects of plasma compressibility, finite pressure in the downstream region of the field lines, and nonclassical 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.

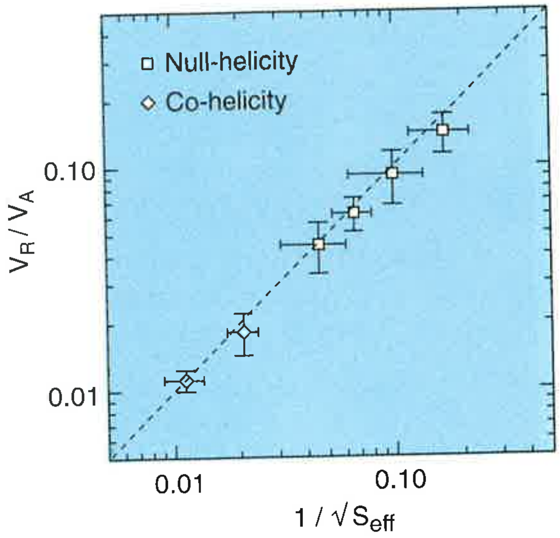


*Figure 3. Experimentally measured reconnection rate (in flow speed, $V_R$, divided by Alfvén speed, $V_A$) in MRX.*

Further experiments investigated the validity of the generalized model for co-helicity reconnection. It was found that the reconnection rate in the co-helicity case agreed with the generalized Sweet-Parker model within experimental error. Figure 3 shows the experimentally measured reconnection rate plotted as a function of the generalized Sweet-Parker value for both null-helicity and co-helicity reconnection. These combined results suggest that the Sweet-Parker model with nonclassical resistivity may explain the fast reconnection required to be consistent with solar flare observations.

Testing 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. Most important is the identification of (non-MHD) mechanisms for the enhanced, nonclassical resistivity.

**The Thickness of the Current Sheet.** An important indicator of the nature of reconnection is the current sheet thickness. In MRX, the thickness was found to be equal to the ion skin depth. Both in the magnetotail and the magnetopause of the Earth's magnetosphere, it has also been observed that the thickness is on the order of the ion skin depth.

The precise current sheet thickness in MRX was measured by a very high resolution magnetic probe array (~5mm spatial resolution). Figure 4 presents the radial profiles of the reconnecting magnetic field $B_Z$ and the current sheet, $J_T$, during null-helicity reconnection. One observes a steepening of the slope of $B_Z$ and a sharpening of the current sheet profile. It is found that the thickness is proportional to the ion skin depth as well the ion gyroradius. This indicates that the upstream magnetic pressure, which drives magnetic reconnection, is balancing the kinetic pressure of the heated plasma in the reconnection region during the quasi-steady-state situation.

**Ion Heating Measurements.** Conversion of magnetic field energy to plasma kinetic energy is a primary consequence of reconnection. This process is believed to play an important role in coronal heating, solar flares, and acceleration of auroral jets in the magnetosphere. Solar observations and in-situ satellite measurements show the existence of extremely energetic particles. However, the direct cause and effect between reconnection and the acceleration and/or heating of these energetic particles is unknown due to the extreme challenge of diagnosing a single reconnection event adequately and, at the same time, observing local plasma acceleration and heating that is

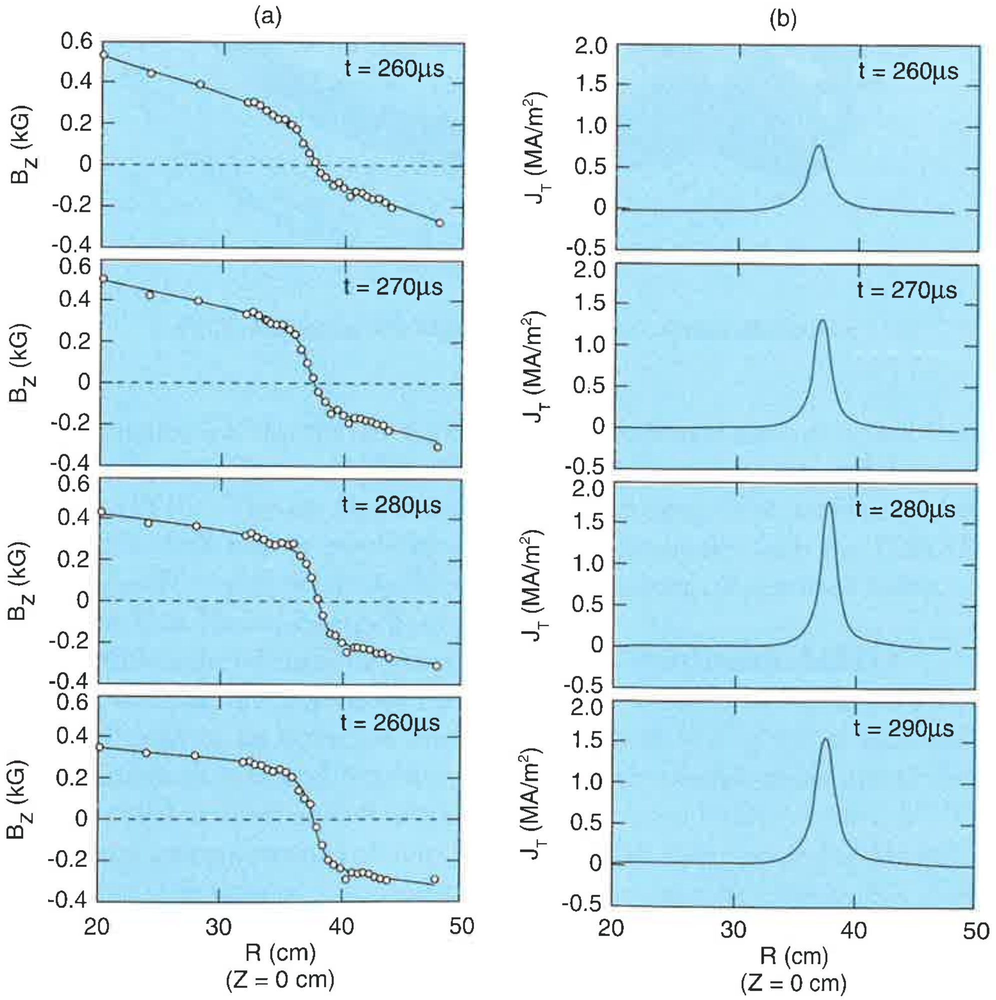


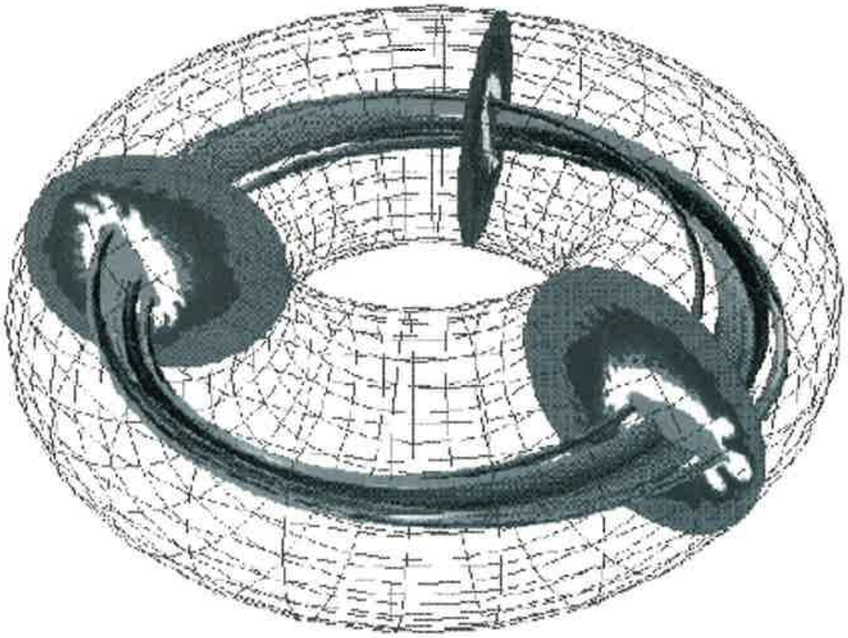
***Figure 4. (a) Radial profile of reconnecting magnetic field ($B_Z$) measured by a high-resolution magnetic probe array. (b) Current sheet inferred from $B_Z$ measurements. The thickness of the current sheet is approximately $c/\omega_{pi}$ and also $\rho_i$.***

clearly consistent with the single reconnection event. In the laboratory this can be done.

In MRX, ions in the reconnection layer ($T_i \approx 25$-$50$ eV) are seen to be consistently hotter than electrons ($T_e \approx 7$-$15$ eV) during reconnection, indicating a direct heating mechanism. Doppler broadening of HeII indicates global bulk heating of ions (global $T_i \approx 4 \rightarrow 12$ eV) during the reconnection process. The higher ion temperature in the reconnection layer (measured by an ion energy analyzer probe) suggests that the heating source is in the reconnection layer and, indeed, due to the single reconnection event.

The Sweet-Parker model predicts an Alfvénic beam in the downstream region. However, ion energy analyzer probe measurements in MRX indicate an upper bound on the flow speed that is much smaller than the Alfvén speed, $V_A$. This is consistent with the generalized Sweet-Parker model with a high downstream pressure. Whereas the Sweet-Parker model predicts that 50% of the magnetic energy will be transferred to directed flow energy and the other 50% to plasma thermal energy, MRX data suggests that magnetic energy can be converted almost entirely to ion thermal energy without an Alfvénic flow. This process may have relevance, for example, to the coronal heating problem.

# Fusion Theory and Modeling



*A 3-D simulation of a high plasma pressure-driven disruption.*

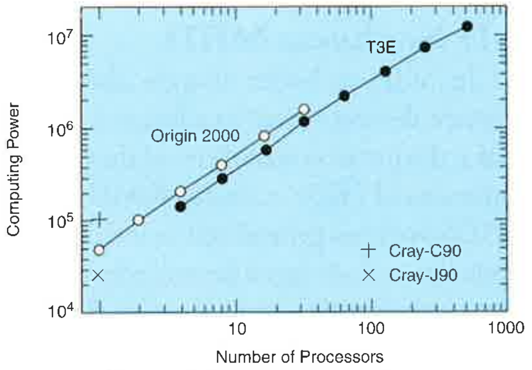
During FY98, the Princeton Plasma Physics Laboratory (PPPL) Theory Department continued its lead role in providing the theoretical and computational capabilities to help the U.S. Fusion Energy Sciences program achieve the scientific understanding and produce the key innovations which will lead to an attractive energy source. Endorsements and requests for enhanced collaborations in both tokamak and alternate concept research areas by the national and international fusion research communities have been stimulated not only by this group's impressive record for generating key seminal concepts, but also by its development and maintenance of the most comprehensive system of toroidal design and analysis codes. Examples of significant progress in the fusion program during FY98 enabled by first-rate scientific results from the PPPL Theory Department are described below.

## 3-D Nonlinear MHD

In order to better analyze alternate concept devices as well as advanced tokamaks, the physics capabilities of the three-dimensional (3-D) extended-MHD code M3D have been generalized to include an option to include more kinetic effects. Finite Larmor radius corrections to the energetic ion pressure tensor in the pressure coupling scheme have been derived and incorporated into M3D. This new capability with gyrokinetic ions and fluid electrons has been used to study the effect of background thermal ions on the fishbone mode, and it was shown that the growth rate is reduced due to Landau damping on the thermal ions. This new capability extends the multi-level capabilities of M3D which also include resistive MHD, two-fluid, and hybrid (MHD background with gyrokinetic energetic particles) models. Another important new capability that was incorporated this year was the addition of an all real space representation to the existing two-dimensional (2-D) real space and one-dimensional Fourier space, unstructured mesh version of the M3D code. This will enable the highly desirable computational flexibility for dealing with separatrix configurations. These important advances have been developed in collaboration with New York University and the Massachusetts Institute of Technology.

## Turbulent Transport Simulations and Analysis

**Gyrokinetic Simulations.** A fully 3-D, general geometry gyrokinetic particle code (GTC), which now uses field-line-following coordinates, has been successfully developed. Massively parallel simulations have been performed for both turbulent and neoclassical transport studies with new results enabled by utilization of the full power of the T3E computer at the National Energy Research Supercomputing Center (NERSC). For example, by measuring the broadening of the radial wavenumber spectrum of turbulence in these global gyrokinetic simulations, the turbulence decorrelation by self-generated zonal flows has been quantitatively calculated for the first time.



● Y-axis: the number of particles which move 1 step in one second.

*The 3-D Gyrokinetic Turbulence Code (GTC) is scalable on massively parallel computers.*

**Gyrofluid Simulations.** Electromagnetic effects, which become especially important in regions of large pressure gradients, have been successfully implemented in recent gyrofluid simulations. Results show that electron Landau damping can significantly increase the turbulent transport. In order to take advantage of the power of the massively parallel processors, the gyrofluid code has been parallelized and the domain decomposition algorithm has been improved from one to two-dimensions, in collaboration with the University of Maryland and the University of Texas.

**Gyrokinetic/Gyrofluid Comparisons.** A new gyrofluid closure for more accurately representing zonal flow damping physics has been developed. This has been used to address the Rosenbluth and Hinton results which suggest that the undamped components of the zonal flows are responsible for the difference between gyrokinetic particle-in-cell and gyrofluid simulations results. Preliminary results including this undamped component find up to 50% lower flux when compared to previous simulations in strong turbulence regimes. This reduces the gyrofluid/gyrokinetic discrepancy from 3 to 2, depending on the details of closure.

**Integrated Analysis.** The physics of zonal flow properties and the random shearing by self-generated zonal flows have been systematically studied via an integrated program of analytical theory together with gyrokinetic and gyrofluid simulations. For example, the effective E×B shearing rate for time-dependent zonal flows has been analytically derived and estimated from the zonal flow statistics of the gyrofluid simulations. It is found to be comparable to the maximum linear growth rate in semi-quantitative agreement with the observations from simulations that turbulence is reduced but not completely quenched by zonal flows.

## Kinetic Electromagnetic Analysis

Substantive progress on the challenge of developing a fully kinetic analysis capability for electromagnetic instabilities has been made. Major advances in providing a firm theoretical foundation have come from using the gyrokinetic approach to study global-MHD modes with kinetic effects. Generalized gyrokinetic equations were derived including the ability to account for high-frequency modes such as ion Bernstein wave and compressional Alfvén waves. Building from earlier low-wavelength electrostatic (global) microinstability codes, a new electromagnetic code, KIN-2D, was developed. Numerical results for the n=1 kink mode and the n=2 toroidicity-induced Alfvén eigenmode (TAE) mode have been successfully benchmarked against the PEST and NOVA-K codes.

## Basic Turbulence

A theory for submarginal self-sustained turbulence, which can exist even in the face of complete linear stability, has been developed. This work is relevant to the understanding of how turbulence is excited in the tokamak plasma edge, to possible ways of forming effective internal transport barriers, and to the assessment of results from various experimental diagnostics.

## Stellarator Physics

Excellent progress on key physics issues arising in the design of a compact stellarator experiment continued to be made during FY98 with numerous papers published. Results were obtained in the following areas:

**MHD.** Substantial advances were made in understanding the 3-D stabilization of external kink modes and in the application of that understanding to improved stellarator designs. A key conclusion is that kink stability can be independently controlled through externally generated shear and through an appropriate 3-D corrugation of the plasma boundary that produces little shear. To produce the required corrugation, the Terpsichore stability code, which was modified to improve its robustness and flexibility, was coupled to an optimizer.

**Transport.** Comparison of Monte Carlo bootstrap calculations with analytic bootstrap expressions has led to an understanding of resonances that appear in the standard analytic expressions, and to an improved treatment that has been incorporated into the bootstrap code imported from the National Institute for Fusion Studies (Japan). Application of the new gyrokinetic GTC code (which includes a momentum conserving collision operator and electric field effects) to the analysis of neoclassical transport in quasi-axisymmetric configurations has uniquely provided more accurate estimates of the global confinement times. Progress in the microinstability area has featured the generalization of the FULL code from using only axisymmetric MHD equilibria to using fully 3-D stellarator equilibria. The electrostatic version this code has now been interfaced with 3-D numerical equilibria computed with the VMEC code.

**Design.** An important innovative advance in developing 3-D coil design tools involved the use of singular value decomposition techniques for stellarator coil optimization. This has made practical the "reverse engineering" technique of first finding a desirable plasma configuration, and then later developing an "optimized" set of buildable coils that could produce the configuration.

## Disruption Modeling

A series of 2-D (TSC code) and 3-D (M3D code) simulations have been carried out for pellet injection scenarios in tokamaks and for runaway generation during disruptions in high-current plasma discharges. The 3-D pellet simulations showed the importance of MHD forces in the mass-distribution of an injected pellet, while the 2-D simulation was able to incorporate this effect in a "back-averaged" model which reproduced the experimental results and included a detailed transport and radiation model. For runaway generation, the 3-D model was used to demonstrate the effects of 3-D MHD instabilities in defeating the avalanche process if the instability amplitude is sufficiently large, and the 2-D model was used to demonstrate that runaways could be avoided completely if the disruption is induced by a sequence of impurity-doped "killer pellets" and if the poloidal field coils are ramped down simultaneously with the pellet injection. Both of these codes also made predictions of induced halo currents in the conducting structure.

## Plasma Boundary Physics

The DEGAS 2 neutral transport code has now been extensively benchmarked against the EIRENE Monte Carlo code. Moreover, it has been successfully coupled to a fluid plasma code UEDGE (in collaboration with the Lawrence Livermore National Laboratory) and tested in the coupled mode. Regarding applications, DEGAS 2 has been used extensively to simulate C-Mod (a device at the Massachusetts Institute of Technology) H-alpha spectra, the so-called "death ray" phenomena, and has made use of the newly added ion-neutral elastic scattering feature.

## Resistive Wall Modes

A circuit equation formulation of resistive wall mode feedback stabilization schemes for tokamaks has been developed. This was a major step forward, as it allows direct comparison of all the various recently proposed schemes for controlling resistive wall modes. The formalism is analogous to the circuit equation approaches commonly used for the design and analysis of n=0 control systems and uses concepts from electrical circuit theory which clearly show the importance of the sensors and the actuators. This has been developed for a straight plasma column with one unstable mode, but is in the process of being extended to a toroidal configuration.

## Energetic Particle Physics

A new kinetic/MHD hybrid code, HINST, has been developed to study the stability of high-n TAE modes in larger plasmas (e.g., relevant to International Thermonuclear Experimental Reactor design studies). This code keeps non-perturbatively kinetic effects of energetic particles as well as thermal particles, and includes all relevant physics for the TAE stability problem. To more properly account for the kinetic effects of all particle species, a low-frequency kinetic-fluid model has been introduced to help improve the capabilities of kinetic-MHD codes such as the NOVA-K, HINST, and MH3D-K. It will also aid the analytical understanding of energetic particle dynamics.

# Space Plasma Physics

During FY98, Space Plasma Physics research was focused in two areas: (1) understanding kinetic effects on low-frequency phenomena in the magnetosphere and (2) solar flares, magnetic reconnection, and merging of helical magnetic field structures. To study kinetic effects on low-frequency phenomena involving multiscale coupling, a new kinetic-fluid model was developed which improves the kinetic-MHD model previously developed at the Princeton Plasma Physics Laboratory. In addition to providing the theoretical basis for numerical modeling of multiscale coupling phenomena, the improved kinetic-fluid model has allowed significant progress to be made in several areas in magnetospheric physics.

The magnetic field and plasma data of the Active Magnetospheric Particle Tracer Explorer/Charge Composition Explorer (AMPTE/CCE) satellite were analyzed for different substorm events and a new physical process of substorm onset and current disruption was identified. Applying the kinetic-fluid model, the kinetic ballooning instability was identified as responsible for the explosive growth of magnetic field perturbation and subsequent plasma current disruption. The kinetic-fluid formulation has also been used to understand the parallel electric field that is required to accelerate electrons along aurora field lines leading to precipitation. It is believed that discrete auroral arcs are sometimes associated with shear Alfvén wave field line resonances. It has been demonstrated that non-MHD effects, such as finite ion Larmor radius and electron inertia, can cause a large parallel electric field to modify the waves into dispersive shear Alfvén waves (kinetic and inertial).

A new physical process has been identified whereby homologous flares can successively take place in a magnetic arcade at the same place with a short-time interval on the order of one day in the solar atmosphere.

## Substorm Onset Mechanism and Current Disruption

A new scenario of AMPTE/CCE spacecraft observation of substorm onset and current disruption and the corresponding physical processes has been identified. By examining the AMPTE/CCE magnetic field and plasma data, it was found that toward the end of the late growth phase, the plasma beta increases to over 50 and a low-frequency instability with a wave period of 50-75 seconds is excited and grows exponentially to a large amplitude at the onset of current disruption (also previously called explosive growth phase). During the explosive growth phase, a large upsurge in the duskward ion bulk drift to nearly the ion thermal velocity is found near the local midnight sector, and at the current disruption onset, higher-frequency instabilities (with periods of 15 seconds, 10 seconds, etc.) are excited. As the higher-frequency instabilities quickly grow to large amplitudes, they combine with the kinetic ballooning instability (KBI) to form a strong plasma turbulence, which may lead to anomalously large plasma transport and heating in the current disruption phase. In a few minutes, the plasma beta decreases and the pressure profile relaxes to a more quiet time-like profile, and the magnetic field recovers from a tail-like geometry to a more dipole-like geometry.

The KBI theory resolves two key issues needed to further understand the physical processes of the current disruption and subsequent magnetic field dipolarization:

- the excitation mechanism and the high plasma beta threshold (>50%) of the low-frequency instability that underlines the explosive growth phase;
- the physical mechanism of the enhanced duskward ion flux that occurs only during the explosive growth phase and leads to excitation of higher-frequency instabilities.

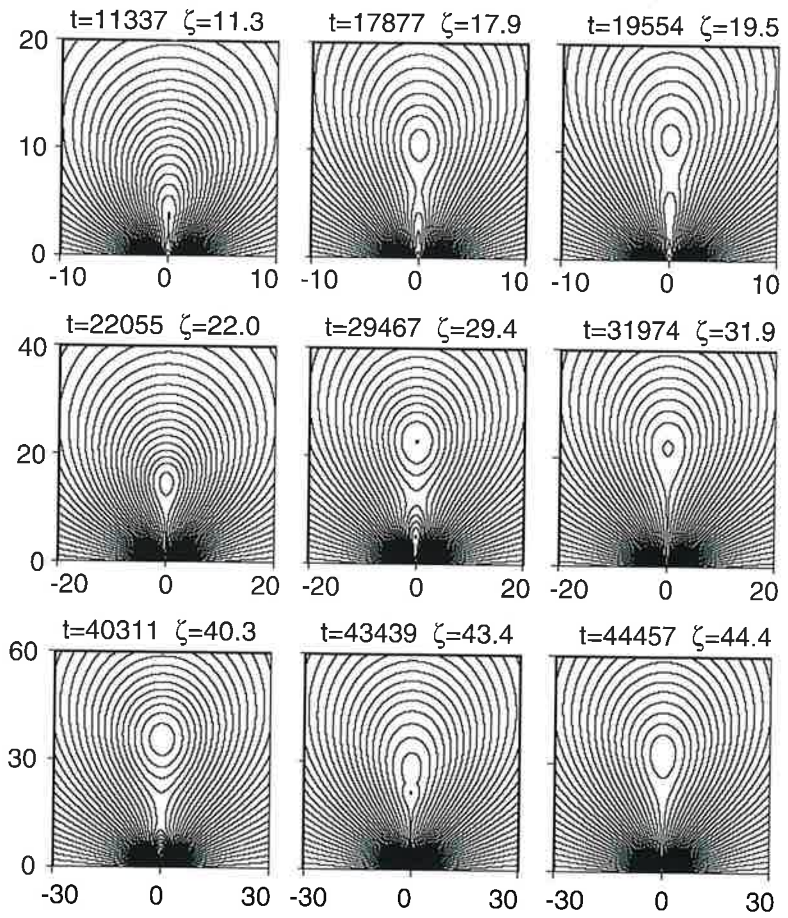
The new substorm scenario emphasizes a global low-frequency KBI mode that can naturally account for the explosive growth phase and the initiation of subsequent current disruption through a combination of KBI and higher-frequency instabilities.

## Homologous Solar Flares, Magnetic Reconnection, and Merging of Helical Magnetic Field Structures

The physical process of homologous solar flares, which repetitively occur at the same place in an active region with a short time interval on the order of one day, have been studied. The physical process of repeated flaring events is considered to be associated with magnetic energy release, which takes place via successive magnetic reconnection processes. It has been demonstrated in numerical 2 and 1/2-dimensional MHD simulations that successive generation and merging of magnetic islands can occur in a bipolar magnetic arcade due to continuous shearing and/or merging footpoint motion.

It is well known that a magnetic island with a helical magnetic field can be created by magnetic reconnection in a sheared magnetic arcade when the footpoint shear is above a critical value. However, an island so generated may not rise very far, if it cannot overcome the magnetic tension force of the surrounding line-tied arcade field. But if the continuing footpoint shear/merging motion creates another magnetic island just below the existing upper island, this new island can rise faster and merge with the upper island very quickly to form a bigger island. Both the reconnection and island merging processes can partially release magnetic energy and produce flaring events. The combined island continues to rise with a faster speed than the original upper island. As this process is being repeated, several impulsive events of magnetic energy release can take place and the growing magnetic island is eventually driven away from the sun. Different types of shear-increasing motions can produce different upward Poynting flux distributions and the time interval between flaring events is accordingly varied.

In summary, significant progress has been made in understanding critical phenomena in the magnetosphere and solar atmosphere. A new kinetic-fluid model for understanding low-frequency phenomena involving multiscale coupling processes in high beta plasmas has been developed. The kinetic ballooning instability has been identified as the key



*Homologous solar flares by repetitive generation and merging of magnetic islands. Magnetic field lines are shown in a time sequence. When field line footpoints of a magnetic arcade are sheared by photospheric flows, magnetic reconnection can take place in the coronal field and create a magnetic island. A new magnetic island is created in the underlying arcade by a continuing shearing motion and quickly merges with the upper island to form a bigger island. This process is repeated in some time interval as the island moves away from the solar surface.*

physical mechanism responsible for substorm onset and subsequent current disruption in the magnetosphere. A new physical mechanism has been identified for understanding homologous flare events in the solar atmosphere via magnetic reconnection and merging of magnetic islands, which result from continuous field line footpoint motion in the photosphere.

# National Spherical Torus Experiment

The National Spherical Torus Experiment (NSTX), approaching completion at the Princeton Plasma Physics Laboratory (PPPL), is designed to prove the physics principles of a spherical torus (ST) plasma. First plasma is scheduled for mid-February 1999, two months ahead of the U.S. Department of Energy's First Plasma Level I Milestone.

The cross section of the NSTX device is shown in Figure 1. An ST plasma has a minor radius approaching its major radius and its cross section approaching a half circle. As a result, the ST plasma appears spherical, while a conventional tokamak plasma has the well-known "donut" shape.

This difference in shape is expected to provide several advantages, such as the ability to contain a significantly higher plasma pressure for a given magnetic field (i.e., a higher plasma beta, the ratio of plasma pressure divided by the magnetic field pressure). Since the amount of fusion power produced is typically proportional to the square of the plasma pressure, higher plasma pressure leads to smaller and more economical fusion power plants.

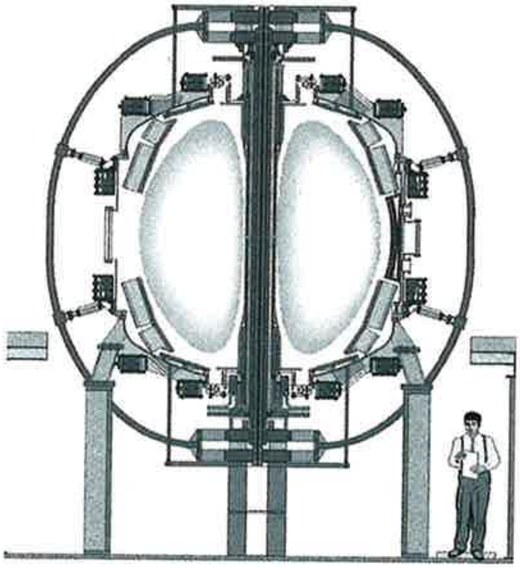


*Figure 1. Cross sectional schematic view of the National Spherical Torus Experiment (NSTX).*

The NSTX device is being built jointly by PPPL, the Oak Ridge National Laboratory (ORNL), the University of Washington at Seattle, and Columbia University. PPPL provides the site for the NSTX, has lead responsibility for the NSTX Project, and coordinates the design effort. ORNL is providing the NSTX Program Director, the physics-related support for plasma equilibrium and plasma scrape-off layer, and the engineering of plasma facing components. In addition, the high harmonic fast wave heating and current-drive system is being constructed in partnership of PPPL and ORNL. The University of Washington is providing the conceptual design of coaxial helicity injector and Columbia University is providing physics support in the area of the high-beta plasma stability. The NSTX project takes advantage of the equipment and infrastructure already available at PPPL, saving time and money.

FY98 was a very productive year for device construction and facility preparation. The major FY98 construction milestones were accomplished on schedule, within budget, and with an excellent safety record. Owing to the successful construction activity, the project is presently preparing for first plasma in February 1999, two months ahead of the DOE Level I Milestone.

## NSTX Mission

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

- nonindictive 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.

The NSTX Research team will investigate the ST plasma regimes that promise small fusion cores for near-term applications such as the volume neutron source, and for future applications such as electric power production. The plasma parameters extend beyond the present state of the art in magnetic fusion energy and are characterized by:

- simultaneously high toroidal beta (25-45%), self-driven current fraction (40-80%), 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 ST devices achieving increases in the plasma current and pressure by an order of magnitude beyond NSTX, with only modest increases in plasma size. These devices include a pulsed Performance Extension experiment with about 10 MA of plasma current, and a steady-state Energy Technology Development device with a similar current.

## NSTX Research Program Activities

An NSTX Program Advisory Committee (PAC), composed of senior fusion scientists from the national and international fusion communities, was formed by the PPPL Director in 1996. The PAC actively reviews and advises the PPPL Director on the priority and plans of the NSTX Research Program, in particular:

- NSTX research plans, priorities, and milestones, consistent with the DOE-approved workscope;
- Major new NSTX research initiatives to be proposed to DOE; and
- Adjustments to program priorities, taking into account the mission of NSTX and the overall directions of the U.S. and world fusion programs.

The NSTX PAC has thus far met on November 21-22, 1996; May 15-16, 1997; September 17-18, 1997; February 11-12, 1998; and September 24-25, 1998. Through these meetings, the PAC has strongly influenced the NSTX design and research program preparation. Through it's advisory role the Committee will continue to provide valuable scientific leadership to the NSTX Program.

During FY98, the PAC endorsed the objectives and the formulation processes for the NSTX national research program and team. The Committee strongly recommended that all participants follow the process and offered many useful suggestions for improvement. The PAC also reviewed and recommended the collaboration emphasis for the initial phases of the NSTX research program. The reports of the PAC meetings can be viewed at: **http://nstx.pppl.gov/nstx/Research_Program/Program_Advisory_Committee/.**

The NSTX Research Forum, held once a year, is a major component in the national process of the NSTX Program. The FY98 (second) Forum was held December 3-5, 1997. More than seventy researchers from many institutions attended. The purpose of the Forum is to reach out to the fusion community for input in developing the scientific elements of the NSTX Research Program. The FY98 Forum was successful in sharing the excitement and "ownership" of the scientific research program being planned for NSTX. The presentations and discussions were broad and informative. Thirteen overview and review talks were given in the plenary information session. More than sixty contributed presentations were made in the five parallel working group sessions. The summaries of the NSTX working group discussions during the Forum are available at: **http://nstx.pppl.gov/nstx/Research_Program/Meetings/.**

These summaries provide up-to-date information on the broad and exciting elements of scientific investigation of the high temperature ST plasmas expected in NSTX. This information is of interest to fusion scientists considering collaborative research on NSTX.

Letters of Interest to collaborate in NSTX research were solicited and received from about 30 research groups during January-February 1998, following the Research Forum. These, together with pre-proposals from PPPL researchers, formed the basis for the formulation of the initial NSTX Research Program. Following the PAC review and advice (February 11-12, 1998), the NSTX Research Program Outline was issued to help researchers interested in submitting proposals to DOE for NSTX collaboration funding beginning in FY99.

DOE received a large number of collaboration proposals in April, 1998. A peer-review process conducted by DOE led to the selection in November, 1998 of researchers from 14 fusion institutions (universities, laboratories, and industry). The NSTX Research Team is composed of excellent researchers with highly complementing expertise and experience from:

Columbia University
Fusion Physics & Technology
General Atomics
Johns-Hopkins University
Lawrence Livermore National Laboratory
Los Alamos National Laboratory
Massachusetts Institute of Technology
Oak Ridge National Laboratory
Princeton Plasma Physics Laboratory
Sandia National Laboratories
University of California, Davis
University of California, Los Angeles
University of California, San Diego
University of Washington

The first meeting of the NSTX Research Team was planned for January, 1999. Information is available at: **http://nstx.pppl.gov/nstx/Research_Program/.**

## Physics Activities

NSTX Project Physics has benefited greatly from the involvement of scientists from collaborating institutions. These researchers have contributed to several of the major physics efforts over the course of the year. One of these efforts was the assessment of the effect of the finite number of poloidal field (PF) shaping coils on the precise shape of the outer boundary, and, thus, on the plasma stability. This effort was carried out by Columbia University and PPPL. An off-midplane "dimpling" of the outer boundary resulted from the proximity of one pair of PF coils to the plasma surface, and because of the change of curvature of this surface, the plasma performance would be degraded in terms of achievable toroidal beta ($\beta_T$)and bootstrap current levels by as much as 30%. The problem was solved by adding a vertical-field-producing PF coil that was approximately 20 cm farther away from the plasma than the original set at the same vertical location, and moving the original set vertically. With this new PF coil set, the dimpling disappeared (see Figure 2), and the 40% $\beta_T$ and ~70% bootstrap current values were recovered. The additional PF coil has the added benefit of allowing even greater shape flexibility in NSTX.

A "current soak-through" code has been adapted by the University of Washington to calculate the time evolution of a coaxial-helicity-injected (CHI) plasma from time of initiation to a time about 10 msec later, when approximately 500 kA of plasma current is contained within closed flux. The code was used to determine the coil currents necessary to hold the plasma in the presence of the passive plates and vacuum vessel eddy currents, during CHI start-up. The results show that this can be done within the power supply capabilities. The most challenged coil is PF1b, for which approximately 18 kA of current is demanded; 20 kA is the design limit of the coil.

Radio-frequency (rf) modeling has been performed by a number of collaborating institutions. Modeling done at ORNL has directly supported the design of the high harmonic fast wave antenna for NSTX, addressing such issues as the size of the plasma and antenna gap to optimize loading, tilting the rf straps, and determining the location of rf sheaths. Work with the PICES full-wave code indicated that current profile control is possible at moderate beta by changing the phasing of the antenna. Work is being carried out at PPPL and the University of California at San Diego using full, hot-plasma ray-tracing codes as an analysis tool. One of the key issues is to represent the launched wave spectrum by a finite number of rays at suitable starting locations and wave numbers. Researchers at the Massachusetts Institute of Technology

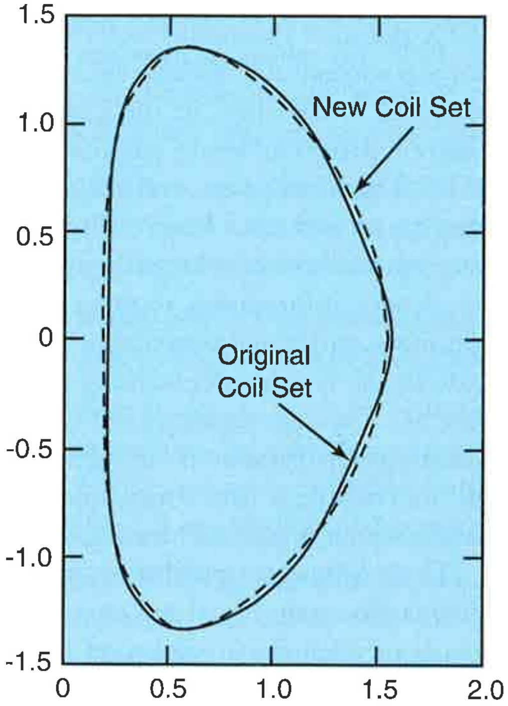


*Figure 2. The "dimpling" effect of the outer plasma caused by the original set of poloidal coils is shown by the solid line. This was corrected, as shown by the dashed line, with the addition of a new set of poloidal field coils strategically placed.*

have initiated studies using electron Bernstein waves for heating and current drive. Preliminary ray tracing computations show very localized power deposition of the wave.

A great deal of activity has taken place to support first plasma operation on NSTX. Sets of waveforms have been developed for unipolar ohmic heating operation that will create the low stray field region necessary for inductive breakdown of the plasma for a variety of start-up configurations. Tools were developed that will allow reconstruction of the magnetic field topology and plasma from a limited set of flux loop measurements. Plans were developed to finish coil impedance measurements and calibrate the Day 0 magnetics during coil testing. Finally, the Day 0 and Day 1 control system strategy and algorithms underwent successful reviews in preparation for operation.

## Major Design Changes

During FY98, the NSTX underwent three major design changes. First, the plan to use the domes from PPPL's former S-1 Spheromak as part of NSTX vacuum vessel was abandoned. The type of weld used on the S-1 domes is known to crack under the high stress situations anticipated on NSTX, such as high-temperature baking. Instead, it was decided to procure two new domes to be directly welded to NSTX's center cylindrical section, rather than having large flange sections connecting the domes to the center cylinder. This new design provides a better vacuum vessel with proper weld type, a new port configuration to optimize the diagnostic access, and lower overall cost due to the elimination of large flange sections.

The second significant design change was the addition of a new set of PF5 coils. As noted in the physics section above, the MHD stability calculations indicated that the original PF coil configuration could cause significant performance deterioration (20-30%) due to the proximity of the PF4 coils to the plasma. After considerable investigation, it was decided best to install an additional larger diameter PF coil pair (PF5). The original PF4 was retained due to the potential usefulness of improved plasma boundary shape control capability. The PF5 coil was ordered in May, 1998 and delivered on schedule to PPPL in August, 1998.

The third design change relates to the CHI bias power supply configuration. The CHI bias approach utilizing a high-voltage capacitor bank was abandoned in favor of a rectifier power supply approach. The rectifier approach gives much more control on the bias voltage waveform and, therefore, greater device safety and operational flexibility. It was also decided to allow the outer part of the vacuum vessel to be biased compared to the original scheme of biasing the center stack only and keeping the outer vacuum vessel grounded. The direct center stack biasing approach has a greater probability of damaging the center stack ohmic-heating solenoid.

## NSTX Device Construction

FY98 was a very productive year for the device construction. Critical device components were fabricated and delivered to the Test Cell for the final NSTX assembly.

One of the first components to arrive was the inner toroidal field (TF) magnet coil. This 16-foot-long coil was successfully fabricated with a radial precision of better than 0.01 inch. The next major component to arrive was the 14-foot-long ohmic-heating (OH) solenoid. It was also fabricated with radial precision of better the 0.01 inch. The inner TF and the OH solenoid were fabricated by Everson Electric. The critical installation of the OH solenoid over the inner TF coil to form the core of the center stack was carried out at PPPL. The subsequent installation of PF1a, 1b, Rogowski coils and flux loops for measuring the plasma current, thermal insulation, and Inconel casing completed the main center stack assembly. After delivery to the Test Cell, protective graphite tiles (carbon-fiber composites) were installed on the Inconel casing, prior to the installation of the center stack into the NSTX vacuum vessel as shown in Figure 3.

In the meantime, the vacuum vessel was fabricated at the Process Systems International, Inc. After the delivery of the vessel in the summer of 1998, support structures for magnets and outer divertor plate were welded to the vacuum vessel (as shown in Figure. 4). The completed vacuum vessel was delivered to the NSTX Test Cell at the end of the fiscal year for the final assembly.

*Figure 3. Completed NSTX center stack.*

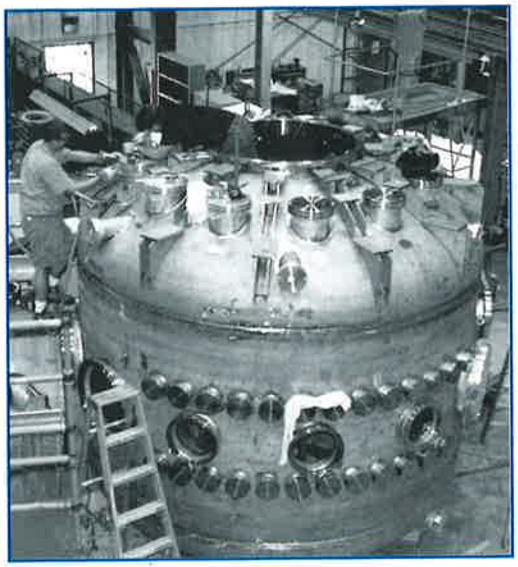


*Figure 4. Vacuum vessel during fabrication at the Princeton Plasma Physics Laboratory.*

## NSTX Test Cell and Auxiliary Facility Preparation

In the area of auxiliary systems and support facility preparation, much of the first plasma subsystems were completed during FY98.

The NSTX Test Cell (plan view is shown in Figure 5) was prepared by clearing the D-Site Hot-Cell which contained the DECON (decontamination) facility and the neutral-beam injector (NBI) clean room. The NBI clean room and DECON facility were moved to another part of D-site.

In October 1997, the NSTX Test Cell was handed over to the NSTX Project from the Tokamak Fusion Test Reactor (TFTR) Decommissioning Team. First to arrive in the NSTX Test Cell was the device platform. The NSTX Groundbreaking ceremony was held in May 1998. After the ceremony, a NBI beam box (a spare from TFTR) was placed in its final location in the NSTX Test Cell. The NBI system is scheduled to be commissioned on NSTX in spring of 2000. The torus vacuum pumping system was delivered to the Test Cell in the summer of 1998 and the gas injection system was installed shortly thereafter.

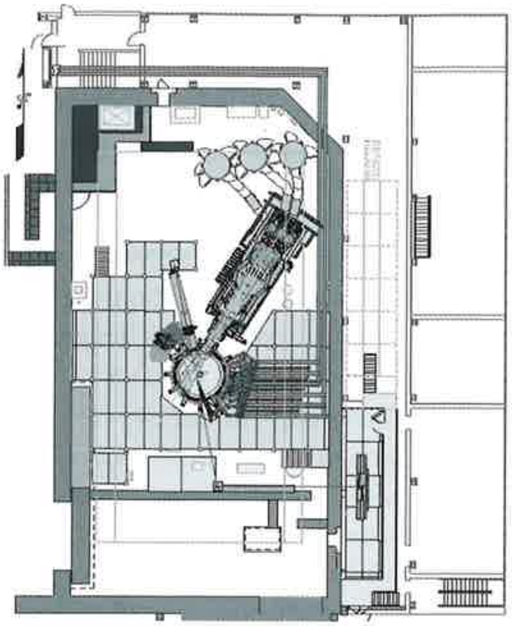


*Figure 5. Schematic plan of the NSTX Test Cell.*

New power cables were installed from the TFTR power cable transition area to the NSTX Test Cell through the TFTR basement and mechanical equipment room. Most of the power systems modification in the Field Coil Power Conversion building was also completed.

The former TFTR Control Room was cleaned and converted into the NSTX Control Room. A new central instrumentation and control system based on the EPICS (Experimental Physics and Industrial Control System) was installed. A new fiber optic cable network was installed to facilitate communication between the control room and the rest of the NSTX and PPPL facilities. A real-time plasma position-control system using a Skibolt computer was readied for the power systems control.

## NSTX Diagnostics

In FY98, the diagnostic efforts on NSTX were focused in a number of areas. The first was the design and initial fabrication of the in-vessel sensors, including thermocouples, flux loops, Rogowski loops, and Mirnov coils as well as the ex-vessel Rogowski coils and flux loops. Sensors located on the center stack required extra effort due to the tight space constraints and high-temperature requirements.

Another area involved the definition of diagnostic ports in the vacuum vessel, the determination of diagnostic sight lines, the design of several vacuum interfaces, and allocation of platform space for a number of diagnostics. This work will form the basis for many future installations.

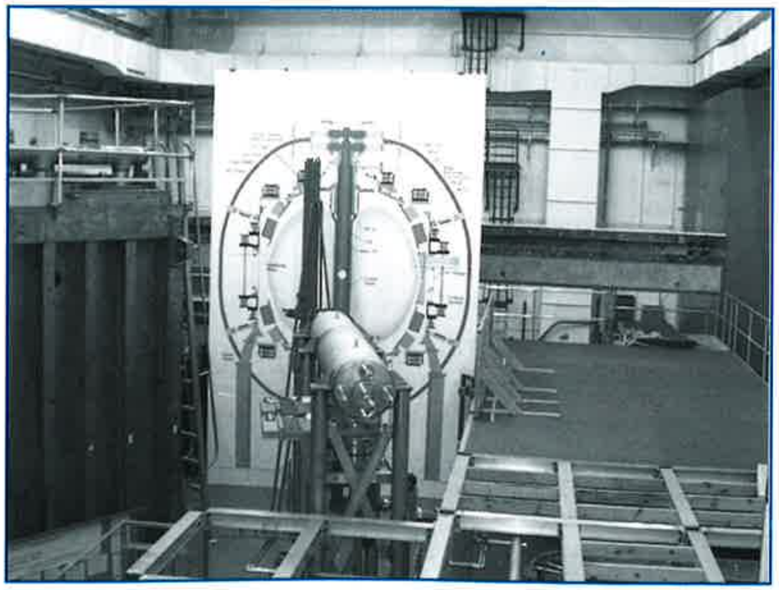


*Figure 6. A view of the NSTX Test Cell near the end of FY98.*

Special consideration was given to diagnostics needed for first plasma. These included a subset of the sensors mentioned above, along with visible and infrared TV cameras and a 170-GHz microwave interferometer.

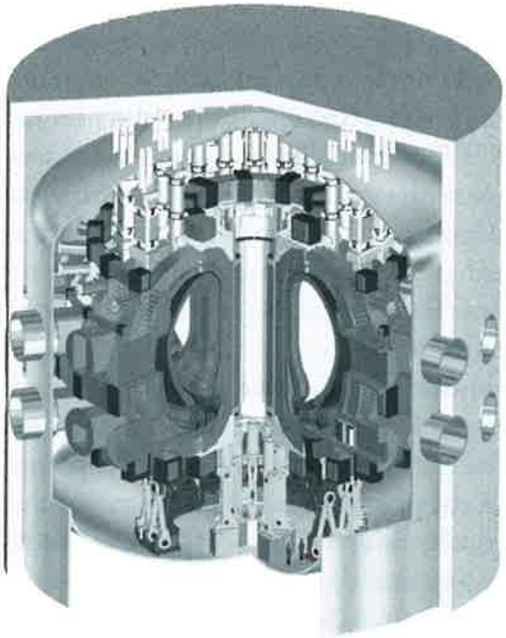
The preparation by collaborators of several proposals for research involving diagnostic installations was another major area of effort. Off-site researchers will be relied upon to provide essential diagnostic information for the National Spherical Torus Experiment.

Because of the early need for time-resolved electron temperature and density profile measurements, and the lead time needed to install a complicated system, there was considerable design effort during FY98 on a multi-pulse Thomson scattering system. A conceptual design was completed and detailed design and fabrication was begun.

# International Thermonuclear Experimental Reactor

In FY98, the International Thermonuclear Experimental Reactor (ITER) project completed the Final Design Report, as well as documentation of the ITER physics basis for publication in *Nuclear Fusion*. The Princeton Plasma Physics Laboratory (PPPL) continued its role in ITER physics and engineering work with PPPL staff assignments to the Joint Central Team (two physicists in San Diego; one engineer in Garching, Germany; and one engineer in Naka, Japan), supported the U.S. Home Team Design activities (both physics and engineering), and coordinated and participated in 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, Chair of the ITER Diagnostics Expert Group, and two U.S. Home Team Task Area Leaders in physics design. PPPL work as part of the U.S. Home Team focused on physics design, diagnostics design, and engineering design.

The ITER Project completed its six-year Engineering Design Activities phase in July, 1998. Design tasks in FY98 were focused on delivery of the Final Design Report and the more comprehensive detailed design documents. The Final Design Report was 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 acceptance by the ITER Council in July, 1998.



***Artist's rendition of the International Thermonuclear Experimental Reactor.***

## Reduced Cost ITER Studies

In an effort to reduce the cost of the ITER device, numerous options were examined. As part of those studies, the Tokamak Simulation Code (TSC) was used to model the discharge scenarios. In particular, the Low Aspect Ratio Machine (LAM) was modeled from early plasma current ramp-up through the end of burn. The simulation verified that an energy multiplication factor (Q) equal to 10 could be obtained with the assumed fuel and impurity densities and 50 MW of auxiliary heating power. The poloidal field coils were all within their allowed limits and the plasma position, shape, and current were maintained adequately. Calculations showed that the plasma consumes 32 Vsec during the 600 sec current flattop phase, and the total flux consumption through the end of burn is 322 Vsec. The bootstrap current lowered the flattop volt-second consumption by 16%. The plasma shaping is stronger than in the previous ITER design. However, it was shown that the single null is robust to disturbances. Argon was introduced in this plasma to enhance radiation and thereby reduce the heat load to the divertor chamber, and this effect was demonstrated in the discharge simulations. Two primary issues with the argon were uncovered in the simulations: the radiated power was a strong function of the plasma edge temperature, which is usually driven by the presence of the H-mode, and the argon can only be introduced after plasma current ramp-up to avoid excessive radiative losses.

## Advanced Tokamak Burning Experiment

As part of the U.S. Home Team effort to support the reduced-cost ITER studies, a double-null configuration was examined, called the Advanced Tokamak Burning Experiment (ATBX), with the same burning plasma mission (e.g., Q = 10). The TSC was used to examine the tradeoff between internal (near the plasma) and external (outside the vacuum vessel) feedback control coils for plasma vertical position control. Extensive simulations were done using step, random, and drift disturbances combined with a specific proportional-derivative gain strategy. In addition, two passive structure models were treated, one with only the steel structure and the other with copper stabilizer plates, added to the steel structure. Two options emerged, external feedback coils with the copper stabilizer plates and internal feedback coils with the steel only structure. The feedback control powers were 25 and 50 MW, respectively. These studies showed the importance of the passive conducting structure surrounding the plasma in determining the controllability of the plasma and feedback powers required.

## ITER Shape Control Optimization

The TSC was used to provide nonlinear simulations of the plasma position, shape, and current control algorithms designed for the International Thermonuclear Experimental Reactor. Since the control algorithms were designed using simplified plasma models, a series of tests were developed using the TSC to check the applicability of the different control algorithms to a more comprehensive and realistic plasma model. In comparing the linear plasma response models with the TSC simulations, the sensitivity of the result to numerical assumptions used in TSC, particularly plasma inertia and vacuum temperature, were used to improve the TSC evolutions. At the same time, plasma current diffusion and surface current generation, which are not included in the linear plasma models, were shown to have a significant effect, depending on the particular plasma behavior. Several plasma disturbances were used to isolate various controller and plasma model effects. These analyses verified the overall accuracy of the linear response models, while also indicating that fully nonlinear simulations are necessary to obtain realistic plasma and controller behavior.

## Fast Plasma Safety Shutdown Modeling

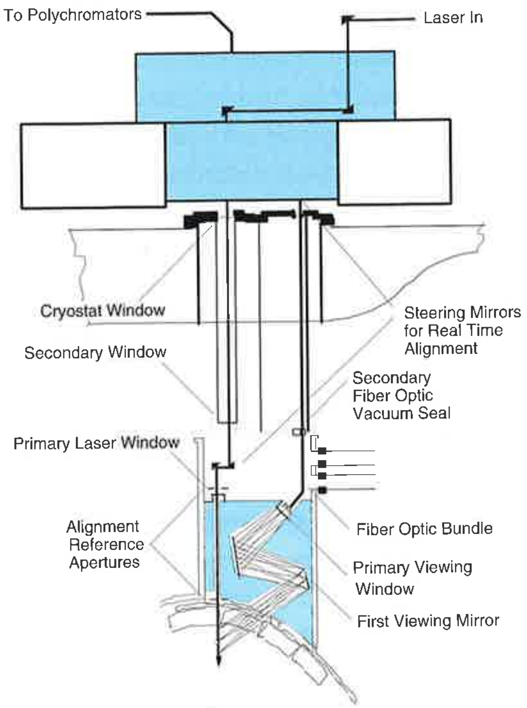
The TSC has been used to develop a technique for rapid termination of an ITER discharge that does not lead to the generation of large runaway electron currents. In the fully two-dimensional time-dependent TSC model, a sequence of 10-15 deuterium pellets doped with a trace of krypton was injected in 5-msec intervals. The increased density and the impurity radiation bring the plasma temperature down to a few hundred electron volts, but without total collapse. Simultaneously, the poloidal field coil currents are ramped quickly to zero current, while retaining the vertical control system needed for radial force balance. It is found that the an initial plasma current discharge of approximately 20 MA can be terminated in close to a second, with the critical electric field throughout the plasma never substantially exceeding that causing avalanche runaway electrons to develop. The time history of the plasma beta, internal inductance, and edge safety factor during this second indicate that the plasma should remain MHD stable during this entire sequence. This simulated sequence for ITER is very similar in dimensionless parameters to one of the Tokamak Fusion Test Reactor krypton pellet discharges performed last year. In this discharge, the TSC simulation was in excellent agreement with the experimental data.

## PPPL Diagnostics Design Activities

Research and development of diagnostics for the ITER Engineering Design Activity was carried out at a number of U.S. institutions under the leadership of the Task Area Leader from PPPL. A set of thirteen design reports and seven R&D reports were provided in July to complete the U.S. contribution to the ITER Final Design documentation and summarized the progress over approximately the last year. The designs all addressed the key issue of the interface of the diagnostics with the main tokamak and facility components. The designs ranged in quality from a scientific conceptual development to a relatively well engineered design. However, no system could be engineered to the full integration of the diagnostic with the tokamak components because of the lack of finality of the tokamak component designs and of the need to combine many diagnostics onto one port with complex shield-labyrinths. The PPPL contribution was to extend the quality of the design for a number of diagnostic systems already started in previous years as part of the U.S. contribution to ITER.

At the highest level of completion is the design of the position control reflectometer where there was a joint design effort with colleagues at the University of California, Los Angeles. This involved very complex design issues in the integration of many waveguides in various positions through the blanket module support plate and between the blanket modules. An engineering design of the edge Thomson scattering system was completed. To get the required spatial resolution, the measurement is done in the expanded flux-surfaces at the top of the plasma. Thus the access is through the top port and is very constrained by device penetration limitations. This design is shown in the figure on the next page.

The motional Stark effect diagnostic for measurement of the safety factor, q(r,t) also reached the engineering design phase in collaboration with colleagues from Fusion Physics and Technology. The engineering design was completed for the neutron activation system, this time in col-



***Layout of the optics for the International Thermonuclear Experimental Reactor Thomson scattering system for measuring the electron density and temperature in the plasma edge.***

laboration with the Los Alamos National Laboratory. The design of the other U.S.-assigned neutron diagnostic, the neutron source strength monitors, reached the scientific design phase, but engineering design had not yet started at the end of July.

The visible Bremsstrahlung system for measuring the impurity levels ($Z_{\text{eff}}$) is at the scientific design level, with the key issue of survival of the plasma-facing mirror still to be resolved. The design of the lost alpha-particle detectors was less advanced, since some aspects of the detectors in the cruel environment remain to be investigated and the possibility of using an infrared camera, sharing optics with the visible camera system is also being considered.

## PPPL Engineering Design Activities

Engineering support for ITER continued in a broad number of areas:

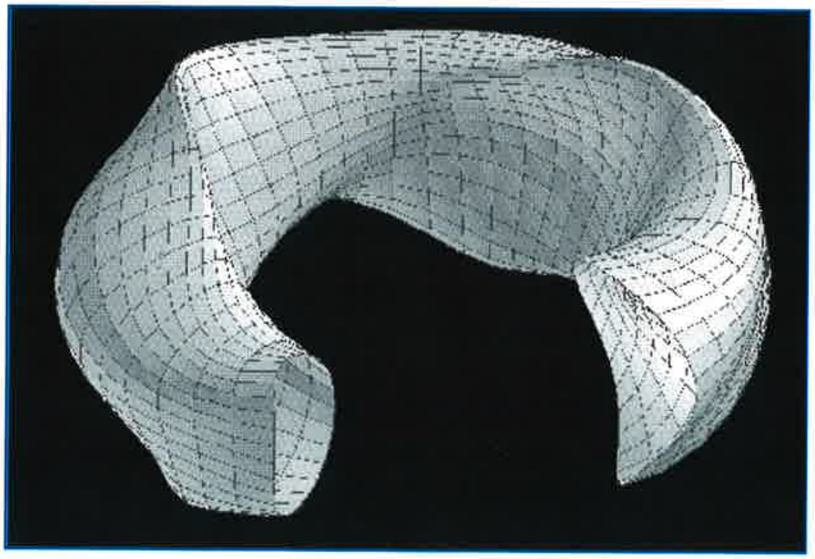
- Power supply design;
- Central solenoid Model Coil Vacuum/Pressure Impregnation;
- Analysis and design for the ITER Laser Metrology;
- Divertor disruption analyses;
- Analysis of the central solenoid buffer zone;
- Design and analysis of ferromagnetic inserts for ripple reduction;
- Analysis of vacuum vessel weld shrinkage; and
- Analysis of thermal stresses due to loss of coolant and loss of flow in the vacuum vessel.

PPPL engineers participated a U.S. Home Team study of the reduced cost option, ATBX, in the areas of design integration and plasma stabilization and control.

## ITER Physics Expert Groups

PPPL had members on six of the seven ITER Physics Expert Groups, which are charged with coordinating physics R&D in support of ITER design and with compiling the ITER-relevant physics results in the ITER Physics Basis. The expert groups were very effective in facilitating international focus on reactor-relevant physics issues, and the groups produced the Physics Basis material, which is being published in *Nuclear Fusion.*

# Stellarators



***Surface of three-field-period candidate plasma configuration studied as the reference plasma for the National Compact Stellarator Experiment.***

Stellarators, a family of plasma confinement concepts characterized by three-dimensional magnetic fields, are the most developed magnetic fusion concept after the tokamak. The stellarator has advanced greatly since its invention by Princeton Plasma Physics Laboratory (PPPL) founding Director Lyman Spitzer, Jr. in the 1950s. Now, two large superconducting-coil stellarator experiments in the billion-dollar class are under way. The Large Helical Device (LHD) recently became operational in Japan and the Wendelstein 7-X is under construction in Germany.

The interest in stellarators world-wide stems from their potential as a steady-state reactor featuring disruption-free plasma operation, low recirculating power, and good plasma performance. However, reactor projections based on current stellarator knowledge point to designs with relatively high-aspect ratio (the ratio of major radius to minor radius of the toroidal plasma) and large size compared to tokamaks. An important question for stellarator research is whether more compact reactor designs are possible. Could the advantages of stellarators also be realized at dimensions and performance levels close to those of advanced-tokamak reactors, such as the ARIES-RS, which has a major radius of 5.5 m and a neutron wall load of 4 MW/m$^2$?

Researchers at PPPL, in collaboration with colleagues from the U.S. and abroad, have been studying design concepts for low-aspect-ratio "compact stellarators" that could be the basis for smaller stellarator reactors. In 1997, a capability for computing compact-stellarator plasma configurations optimized to have low plasma transport and high plasma beta (the ratio of kinetic to magnetic pressure in the plasma) was developed. In 1998, a way to stabilize external kink modes — helical deformations of the plasma surface that can be unstable in steady-state, high-beta toroidal plasmas — by three-dimensional shaping of the plasma toroid was discovered. This discovery could eliminate a design complication of advanced tokamaks — the need for a conducting wall close to the plasma to stabilize these modes. If tokamak-like beta values can be achieved without a wall in stellarators, it would be an important advantage.

Concept advances were made possible by applying advanced computational tools, including some developed at PPPL, to the problems of stellarator design. Experiments are needed to test 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 such experiments. In 1998 PPPL, in partnership with the Oak Ridge National Laboratory, organized a national project team and began to develop the plasma and coil configurations and machine concept for this facility, the National Compact Stellarator Experiment (NCSX), which would be sited at PPPL.

## Compact-Stellarator Plasma Design Innovations

A 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 insofar as its effects on energetic particle drift trajectories are concerned. This property makes it possible to have particle drift trajectories that are as well confined as those in exact symmetry, e.g., in tokamaks, and hence have low alpha particle losses and low neoclassical transport.

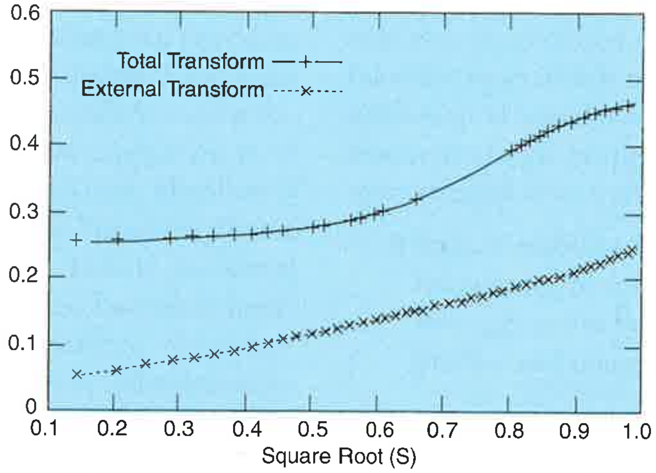
In quasi-axisymmetric (QA) devices (a class of quasi-symmetric devices) the helical twist, or rotational transform, of the confining magnetic field is provided by a combination of the plasma's self-generated bootstrap current and three-dimensional stellarator coils, making this concept a hybrid of a stellarator and an advanced tokamak. Rotational transform is necessary for plasma confinement. In a QA stellarator, the bootstrap current is comparable to that in a tokamak and flows in a direction that adds to the transform from the stellarator coils. Bootstrap currents are driven by the plasma's internal pressure gradients, and are therefore sustained by plasma self-heating and not by current drive. They are also predicted to suppress the unstable growth of magnetic islands, which could otherwise destroy the configuration and disrupt operation, if the shear in the rotational transform is arranged to be in the appropriate direction. Quasi-axisymmetric configurations with aspect ratios of 2.1 to 3.4 (similar to tokamaks), with beta values up to 7.5%, and with 50% to 80% of the transform supplied by bootstrap current, were studied in 1998 as part of the NCSX design activity.

A key earlier innovation in compact stellarator design was the development of a strategy to ensure plasma stability against ballooning modes at high beta. It was found that high ballooning beta limits can be obtained in QA stellarators by introducing a strong axisymmetric component to the shaping, as is done in advanced tokamak configurations. In 1998, a solution to the problem of stabilizing the external kink modes without a conducting wall was developed by PPPL scientists in collaboration with Swiss colleagues. It was found that the kink modes can be stabilized either by introducing magnetic "shear," a steepening in the rotational transform near the edge of the plasma, or by corrugating the surface of the plasma in an appropriate way. Improvements in the configuration design tools were made to enable use of both of these effects. Using the newly-developed capabilities, high-beta configurations stable to both external kink and ballooning modes were generated.

Of particular interest was a plasma configuration developed as a candidate for the NCSX experiment. With a major radius of 1.5 m and an average minor radius of 0.4 m, it was sized to fit within the existing Princeton Beta Experiment-Modification tokamak facility, with allowance made for the three-dimensional field shaping coils that would be required. This three-field-period QA configuration, shown in the figure at the beginning of this report, was calculated to be stable to external kink and ballooning modes at a beta of 4%. The rotational transform profile for this configuration, shown below, is monotonically increasing toward the edge, which is favorable for avoiding unstable island growth in long-pulse operation, and provides some shear which plays a role in stabilizing the kink modes. Analyses were begun in late 1998 to determine the transport properties and coil requirements associated with the shape characteristics of this plasma configuration.

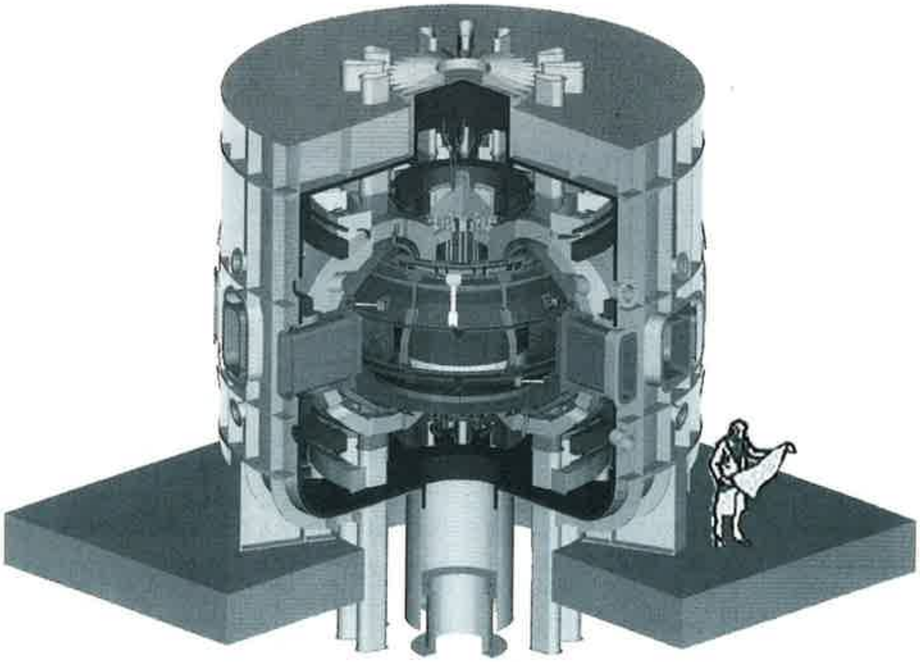
These innovations combine to open up a new path toward compact stellarator reactors with high beta and good confinement. In comparison with tokamaks, compact stellarators offer the advantages of being potentially disruption-free and providing greater design freedom to impose magnetic configuration properties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

The NCSX would support experimental research aimed at testing the basic physics properties of compact stellarators, especially the crucial issue of disruption avoidance at high beta. The experiment would be the centerpiece of a national compact-stellarator proof-of-principle program to develop the knowledge base needed to assess stellarator reactor potential and support decisions on moving to the proof-of-performance stage.



***Rotational transform profile for the plasma configuration shown in Fig. 1. The "external transform" curve indicates contribution from external coils. The "total transform" is generated by a combination of the external coils and bootstrap current.***

# Korea Superconducting Tokamak Advanced Research



*Artist's rendering of the Korea Superconducting Tokamak Advanced Research 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 built in Taejon, South Korea. Members of the group, led by the Princeton Plasma Physics Laboratory, include personnel from General Atomics, Lawrence Livermore National Laboratory, Northrop-Grumman Corporation, Massachusetts Institute of Technology, and 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 are an important element of the modular strategy for proceeding with fusion in the United States.

The KSTAR tokamak will feature 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 radiofrequency 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 FY98, the U.S. team was responsible for a major part of the tokamak design. The U.S. scientists participated in a highly successful international KSTAR review: the Tokamak Systems Engineering Review in early December 1997, held in Taejon, South Korea. The Tokamak Systems Engineering Review team found that the design 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.

An Ancillary Systems Engineering Review was held in the summer of 1998. The U.S. team played 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. The primary review committee finding was that the functional and performance requirements of the systems reviewed are appropriate and adequately defined. The design concepts are sound and demonstrate a state-of-the-art approach to the design task. They provide a good basis for the detailed design of the systems which is to follow.

FY98 was a watershed year for the KSTAR Project in that ground was broken and site preparations completed for the KSTAR experimental hall and facilities. The construction contract was awarded in the fall of 1998 and final design of the facility buildings was well underway.

This period of significant progress occurred despite a full Korean Government review of the KSTAR and other major projects. As a result of this extensive review, the mission, design parameters, and purpose of KSTAR were confirmed and authorization received to proceed with the Phase II of the Project which includes construction.

***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 | 14 MW |
| Ion Cyclotron | 6 MW | 6 MW |
| Lower Hybrid | 1.5 MW | 1.5 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 (PPPL) Off-Site Research Program focuses on achieving fusion science goals through collaborative research using remote facilities, including Alacator C-Mod at the Massachusetts Institute of Technology (MIT) in Cambridge, MA, DIII-D at General Atomics in San Diego, CA, and facilities abroad, especially the Joint European Torus (JET) in Europe and JT-60U and the Large Helical Device (LHD) in Japan. These collaborations permit the Laboratory researchers to apply their expertise and tools to address high-impact scientific issues, utilizing the most capable facilities worldwide. PPPL's joint theoretical and experimental teams are integrated into the remote research activities.

The PPPL tokamak collaborations address both burning plasma physics and tokamak concept improvement, emphasizing advanced plasma control to achieve extended performance and increased understanding. The non-tokamak collaborations permit researchers to explore the physics of alternative configurations, as part of the program in overall concept improvement.

## International Collaborations

The program on international collaborations grew at PPPL in FY98, with relatively strong participation at JET in England and at the JT-60U device in Japan. While much smaller in scope, active collaborations were continued on the Small Tight Aspect Ratio Tokamak (START) device in England, on TEXTOR in Germany, on Tore-Supra in France, and on the Compact Helical System in Japan. A new aspect of the collaborations has been the start of a joint program studying tritium use in the Tokamak Fusion Test Reactor (TFTR) under an Annex to the Department of Energy/Japan Atomic Energy Research Institution (JAERI) Collaborative Agreement.

At the start of the fiscal year, JET completed the high-performance deuterium-tritium (D-T) burning-plasma and fast-ion physics program. PPPL staff participated in alpha-physics analysis, operation of the neutron activation diagnostic system, and transport analysis with the TRANSP code. Experience developed on TFTR was especially helpful in the difficult measurement of alpha-particle heating. PPPL had responsibility for analyzing edge localized, high-confinement mode plasma discharges. This work, which formed a strong component of the D-T studies, was done using the PPPL code TRANSP. Altogether more than 60 pulses with different choices of hydrogen, D, D-T, and T neutral-beam injection and gas fueling were studied. In addition, a number of hot-ion high-confinement mode and "optimized-shear" plasmas were analyzed.

One goal of the collaboration at JET was to join in studies of the optimized-shear advanced tokamak plasmas which are expected to provide improved performance. Reliable measurements of the safety factor, q, of the plasma are particularly important to understanding the physics of such operation. A motional stark effect (MSE) diagnostic was installed in order to make these measurements. Design and construction of the diagnostic hardware, completed in FY98, was done jointly by PPPL and JET. The MSE diagnostic was commissioned in the summer and initial data were taken during JET operation in September.

A higher level of collaboration was achieved at JT-60U where seven different physics tasks were approved for PPPL physicists. The studies led to two first-author publications and co-authorships of other papers at the International Atomic Energy Agency Meeting in October, 1998. One of the papers addressed a comparison of the magnetohydrodynamic (MHD) activity localized near the internal transport barriers (ITBs) in JT-60U and TFTR plasmas. In both devices there are steep pressure gradients near the transport barriers and localized MHD activity is seen. Stability analysis of equilibria modeling of the experiments supports identification of the modes as being an ideal-MHD n=1 instability. The mode width depends on the local value of q and is larger when q is smaller. It is also found that the edge current density has a role in coupling the internal mode to the plasma edge and the energetic particles can drive fishbone-like modes.

The first measurements of the radial correlation length of density fluctuations in JT-60U plasmas with an ITB were obtained in FY98. The measurements were made using the newly installed correlation microwave reflectometer operating in the upper X-mode. The reflectometer diagnostic was built at PPPL under contract to JAERI. During the pulse, before transport barrier formation, reflectometer measurements indicate density fluctuation levels $\tilde{n}/n \sim 0.1$-$0.2\%$ and radial correlation lengths 2-3 cm ($\kappa_r \rho_i \leq 0.5$) in the central plasma region ($r/a < 0.3$). A rapid increase ($\tilde{n}/n \sim 0.5\%$) in the density fluctuation level is observed within 50 msec of the turn on of high-power neutral-beam injection during the formation phase of the ITB. Inside the ITB (Figure 1), the radial correlation length of density fluctuations is found to be short ($\delta_r \sim 0.5$ cm at $r/a \sim 0.57$) and corresponds to $\kappa_r \rho_i \sim 3$. The reflectometer has also succeeded in mak-

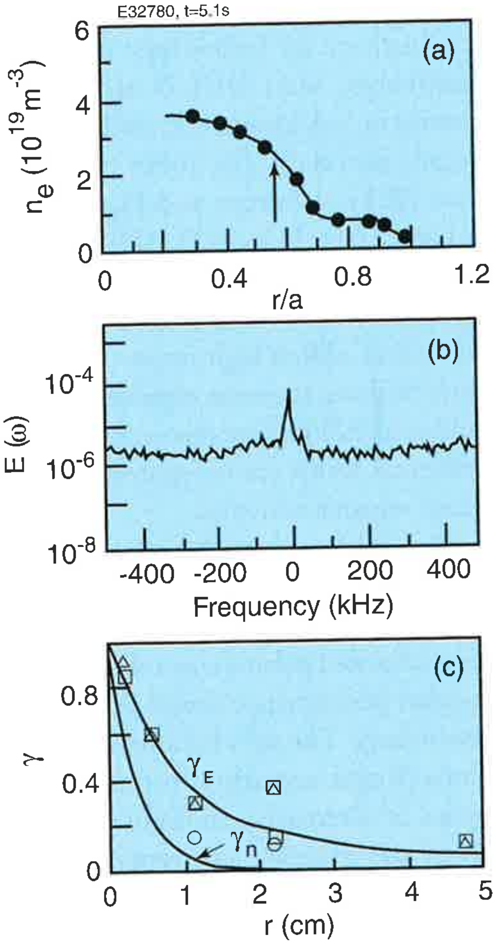


***Figure 1. Density profile and cutoff layer position in the internal transport barrier marked by arrow (a), frequency spectrum of reflectometer signal showing good coherent reflection (b), and radial correlation measurements (c). Fitted signal correlation gives: $\tilde{n}/n \approx 0.5\%$ and $\delta_r \approx 0.5$ cm.***

ing initial measurements of Alfvén Eigenmodes driven by energetic ions during negative ion beam injection and heating at the ion cyclotron frequency.

In addition to the experimental studies of fluctuations, linear growth rates for instabilities such as the toroidal drift mode (trapped-electron-ion-temperature-gradient mode) have been calculated for JT-60U improved core confinement plasmas. This calculation has employed PPPL's comprehensive linear microinstability code (the FULL code). The resulting growth rates have been compared with the E×B shearing frequencies estimated for the experiment. When the shearing frequency, $\omega_{E\times B}$, is of the same order as or larger than the growth rate, $\gamma_L$, the instability is expected to be stabilized and anomalous tranport suppressed. This could provide an explanation for the experimentally observed internal transport barriers in JT-60U. Figure 2 shows the calculated values for one JT-60U plasma discharge.

A detailed comparison of the relatively flexible PPPL-based transport code (TRANSP) with TOPICS, the code currently used on JT-60U, was another part of the collaboration. To facilitate the comparison, an NBLIST/Ufile translator package was completed on the ceres.naka.jaeri.go.jp workstation at JT-60U, allowing preparation of complete input of JT-60U "Ufiles" datasets for TRANSP analysis. This software is now being used to prepare JT-60U TRANSP runs.

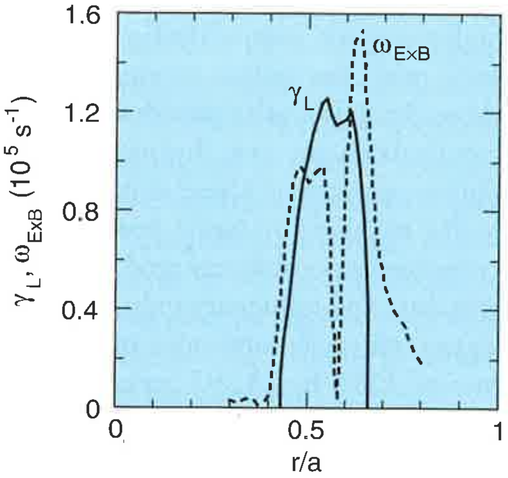


*Figure 2. Radial profiles of the linear growth rate $\gamma_L$ for the toroidal drift mode and the E×B shearing frequency $\omega_{E\times B}$, for a JT-60U improved core confinement plasma.*

In that part of the collaboration devoted to the physics of the JAERI 500-keV neutral-beam system, the mission has been to improve the usable power, pulse length, and characteristics (such as particle energy spectrum and divergence). During the first two years of operation, worse than expected divergence and stripping losses within the complex accelerator structure had resulted in limited beam energy and pulse lengths. During FY98, the stripping was decreased within the accelerator to the point where essentially all of the transmitted neutral beam is at the full acceleration energy. The energy spectrum for this beam system is now far cleaner, and thus much better known, than for any positive-ion-based system which has been used. This reduction in stripping has also lowered the undesirable power loading on the ground and accelerator grids, permitting longer pulse lengths at higher powers. Changes were also made to insure that the plasma and cathodes in the ion sources are in equilibrium by the time beam extraction begins. During the first two years of operation they were not in equilibrium, resulting in temporally and spatially varying beam characteristics that reduced pulse length and power capability due to rising power loading on the grids as the pulse continued. Operational changes made in FY98 have resulted in the plasma and accelerator line density parameters being at near-equilibrium values by the start of beam extraction. This has now solved the temporal part of the optics variability, and has partly solved the spatial variability. A high-resolution scan of the beam uniformity, with the source in equilibrium, shows that it is much better than had previously been the case during nonequilibrium extraction. These improvements to the negative-ion-based neutral-beam system made possible very productive current drive and toroidicity-induced Alfvén eigenmode excitation studies in the summer of 1998 by JAERI personnel and other collaborators.

Two PPPL X-ray diagnostic physicists collaborated at the TEXTOR-94 tokamak. In the framework of an American-German-Japanese collaboration, a fast tangential soft X-ray camera (TSXC) was designed and built. The goal of this project is the development of two-dimensional tangential X-ray imaging for the study of MHD fluctuations, especially for the exploration of disruptive events, such as sawtooth crashes or the terminal phases of high-beta disruptions. The camera was undergoing laboratory testing at the end of the year. It will begin operation on TEXTOR early in 1999.

A new technique in two-dimensional X-ray imaging spectroscopy uses doubly-bent crystals for Bragg reflection in order to obtain X-ray images where one axis is wavelength and the second axis is plasma radius. This instrument represents a diagnostic breakthrough, because spatially and temporally resolved spectroscopy can be performed on large, reactor-size machines with a relatively compact, inexpensive instrument. For this project, equipment from the TSXC camera, namely a scintillator screen and a X-ray image converter tube, is used as a detector in the TEXTOR X-ray crystal spectrometer. The recorded helium-like argon spectra demonstrated that simultaneous radial ion and electron temperature profiles can be obtained with such an instrument at the video rate (16 msec). The ion temperature was deduced from Doppler broadening and the electron temperature from the ratio of dielectronic and resonant lines.

A spectrum analyzer was provided and used on START to examine the emission spectrum of the START plasma in the frequency range of 0.2-20 MHz. No clear coherent modes were detected with electrostatic probes. No clear coherent modes with frequency greater than ~2 MHz were observed using Mirnov coils as detectors. However, on a number of discharges a high-frequency mode at 700-800 kHz was seen. This mode appears to be similar to ion cyclotron emission observed earlier in neutral-beam heated high-beta discharges. The results of these experiments have been reported at the 1998 European Physical Society conference.

Using a probe developed earlier through a PPPL/National Institute for Fusion Science collaboration, the rate of neutral-beam ion loss in the Japanese Compact Helical System device was measured under various conditions. Beam ion orbits were also computed and compared to the probe measurements. This comparison indicated that transition-type orbits produced the strongest loss signal at the probe.

The collaboration on Tore-Supra has continued with some theoretical studies on turbulent transport with the ergodic divertor and toroidicity-induced Alfvén eigenmodes present.

In a new collaboration with the JAERI Tritium Engineering Laboratory, detailed analyses of tiles, which formed part of the inner bumper limiter of TFTR for the D-T operation, have started. The analyses make use of an oven for baking the tiles to quantify the total tritium content in a tile after its removal and an articulated arm which is able to place detectors contiguous to tiles still in place in the tokamak. This equipment had been built under contract from JAERI. At year-end all procedures for operating the oven in the tritium vault had been checked out and measurements of tiles exposed to D-D plasmas had started.

## Doublet-III-D Collaboration

During FY98, PPPL became a major collaborator in the tokamak program at the DIII-D National Fusion Facility at General Atomics (GA). Both institutions benefit from the increased PPPL participation. Valuable physics and engineering resources at PPPL are now available to GA, and PPPL can play an active role in advanced tokamak research on DIII-D.

PPPL contributes to the DIII-D program in three principal areas. (1) PPPL scientists directly participate in the DIII-D experimental campaign. (2) PPPL provides physics support through scientific programming and code development, diagnostic engineering, and technician effort, and design and implementation of new diagnostic capability. (3) PPPL provides operations support through provision of full-time technical personnel and the development or procurement of hardware necessary for the DIII-D research program.

PPPL physicists have taken part in the DIII-D scientific program for a number of years, largely through interactions between individuals at PPPL and GA. This traditional collaboration, which typically involves analysis of MHD stability, microinstability, and transport in specific DIII-D discharges, continued in FY98 and was augmented by more direct participation in the DIII-D experimental program. PPPL physicists led or participated in a number of important investigations. These included experiments which produced high-performance plasmas with steady-state internal transport barriers, experiments in which resistive wall modes were reproducibly observed, using saddle loop sensors installed by PPPL, and an experiment to investigate sawtooth stabilization by minority ion cyclotron radio-frequency (ICRF) heating and by neutral- beam injection. Other contributions include spectroscopic measurements in divertor experiments, analysis of Alfvén instabilities in ICRF-heated plasmas, and observations of short wavelength fluctuations in experiments with fast wave current drive.

The highest priority diagnostic task for the PPPL/DIII-D collaboration during FY98 was an upgrade of the Thomson scattering systems. The previous systems, with horizontal viewing of vertical laser beams, could not measure electron temperature and density in the central core of DIII-D plasmas. As part of a joint effort with the Lawrence Livermore National Laboratory and GA, PPPL designed, fabricated, and installed critical in-vessel and ex-vessel components for the tangential central Thomson scattering system (Figure 3) and participated in system tests. The initial stray light test was satisfactorily completed on schedule in August. Subsequent stray light and Rayleigh scattering tests were performed after completion of the system installation and implementation of slight modifications and refinements to some of the components. These highly successful tests demonstrated that system performance of the new spatial channels should meet all expectations. This will enable measurement of complete spatial profiles of electron temperature and density during the 1999 experimental campaign.

Active feedback control of MHD instabilities in DIII-D is a major goal of advanced tokamak research and a principal area of concentration for the PPPL/DIII-D collaboration. Of particular interest is control of the resistive wall mode, which limits the achievable pressure in

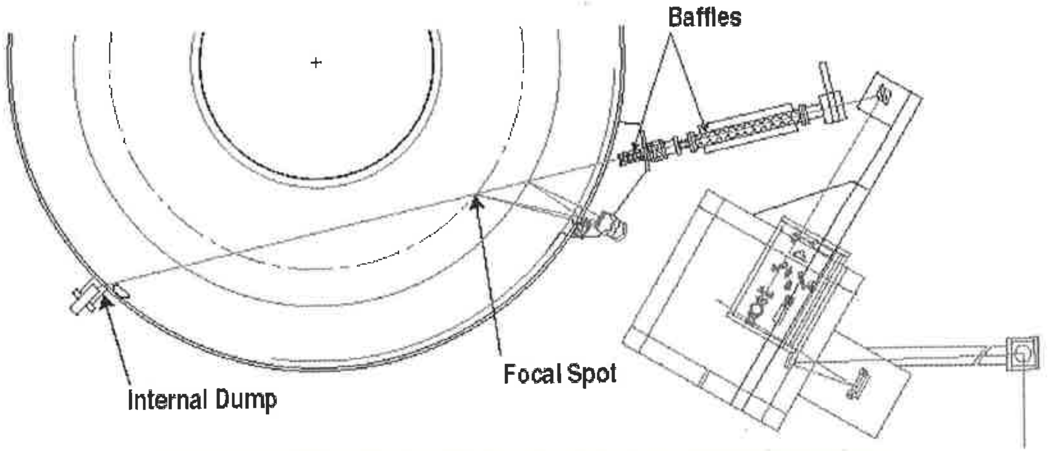


*Figure 3. Layout of tangential central Thomson scattering system.*

high-performance plasmas. In support of the MHD research program on DIII-D, PPPL installed a new six-coil set of saddle loop sensors (Figure 4) in FY98 and is procuring a power supply for active feedback stabilization experiments. The saddle loops easily detected the onset and evolution of resistive wall modes during the 1998 experimental campaign. The feedback power supply is scheduled for delivery in early 1999 and should be fully operational by May 1999.

The first tests of active feedback stabilization of MHD modes in DIII-D plasmas will be carried out in 1999. In these tests, the saddle loops will provide feedback signals for the new power supply, which can independently energize three coil pairs of the existing six-element error field correcting coil set (C-coils) at modulation frequencies up to 100 Hz. The goal is to stabilize long wavelength modes by simulating the electrical response of a perfectly conducting wall around the outer midplane of DIII-D. In future years, these experiments will be extended to higher performance plasmas by procuring two additional feedback power supplies and by expanding the saddle loop and C-coil sets from six coils each to eighteen coils each.

PPPL technical support of the DIII-D facility has been especially effective. A PPPL operations engineer, a radio-frequency (rf) power engineer, and an rf technician played crucial roles in the very successful FY98 experimental campaign and also conceived and implemented a number of improvements in the facility. An outstanding example of such improvements is a novel modification of the patch panel hardware for the field shaping coils.

The very flexible magnetic field shaping capability of DIII-D is achieved by

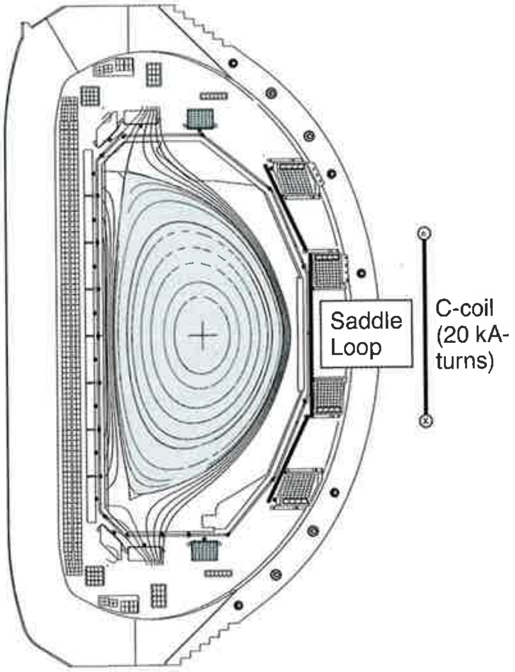


*Figure 4. Cross section of DIII-D showing positions of saddle loop sensors and active feedback coils.*

manually repositioning large metal pins, which interconnect the poloidal field bus bars in a wide variety of electrical configurations. The mechanical attachments of the pins have now been changed from an arrangement using four bolts per pin to one that does not require bolted connections. This allows the field-shaping coils to be reconfigured much more quickly than before and will greatly enhance experimental flexibility. A typical daily configuration change, which involves repositioning approximately 50 pins, previously required about an hour. The same change can now be made in less than 15 minutes.

During the next five years, the DIII-D research plan will concentrate on advanced tokamak experiments, with particular emphasis on active control of MHD modes, as mentioned above, and on manipulation of current profiles with high power electron cyclotron heating (ECH) and electron cyclotron current drive (ECCD). A key element in the program is a substantial increase in the available ECH/ECCD power. Two 1-MW 110-GHz gyrotrons were operational during the 1998 DIII-D experiments. Three gyrotrons are now on-site, and three more are on order. The output beams of each of the six gyrotrons will have to be independently transmitted to the tokamak and injected in a controlled way.

In support of this most important activity, PPPL is developing and will soon deliver a steerable ECH/ECCD launcher (Figure 5). The launcher will be able to remotely control the toroidal and poloidal injection angles of two 1-MW gyrotrons. This will allow DIII-D physicists, for the first time, to change the direction and radial location of electron cyclotron current drive on a shot-to-shot basis and will greatly improve the ability to distinguish the effects of heating and current drive. The launcher is expected to be available for installation in April, 1999. Two more launchers are planned for delivery in the first quarter of FY2000.

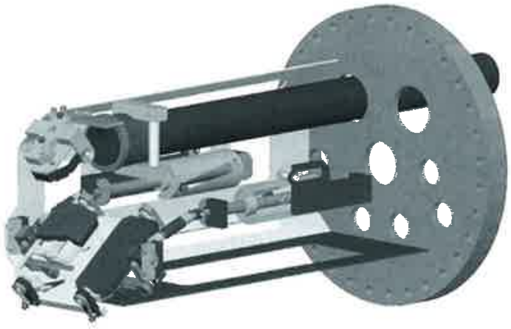


***Figure 5. Cutaway view of steerable launcher for electron cyclotron heating and current drive.***

## Alcator C-Mod Collaboration

During FY98, PPPL involvement with the Alcator C-Mod project at the Massachusetts Institute of Technology (MIT) increased. The collaboration between PPPL and MIT is designed to involve PPPL in machine operations, physics research, and diagnostic construction and in expanding the auxiliary heating systems. Major goals of the program are to continue the physics explorations of rf heating and current drive and transport previously explored on TFTR.

During FY98, experiments on mode conversion heating of multi-ion species plasmas were carried out, along with supporting theoretical calculations. In preparation for the FY98 operations run on C-Mod, PPPL provided two workstations that were integrated into the MIT data acquisition system. These workstations will be used by PPPL physicists. Additionally, two new variable frequency rf sources were commissioned for use with the existing antennas and for future use with a new antenna being prepared by PPPL. A new electron temperature diagnostic was moved from TFTR to C-Mod. This grating polychrometer permits the electron temperature to be measured at twenty radial positions. This increase in spatial resolution was used in conjunction with the ICRF mode-conversion experiments to verify the rf deposition and was compared with theoretical calculations.

An increased number of PPPL physicists participated in operations. One PPPL physicist became fully qualified as an rf operator. Data from the x-point Thomson scattering system was obtained for the first time, yielding a rough estimate of an x-point temperature but suffering from low signal levels.

In addition to the operations activities, significant construction activities were begun or continued at Princeton. These included the completion of a new four-element ICRF antenna which will allow a significant increase in auxiliary power capability, as well as the ability to launch directed waves for current drive. Installation of the antenna will take place in early FY99. Also, a complicated optics assembly was built for in-vessel installation to allow motional Stark effect measurements of the plasma's internal poloidal magnetic field by viewing light from a diagnostic neutral beam. This diagnostic also will be installed in early FY99.

These additional capabilities, prepared during FY98, will allow significant new explorations during the FY99 experimental campaign.

# Collaborations

## Laboratories

A.F. Ioffe Physical-Technical Institute, St. Petersburg, Russian Federation
Argonne National Laboratory, Argonne, IL
Association Euratom-CEA, Cadarache, France
Association Euratom-CRPP-EPFL, Lausanne, Switzerland
Association Euratom-FOM, Nieuwegein, Netherlands
Associazione Euratom-ENEA, Frascati, Italy
Battle Memorial Institute, Washington, DC
Brookhaven National Laboratory, Upton, Long Island, NY
Ecole Royal Militaire, Brussels, Belgium
Environmental Measurements Laboratory, U.S. DOE, New York, NY
Fermi National Accelerator Laboratory, Batavia, IL
Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID
Institute for Nuclear Research, Kiev, Ukraine
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 Laboratories Establishment, Ibaraki, Japan
Japan Atomic Energy Research Institute, Tokai 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
Max Planck Institut für Quantenoptik, Garching, Germany
National Institute for Fusion Science, Toki, Japan
National Institute for Science and Technology, Washington, DC
New Jersey Department of Environmental Protection, Trenton, NJ
National Renewable Energy Laboratory, Golden, CO

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
Thomas Jefferson National Accelerator
Facility, Newport News, VA
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
Bristol-Myers Squibb, Lawrenceville, NJ
Camac-Cookson Fibers, Bristol, PA
CompX, Inc., Del Mar, CA
DuPont Chemical Corporation,
Wilmington, DE
Fusion Physics and Technology, Inc.,
Torrance, CA
General Atomics, San Diego, CA
Lodestar, Boulder, CO
Lucent Technologies, Murray Hill, NJ
Mission Research Corporation,
Newington, VA
Northrop Grumman Aerospace
and Electronics Corp., Bethpage, NY
Ontario Hydro,
Toronto, Ontario, Canada
Princeton Electronic Systems,
Princeton Jct., NJ
Princeton Scientific Instruments, Inc.,
Princeton, NJ
Qualprotech,
Oakville, Ontario, Canada
Raytheon Engineers and Construction,
New York, NY
SAIC, San Diego, CA
Union Camp Corporation,
Lawrenceville, NJ
Wellman,
Charlotte, NC
Westinghouse Corporation,
Pittsburgh, PA
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
A+ for Kids, Plainsboro, NJ
Bordentown High School,
Bordentown, NJ
Burlington City Schools, Burlington, NJ
Caltech, Pasadena, CA
Carnegie Science Center, PA
Center for Technological Education
Holon, Holon, Israel
The College of New Jersey, Trenton, NJ
Coalition for Plasma Science,
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, Fisk University, Nashville, TN
Florida State University, National High Magnetic Field Laboratory, Tallahassee, FL
Florence Public Schools, Florence, NJ
Fort Discovery: The National Science Center, Augusta, GA
Georgia Institute of Technology, Atlanta, GA
Hiroshima University, Hiroshima, Japan
Hopewell Valley Central High School, Pennington, NJ
Idaho State University, Moscow, ID
Institute of Applied Physics, Academy of Sciences, Nizhny Novgorod, Russian Federation
Institute for Fusion Science, Austin, TX
Invention Factory Science Center, Trenton, NJ
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 Consortium of Specialized Secondary Schools for Science and Mathematics, Washington, DC
New Jersey Institute of Technology, Newark, NJ
New Jersey Technology Council, Plainsboro, NJ
New York University, New York, NY
Oak Ridge Institute for Science and Engineering, Oak Ridge, TN
Peddie School, Hightstown, NJ
Pennington High School, Pennington, NJ
Philadelphia Public School System, Philadelphia, PA
Plainsboro Public Library, Plainsboro, NJ
Pohang University of Science and Technology, Pohang, Republic of Korea
Princeton Center for Leadership Training, Princeton, NJ
Princeton University, Princeton, NJ
Rensselaer Polytechnic Institute, Troy, NY
Shady Side Academy, Pittsburgh, PA
Sigma Xi, the Scientific Research Society, Princeton, NJ
Stevens Institute of Technology, Hoboken, NJ
Swarthmore College, Swarthmore, PA
Trenton Public Schools, 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 Pittsburgh at Greensburgh, Greensburgh, PA
University of Provence, Marseilles, France
University of Rochester, Rochester, NY
University of Texas, Austin, TX
University of Tokyo, Tokyo, Japan
University of Washington, Seattle, WA
University of Wisconsin, Madison, WI
Westminster College, New Wilmington, PA

# Engineering and Technical Infrastructure

The Engineering and Technical Infrastructure Department is responsible for managing Princeton Plasma Physics Laboratory's (PPPL)'s 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 D-Site and the future decontamination and decommissioning of the Tokamak Fusion Test Reactor (TFTR).

## Tokamak Fusion Test Reactor

The safety and radiological cleanliness of the D-Site facility was successfully maintained. Tritium which had outgassed into the TFTR torus and vacuum appendages was reclaimed through the use of drum bubblers installed on the torus, each of the four neutral beamlines, and on the neutral-beam ion sources. Highly tritium-contaminated components such as the tritium delivery lines and the tritium gas injectors were safely removed and packaged for disposal along with approximately 5,000 pounds of tritium-contaminated molecular sieve from the Tritium Vault and the Tritium Storage and Delivery Cleanup Systems.

A plan for disassembling the TFTR vacuum vessel by filling the vessel with concrete and then using a diamond wire saw to cut up the vessel was proposed. U.S. Department of Energy EM-50 funding was secured for a FY99 demonstration of this technique.

## National Spherical Torus Experiment

Virtually all of the components of the National Spherical Torus Experiment (NSTX) were fabricated and tested. Assembly operations proceeded on schedule. The NSTX Test Cell preparations were completed. The experimental platform, high current bus, and coolant lines were installed. Final assembly of the NSTX device is expected to be completed during the first quarter of FY99, followed by power testing early in CY99. First plasma is expected to be achieved by February, 1999.

The Neutral Beam Injection Development Project focused on the aspects of the beam design that impact the physical layout of NSTX equipment and those activities which could minimize construction costs and downtime during the commissioning of the NSTX beam upgrade. The ion source refurbishment facility was recommissioned in the mock-up area and is now ready to decontaminate and refurbish the common long-pulse ion sources planned for use on NSTX. The spare TFTR beamline was positioned on its new support stand in the NSTX Test Cell, cryogenic panels were repaired and tested, and all o-ring seals were replaced. This beamline was cleaned, pumped down, and leak checked at room and cryogenic temperatures. A preliminary design of the beamline-to-NSTX duct provided the specifications of dimensions needed to complete the NSTX vacuum vessel design and has included the reuse of all spare TFTR duct items.

The high-voltage enclosures required for the Neutral Beam Power System were removed from the TFTR Test Cell basement and installed in the NSTX Test Cell. Cable routing, tray and rack locations, and control schemes have been analyzed and laid out. All beamline services were evaluated to determine equipment and piping locations and thus the penetrations required to support neutral-beam injection. A Neutral-Beam Injection General Arrangement Peer Review was held at the conclusion of this fiscal year's activities to present the development effort.

## Korean Superconducting Tokamak Advanced Research

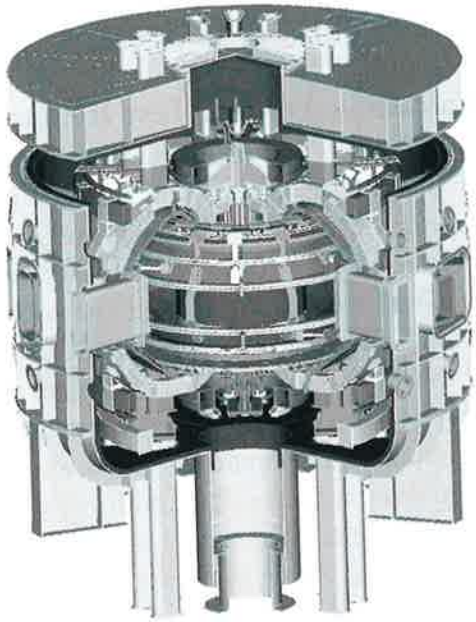
PPPL continued to provide leadership for the U.S. KSTAR (Korean Superconducting Tokamak Advanced Research) Team. The Team participated in a successful Tokamak Systems Engineering Review held in Taejon, Korea, in December of 1997. The purpose of this review was to obtain expert advice on the engineering requirements and design of KSTAR. Laboratory engineering staff provided support in design integration, plasma stabilization and control, and project cost and schedule control.

## International Thermonuclear Experimental Reactor

PPPL Engineering support for the International Thermonuclear Experimental Reactor (ITER) continued in a number of different areas. These included power supply design, the central solenoid vacuum/pressure impregnation effort, analysis and design for ITER laser metrology, divertor disruption analyses, analysis for the ITER central solenoid buffer zone, design and analysis of ferromagnetic inserts for ripple reduction, analysis of vacuum vessel weld shrinkage, and analysis of thermal stresses due to loss of coolant and loss of flow in the vacuum vessel. Engineering staff participated in a U.S. Home Team study of a reduced cost option called ATBX (Advanced Tokamak Burning Plasma Experiment) in the areas of design integration and plasma stabilization and control.

## National Compact Stellarator Experiment

The development of a stellarator "hybrid" called the National Compact Stellarator Experiment (NCSX) based on modifications to Princeton Beta Experi-



***A rendering of the National Compact Stellarator Experiment by a PPPL designer using the Pro-Engineer software design package.***

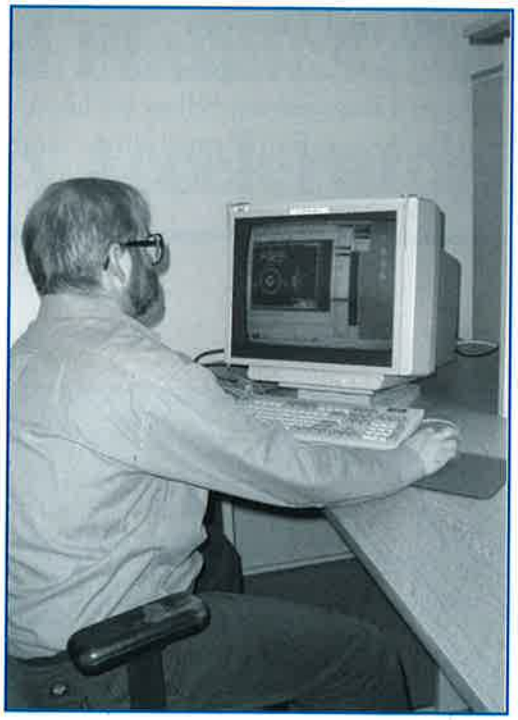
ment-Modification (PBX-M) was undertaken. Analytical tools were developed which provide an effective means to "reverse engineer" a magnetic coil system for a prescribed magnetic topology and to develop the drawings and perform electromagnetic and structural analyses. The PBX-M design modification approach includes an enlargement of the vacuum vessel port opening to allow the installation of a structural shell to support new stellarator windings. The windings would be fabricated of flexible cables. The cables would be conduction cooled by liquid nitrogen to achieve high performance in limited space. Plans call for continued development of this design, followed by a comparative study of a modular stellarator design option which would not involve the use of PBX-M. This comparative study will be used to determine which approach is most advantageous.

## Computer-Aided Design and Drafting

A major upgrade of the Laboratory's Computer-Aided Design and Drafting (CADD) facility to Parametric Technology's Pro Engineer was made in FY98. A cluster of five high-speed DEC Alpha NT workstations was put on-line for use with Pro Engineer. An additional six PC platforms were purchased to upgrade the Intel 486 based PC's which are used for running ComputerVision/PTC Personal Designer software and PT Modeler, a stripped down Pro Engineer. A new HP E-size plotter was added and the CADD servers were consolidated to reflect decreased use of Personal Designer and CADDS5.

## Network

A $450 K three-year plan to provide a 100 Mbps Switched Ethernet backbone infrastructure to PPLnet was begun. The plan will provide infrastructure for four Fast Ethernet Hubs, and more than two hundred 10/100 Mbps Switched Ethernet ports, a new router, and upgraded network management tools. Configuration testing was completed and three switches were installed, in the PPLCC, Theory Wing, and the LSB-West. Initial throughput testing has shown a 70% utilization of the 100 Mbps available bandwidth.


*CADD designer using Pro-Engineer software.*

## Y2K

In FY98, an inventory of all PPPL systems for Y2K compliance was completed and a remediation effort based on cost and benefit and criticality criteria was begun. Y2K network testing was completed, showing that no disruption of network services will be experienced at PPPL due to the millennium changeover. A new Y2K compliant router was ordered in FY98 and will be in place well before the new millennium. In other areas, from operating systems to financial and scientific applications, a focused effort to educate, upgrade, and remediate was begun.

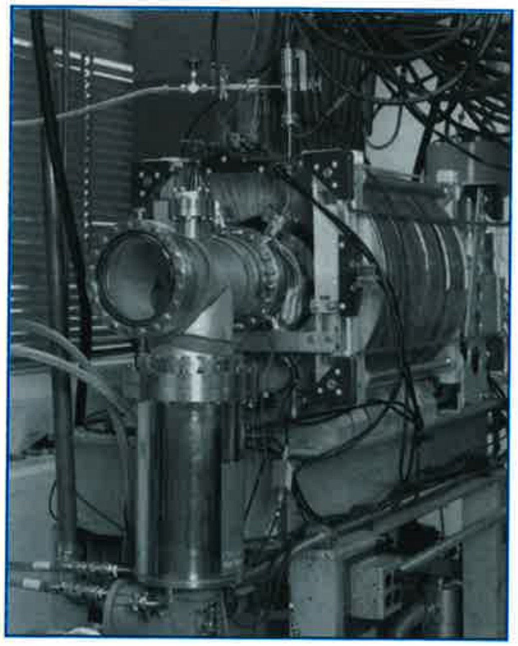
## Awards and Honors

Dr. Long-Poe Ku was named a PPPL Distinguished Engineering Fellow for his extraordinary creativity, capabilities, and accomplishments in developing and applying advanced analysis methods to experimental fusion devices, electron lithography, and the optimization of stellarator plasma configurations.

# Nonneutral Plasmas and High-Intensity Accelerators

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 and instabilities. 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; antimatter plasmas; 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.



***Electron Diffusion Gauge Experiment***

Research on nonneutral plasmas and high-intensity accelerators at the Princeton Plasma Physics Laboratory (PPPL) focuses on two areas: (1) basic experimental investigations of nonneutral electron plasmas confined in a Malmberg-Penning trap, including the effects of electron-neutral interactions on plasma confinement and stability properties and (2) analytical and numerical studies of the nonlinear dynamics and collective processes in intense nonneutral ion beams propagating in periodic-focusing accelerators and transport systems, with particular emphasis on next-generation accelerators for heavy ion fusion, spallation neutron sources, and tritium production.

Experimental research on nonneutral plasmas at PPPL is carried out in a Malmberg-Penning trap, called the Electron Diffusion Gauge experiment (see photo). 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 E × 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. 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 1, where the time $\tau$ for an initial collective excitation, known as the m=1 diocotron mode, to damp to one-half of its initial amplitude is plotted versus background gas pressure for confining magnetic field B = 612 G and electron line density $N = 4.16 \times 10^7$ cm$^{-1}$.

Recent theoretical advances in high-intensity accelerators and beam transport

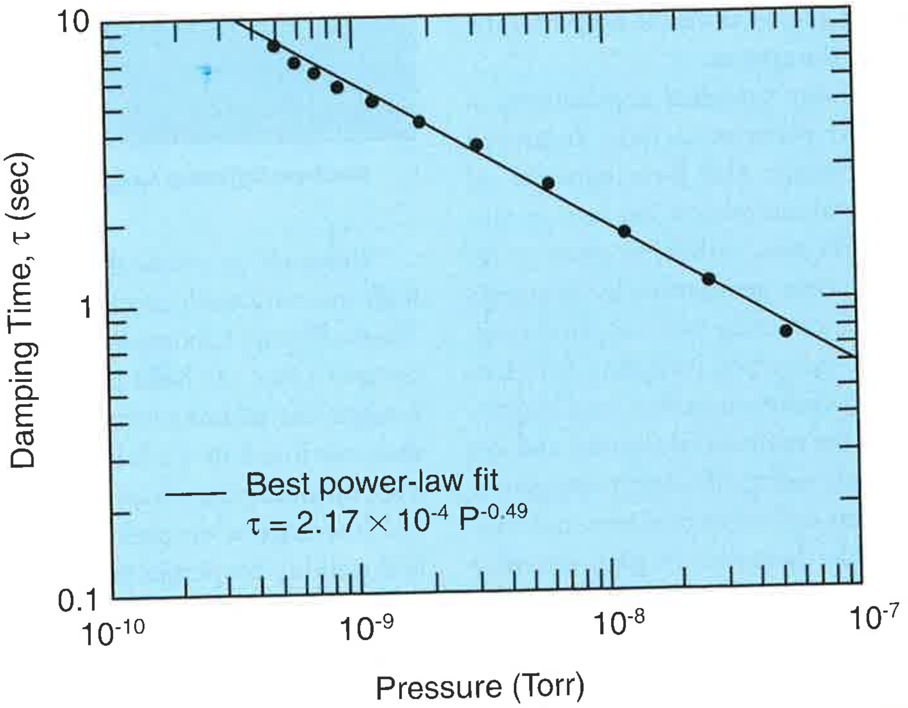


***Figure 1: The time $\tau$ for the m=1 diocotron mode to damp to one-half of its initial amplitude is plotted as a function of the background neutral gas pressure, P. Previous measurements of plasma behavior on this and other nonneutral plasma experiments found that the plasma behavior is insensitive to background gas pressure for pressures less than $10^{-8}$ Torr. Here, it is shown that the diocotron mode is sensitive to background pressure down to at least $5 \times 10^{-10}$ Torr.***

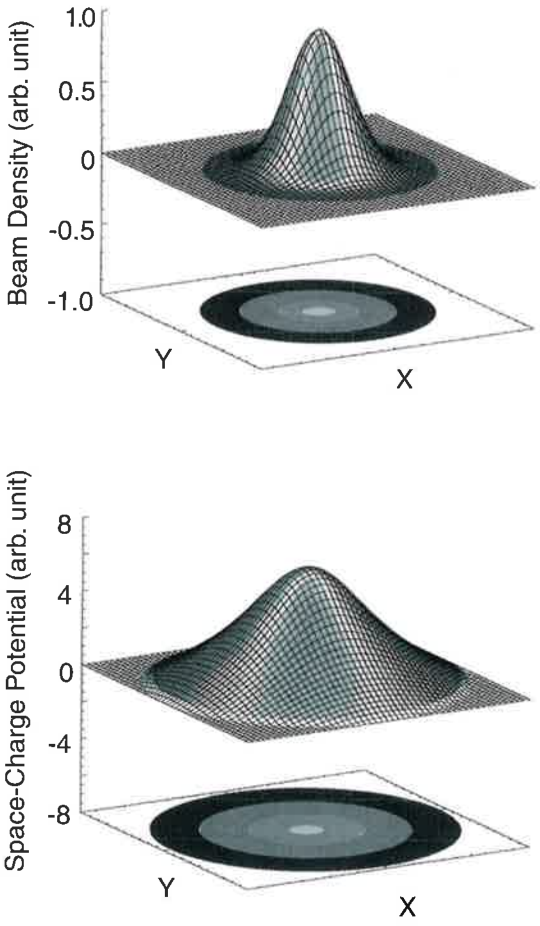


***Figure 2. Projections of beam density profile and space-charge potential onto the transverse plane.***

include the development of a three-dimensional kinetic stability theorem for nonlinear collective interaction in intense nonneutral particle beams, which identifies the class of beam distribution functions that can propagate quiescently over large distances.

In addition, a nonlinear δf simulation code has been developed and applied successfully to model high-intensity matched-beam propagation in periodic focusing transport systems over hundreds of lattice periods. Typical input profiles for a thermal equilibrium beam are illustrated in Figure 2, which shows a projection of the beam density profile n(x,y) and space-charge potential f(x,y) onto the transverse x-y planes for a very-high-intensity cesium beam with directed axial kinetic energy 2.5 GeV. Using a smooth-focusing model, the nonlinear δf simulations show that the beam propagates quiescently over 500 equivalent lattice periods, with fractional density fluctuations bounded by the initial fluctuation level.

# 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 science and their supporting disciplines. CRADAs enable Laboratory researchers and their partners to work on projects of mutual interest. Costs and the results may be shared by the participants. Since PPPL is funded by the U.S. Department of Energy (DOE), 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 by 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 technology transfer projects were underway in FY98.

## American Textile Partnership

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. 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 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 in FY96 because of funding limitations. In FY97, PPPL restarted the project which was continued in FY98.

Measurements have been made at PPPL with the aim of understanding the interaction of light with thin birefringent fibers. In particular, scattering experiments with polarized laser light have been carried out in the visible part of the spectrum. The scattering investigations have been done in the 180 degree — or backscatter — geometry. This geometry was chosen because it is minimally intrusive and, therefore, appropriate for use in a factory environment.

By solving Maxwell's equations as applied to a birefringent dielectric cylinder, it may be shown that, in general, an electromagnetic phase shift exists between scattered components of radiation which are polarized along and across the axis of the cylinder/fiber. The resulting phase shift causes the light backscattered by such a cylinder to be elliptically polarized. The problem of characterizing birefringent fibers therefore reduces to the problem of measuring the phase shift present in the radiation scattered by such fibers. This phase shift may be measured by passing that radiation through three polarizers simultaneously. The three polarizers must be oriented at three different angles with respect to the x axis of a coordinate system — 0, 45 and 90 degrees — in order to make independent measurements of Intensity, $I_x$ ,$I_{45}$ and $I_y$, respectively.

Successful efforts have been undertaken to generate and detect this backscattered radiation using computer-controlled equipment and techniques which are robust enough to survive the harsh environment of a textile factory.

Having detected this scattered radiation, efforts during FY98 were directed toward developing calibration and data analysis techniques which will allow for a unique determination of the backscatter-induced electromagnetic phase difference. This determination must be done in real time and at a sufficiently high sampling rate to be of interest to the textile manufacturing community.

During FY98, efforts to measure the phase shifts from real fibers met with partial success. Measurements indicate a large fiber-to-fiber variation in the induced phase shift from fibers which are nominally identical and should, therefore, exhibit identical phase shifts. The cause of this fiber-to-fiber variation will remain under investigation in FY99.

Two-color polarimetry as a method to determine the sensitivity of the measured phase shift to the wavelength of the laser employed is being pursued. Other experiments to determine sensitivity of the phase shift to the fiber stress are being developed.

When techniques have been developed which allow confidence in the phase shift measurements, the next step will be to compare the absolute value of those measurements to the phase shifts calculated using the code developed by H. Okuda of PPPL. This will allow a determination of the fiber birefringence.

## Modeling for Chemical Synthesis and Waste Treatment

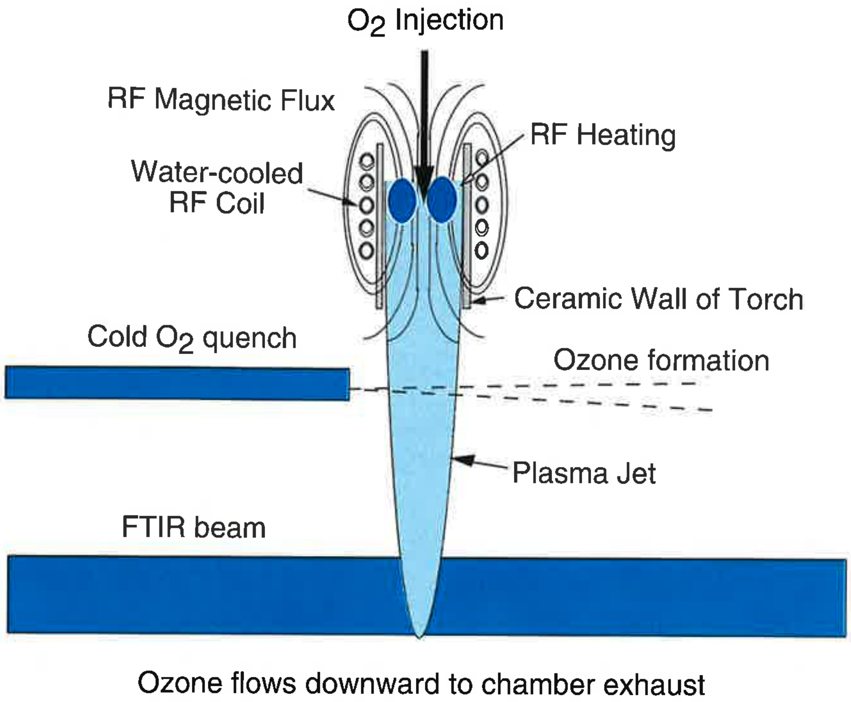
Ozone produced for water supply sterilization and paper pulp bleaching is usually produced by a cold plasma process. During FY98, researchers from PPPL and Drexel University developed a novel hot plasma method of synthesizing ozone.

Computer modeling showed that a nonequilibrium process was required. Drexel's plasma torch was used to produce a stream of dissociated oxygen molecules which then turbulently mixes with a quench stream of cold oxygen gas. The ozone concentration in the reaction chamber was measured by Fourier transform infrared spectroscopy over a wide range of experimental conditions and configurations. The geometry of the quench gas flow, the quench flow velocity, and the quench flow rate played important roles in determining the ozone concentration.

Rapid mixing of the plasma jet and the quench gas is therefore critical in four ways: (1) to prevent recombination of the oxygen atoms, (2) to mix O and $O_2$ so that ozone can be formed, (3) to dilute the atomic oxygen concentration in order to minimize the destruction reactions, and (4) to cool the mixture below 500 K to prevent thermal decomposition of the ozone. The limiting step in the synthesis is thus the mass transfer inherent in the plasma/quench mixing.

Cooling and dilution of the torch jet by the quench gas was accomplished by turbulent mixing in the reaction chamber.

## *Induction-coupled Plasma Torch*



***The Induction-coupled Plasma Torch is used to produce a stream of dissociated oxygen molecules. Ozone is formed when the oxygen molecules are mixed with a quench stream of cold oxygen gas. The ozone concentration is measured with a Fourier transform infrared (FTIR) spctrometer.***

Cooling the entire torch output by mixing would require a quench flow rate of about 1,000 standard liters per minute. In most cases, a small quench jet was used which entrained only a small part of the torch flow; the bulk of the thermal output of the torch was dissipated to the water-cooled reaction chamber walls downstream from the observation region.

Significant amounts of ozone, up to 250 parts per million, were produced in these experiments, demonstrating the technical feasibility of ozone synthesis using a quenched Induction-coupled Plasma torch. The corresponding production rate and yield were approximately 20 grams of ozone per hour and about 2 grams of ozone per kilowatt hour, respectively.

Both the quench gas flow rate and velocity were found to be important in determining the ozone concentration for a given quench configuration. These observations confirmed the initial hypothesis that a high degree of mixing of the quench gas with the plasma flow in a short period of time is crucial for producing high ozone concentrations. The ozone concentration was also very sensitive to the position of the quench jet with respect to the plasma flow, indicating that the quench jet must be directed toward a region of high atomic oxygen concentration for efficient production of ozone. The ozone concentration was also sensitive to the torch radio-frequency (rf) power, with the highest concentrations being obtained at intermediate rf power levels, but the ozone concentration was relatively insensitive to the sheath and probe gas flow rates.

While significant, the ozone concentrations produced in these experiments were lower than the commercially relevant level of 1% by more than an order of magnitude. Quench nozzles with small diameter orifices produced the highest velocity quench jets, which produced ozone locally where the jets interacted with the plasma; however, these quench jets did not interact with a large enough fraction of the plasma jet for high overall efficiency in ozone production. Conversely, the quench configurations that produced larger diameter quench jets which interacted with larger portions of the plasma flow had low velocities which did not lead to efficient mixing of the quench gas and plasma flows, and thus had low local ozone production efficiency.

These observations indicate a path for further development of this ozone synthesis technique: an array of small diameter, high-speed quench flows directed into the hot region of the plasma jet. The nozzles to produce these flows could be arranged in a semicircular array around the plasma (quench flows directed into each other would produce stagnation) and several such arrays of nozzles could be located at different levels below the torch exit nozzle to utilize the entire length of the plasma jet. It might also be possible to build an array of quench nozzles into the body or exit nozzle of the torch. Such an arrangement would make effective use of the bulk of the plasma jet, and thus produce higher ozone concentrations than were obtained in the experiments reported here.

## Radio-Frequency Equipment for Pasteurization Experiments

PPPL entered into a Work-for-Others project with the United States Department of Agriculture (USDA) concerning the use of rf energy to pasteurize liquid foods. The focus of the collaboration was the improvement of USDA's radio-frequency equipment employed in pasteurization research.

Radio-frequency waves offer advantages over the traditional pasteurization method of transferring energy from a hot fluid to the liquid to be pasteurized. The traditional method often heats foods unevenly, possibly resulting in incomplete pasteurization in lower temperature regions and denaturing foods in overheated regions. Using rf waves of the appropriate wavelength may allow pasteurization without heating foods to temperatures that cause food denaturation.

An rf "oven" was used to deliver the power which would facilitate the pasteurization process. The oven consisted of a power oscillator designed to deliver up to 10 kW at 27 MHz. In its original configuration, coupling of significant power to the test fluid was hampered by arcing at the load. In addition, enough rf leaked out of the unit to disrupt the instrumentation.

The PPPL effort was directed at reconfiguring the load for enhanced high- voltage standoff and rf performance, and improving the grounding for better rf containment. As a result, the power developed in the test fluid was increased from less than 1 kW to its rated output of 10 kW, with rf leakage reduced to minimal levels.

The equipment was returned to the USDA Eastern Regional Research Center, where, after overcoming a few problems with installation and operation, it has been operated at full power output for extended periods. Experiments are currently underway for the further investigation of rf pasteurization.

# Invention Disclosures and Patents

## Patents Issued

*Traveling Spark Ignition (TSI) System*
— Szymon Suckewer and Enoch J. Durbin

*Method and Apparatus for Steady-State Magnetic Measurement of Poloidal Magnetic Field near a Tokamak Plasma using only Fixed Air-core Electrical Coils and a Mechanical Strain Gauge*
— Robert D. Woolley

## Patents Applications

*Method and Apparatus for Measuring Micro Structures, Anisotropy and Birefringence in Polymers using Laser Scattered Light*
— Boris Grek, Joseph Bartolick, and Alan Kennedy

*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*
— Robert D. Woolley

## Invention Disclosures

*Hall Thruster with Segmented Cathode Electron Injection*
— N. Fisch and A. Fruchtman

*A Hollow Cathode Magnetron (HCM)*
— Z.H. Wang and S.A. Cohen

*Edge Turbulence Measurements by Laser Induced Fluorescence*
— C.H. Skinner and S.J. Zweben

*Hybrid Aircraft: Capable of Flight as a Helicoper, Autogyro or Fixed-Wing Plane*
— D.A. Cylinder

*New Types of X-ray Imaging Crystal Spectrometers for Extended X-ray Sources*
— M.L. Bitter, B. Fraenkel, K.W. Hill, A.L. Roquemore, W. Stodiek, and S. von Goeler

*Laser-driven Source of Tunable Undulator Radiation*
— G. Shvets, N.L. Fisch, and J.-M. Rax

*Synthesis of Ozone at Atmospheric Pressure by a Quenched Induction-coupled Plasma Torch*
— B.C. Stratton, D.R. Mikkelsen, R. Knight, E. Grossmann, A. Blutke, and J. Vavruska

*Remote Erosion Measurement in a Fusion Reactor*
— C.H. Skinner

*Generation of Periodic Accelerating Structures in Plasmas*
— G. Shvets, A. Pukhov, and N.J. Fisch

*Parametric Amplification of Ultra-short Laser Pulses in Plasma*
— Gennady Shvets, Nathaniel J. Fisch, and Alexander Pukhov

*Nonneutral Plasma Fusion Trap Device*
— Cynthia Kieris Phillips

*Passive Positioning of Hall Thruster Fields*
— Ammon Fruchtman and Nathaniel Fisch

*In-vessel Dust Measurements by a Quartz Microbalance*
— C.H. Skinner and H. Kugel

*High Energy for Sterilization*
— John A. Schmidt

*Micro Hall Thrusters*
— Nathaniel Fisch and Yevgeny Raitses

*Ultra-high-density Feedthroughs and Signal Conduits using Thick-film Printed Circuit Technology*
— Hironori Takahashi

# Graduate Education

***Fiscal Year 1998 graduate students in The Program in Plasma Physics, Department of Astrophysical Sciences, Princeton University.***

The Princeton Plasma Physics Laboratory supports graduate education through the Program in Plasma Physics in the Department of Astrophysical Sciences of Princeton University. Students are admitted directly to the Program and are granted degrees through the Department of Astrophysical Sciences. With more than 193 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 thrusters, plasma devices, nonneutral plasmas, lasers, materials research, and in other important and challenging areas of plasma physics.

In FY98, there were 32 graduate students in residence in the Program in Plasma Physics, holding among them one Department of Energy Magnetic Fusion Science Fellowship, one Hertz Fellowship, one National Science Foundation Fellowship, two Department of Defense National Defense Science and Engineering Graduate Fellowships, two NASA Graduate Student Researchers Program Fellowships, and one Princeton University Honorific Fellowship.

Six new students were admitted in FY98, two from Russia and four from the

U.S. Eleven students graduated in FY98, nine receiving postdoctoral positions at the following: Los Alamos National Laboratory, University of Wisconsin at Madison, Princeton Plasma Physics Laboratory, Lawrence Livermore National Laboratory, University of Colorado at Boulder, and the University of Chicago. One graduate took a position in private industry (Santa Cruz Organization, New Jersey) and one graduate holds a teaching position at The Colorado College in Colorado Springs.

Our graduate students received several awards this year. A fifth-year graduate student won the Princeton University Porter Ogden Jacobus Fellowship in recognition of his distinguished work in the Department of Plasma Physics. The Jacobus Fellowship is an honorific fellowship awarded by the Graduate School and is conferred annually upon the student, who, in the judgment of the University Faculty, displayed the *highest scholarly excellence.* Two awards were received by fifth and sixth-year graduate students from the American Vacuum Society for outstanding scholarship in vacuum science and technology and a fourth student won a Department of Energy Postdoctoral Fellowship.

## *Recipients of Doctoral Degrees in Fiscal Year 1998.*

**Chen, Yang**

| | |
|---|---|
| Thesis: | Numerical Study of the Nonlinear Evolution of Toroidicity-Induced In Alfvén Eigenmodes |
| Advisor: | Roscoe B. White |
| Employment: | University of Colorado at Boulder |

**Herrmann, Mark C.**

| | |
|---|---|
| Thesis: | Cooling Alpha Particles with Waves |
| Advisor: | Nathaniel J. Fisch |
| Employment: | Lawrence Livermore National Laboratory, CA |

**Long, Hui**

| | |
|---|---|
| Thesis: | Hybrid Simulation of High Recycling Divertors |
| Advisor: | Charles F.F. Karney |
| Employment: | Santa Cruz Organization, NJ |

**Menard, Jonathan E.**

| | |
|---|---|
| Thesis: | High-Harmonic Fast Wave Coupling and Heating Experiments in the CDX-U Spherical Tokamak |
| Advisor: | Masayuki Ono and Stephen C. Jardin |
| Employment: | Princeton Plasma Physics Laboratory, NJ |

**Oliver, Hilary J.**

| | |
|---|---|
| Thesis: | A Newton Method for the Magnetohydrodynamic Equilibrium Equations |
| Advisor: | Allan H. Reiman and Donald A. Monticello |
| Employment: | Princeton Plasma Physics Laboratory, NJ |

**Park, Jaeyoung**

| | |
|---|---|
| Thesis: | Studies on a Transition to Strongly Recombining Plasmas |
| Advisor: | Samuel A. Cohen |
| Employment: | Los Alamos National Laboratory, NM |

**Qin, Hong**

Thesis: Gyrokinetic Theory and Computational Methods for Electromagnetic Perturbations inTokamaks
Advisor: William M. Tang
Employment: Princeton Plasma Physics Laboratory, NJ

**Schwartz, Peter V.**

Thesis: Molecular Beam Studies of the Growth and Kinetic of Self-Assembled Monolayers
Advisor: Giacinto Scoles
Employment: The Colorado College, Colorado Springs, CO

**Uzdensky, Dmitri A.**

Thesis: A Theoretical Study of Magnetic Reconnection
Advisor: Russell M. Kulsrud
Employment: The University of Chicago, IL

**Wang, Zhehui**

Thesis: A Hollow Cathode Magnetron: Its Characterization and Energetic Nitrogen Atom Diagnostics
Advisor: Samuel A. Cohen
Employment: Los Alamos National Laboratory, NM

**Wright, John C.**

Thesis: Fast Wave Current Drive Modeling in Tokamaks
Advisor: Cynthia K. Phillips
Employment: University of Wisconsin at Madison, WI

***Stanislav Boldyrev (l), graduate student in the Astrophysical Sciences Department's Program in Plasma Physics, received the Porter Ogden Jacobus Fellowship, given annually to the graduate student who exhibits the "highest scholarly excellence." He is being congratulated by Dean of the Faculty Joseph Taylor at Alumni Day celebrations.***

## Students Admitted to the Plasma Physics Program in Fiscal Year 1998.

| Student | Undergraduate Institution | Major Field |
|---|---|---|
| **Leonid Dorf** | Nizhny Novgorod State University, Russia | Physics |
| **Elizabeth Foley** | University of Massachusetts at Amherst | Physics and Math |
| **Alexander Kuritsyn** | Nizhny Novgorod State University, Russia | Physics |
| **Alexandra Landsman** | Dartmouth College | Physics |
| **Adam Rosenberg** | Cornell University | Applied and Engineering Physics |
| **Jeffrey Spaleta** | Worcester Polytechnic Institute | Physics and Math |

*First-year graduate students in the Program in Plasma Physics in 1998. From left-to-right are Alexandra Landsman — Dartmouth College; Elizabeth Foley — University of Massachusetts at Amherst; Jeffrey Spaleta — Worcester Polytechnic Institute; Alexander Kuritsyn — Nizhny Novgorod State University, Russia; Adam Rosenberg — Cornell University; (missing) Leonid Dorf — Nizhny Novgorod State University, Russia.*

# Science Education

***Andrew Post-Zwicker (left) discussing equipment used to study the conditions under which a gas can become a plasma with Brian Wargo (Freedom Area High School, Freedom, PA) and Uma Jayaraman (Lamberton High School, Philadelphia, PA)***

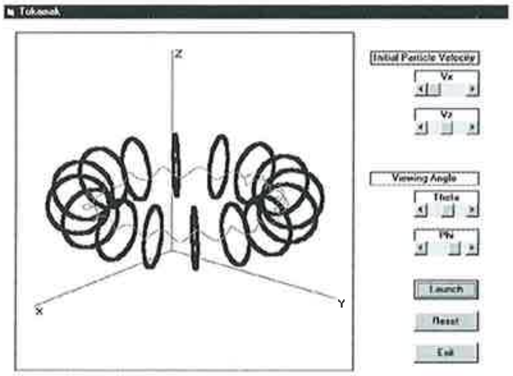
During FY98, the Princeton Plasma Physics Laboratory's (PPPL) Science Education Program continued to build on its past successes. In addition to existing programs for teachers, students, and the community-at-large, a new creative initiative — the Plasma Physics and Fusion Energy Institute — was launched and PPPL joined the Department of Energy's Energy Research Undergraduate Laboratory Fellowship Program.

## The Plasma Physics and Fusion Energy Institute

The Plasma Physics and Fusion Energy Institute "Plasma Camp" was born out of an effort to educate high school physics teachers about a contemporary physics topic by having them participate in real research investigations and engage in pedagogical activities designed for eventual use in their classrooms. Plasma Camp, hosted by a PPPL scientist and a current high school physics teacher, used the research experience as a means of exposing educators to theory and experimental methodology and assisted them in developing lesson plans. Follow-up grants are available to each participant during the school year for the purpose of buying or building plasma-related equipment and for the purpose of paying travel expenses to regional or national meetings to disseminate their new plasma-based curricula to fellow teachers. High school physics teachers were selected from a nationwide pool on the basis of three main criteria: physics background, laboratory experience, and a demonstrated willingness to involve students in innovative and open-ended curricula.

A typical day at "Camp" consisted of a morning lecture on topics such as space plasmas, fusion reactor design, and plasma processing of materials, with the remainder of the day devoted to lab work or curriculum development. The experiments were modifications of those used in the 'Grad Lab' (Princeton University's Astrophysical Sciences 562) and, among other topics, included: plasma formation, plasma spectroscopy, and characterization of plasmas via microwave interferometry.

Teachers were not asked to create a separate unit plan on plasma physics, but rather to apply the subject matter and experimental methods from plasma and fusion science to teach concepts in a broad variety of scientific disciplines. For example, they would use methods in plasma spectroscopy to teach their students optics and atomic physics. In biology, students would investigate the effect of plasma-based light sources on plant growth. A lesson in computer science, or one in electricity and magnetism, would involve an interactive computer simulation of charged-particle orbits along magnetic filed lines in a fusion reactor (photo, below left). The various curricula developed during Plasma Camp are available on the web at (http://ippex.pppl.gov/ippex/summer_institute/).



***A screen capture from software developed by Father Michael Liebl of the Mount Michael Benedictine High School in Elkhorn, NE. The software calculates and displays the path of a charged particle in a toroidal magnetic field (similar to the primary field of a tokamak fusion reactor) during a single loop around the torus. The user can control the particle's initial velocity and the viewing angle.***

In FY 99, Plasma Camp will bring some of the "veteran" teachers back to PPPL to work with the new participants. The veterans will have a chance to run an experiment of their own design on PPPL's Current Drive Experiment-Upgrade and both groups will again spend the majority of their time in the grad lab. The groups will also work together on plasma-based curriculum design and the preliminary assessment of the effectiveness of Plasma Camp.

## Community Outreach and Partnerships

The PPPL Science Education Program continued the Princeton Research Enrichment Program, started in 1996 for talented high school students. The program exposes these students to a scientific work environment. They are able to explore career possiblitites in science and engineering, discuss ethics in science, and participate in hands-on research projects. PPPL continued its relationship with Union Hill High School in Union City, NJ, and added Science High School in Newark, NJ, as a new partner. Science High is New Jersey's only urban high school dedicated to science. PPPL Science Education staff continued their commitment to provide volunteer internships to students attending local area high schools. In 1998, participants included students from the Hun School of Princeton and Steinert High School in Hamilton. PPPL also participated in the Liberty Science Center's Partners-in-Science Program which places high school students in scientific research facilities throughout New Jersey.

PPPL hosted the Summer Teacher Leadership Program sponsored by the A+ for Kids Hoeschst Marion Roussel Institute of Science, Mathematics, and Technology. Thirty-five area teachers participated in 1998. Established in 1997, the goals of the program are to prepare teachers to create and disseminate innovative lesson plans and to increase the number of teachers who can effectively communicate the excitement of teaching science and mathematics to students in grades 4-12.

## Fusion Outreach Efforts

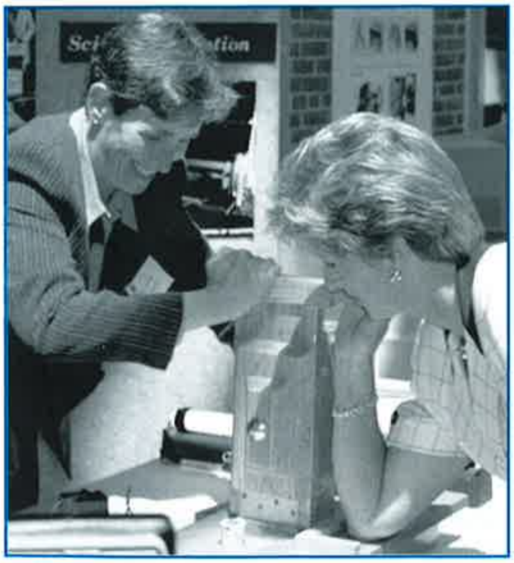
PPPL's Science Education Program participated in a number of fusion outreach activities during FY98. Among them were the Plasma Science Expo at George Washington University, Future Fest (an annual outdoor street festival in Washington, DC), the Coalition for Plasma Science display in the Rayburn House Office Building, and the New Jersey Technology Exposition at Princeton University's Engineering School. PPPL's research, National Spherical Torus Experiment, and educational demonstrations were the focus of the Laboratory's display at the Technology Exposition, which was visited by New Jersey Governor Christine Whitman.

*Tobin Munsat (left) and Andrew Post-Zwicker demonstrate hands-on activities at the 1997 Plasma Sciences Expo in Pittsburgh, PA.*

The PPPL Science Education staff also helped coordinate the community fusion display for the 17th World Energy Congress held in Houston, TX, in September, 1998.

## PPPL-Trenton City Schools Partnership

PPPL continued its partnership with the Trenton Public Schools by engaging other regional and community stakeholders in the effort to improve math and science performance in the District. Specifically, in collaboration with the Princeton University Teacher Preparation program and the Invention Factory Science Center, PPPL secured a major grant from the New Jersey Department of Education to provide teacher professional development in Trenton and two smaller school districts.



*PPPL Science Education Program Head, Diane Carroll (left) watches as New Jersey Governor Christine Whitman takes on the electromagnetic arm wrestling machine during a science and technology conference at Princeton University.*

***Dianne Nunes demonstrates a plasma ball at Future Fest in Washington, DC.***

PPPL provided a series of evening workshops for teachers, "Science-Over-Supper," that allowed elementary and middle school teachers an opportunity to work with scientists from PPPL, Princeton University, and other institutions to explore in greater depth the science topics they were teaching.

With scientists from Princeton University, PPPL also presented, "Exploring Earth," a one-week teacher workshop that introduced Trenton teachers to basic concepts in earth science while providing them the opportunity to experience the process of conducting scientific investigations.

## Undergraduate Research Programs

In addition to PPPL's long-standing National Undergraduate Fellowship Program, in FY98, PPPL participated in the Department of Energy (DOE) sponsored

***Diane Carroll, Head of PPPL's Science Education Program, demonstrates to students the effects of magnetic fields on plasma in an uncoated flourescent light bulb during Pollution Prevention Awareness Day.***

***Participants in DOE's Energy Research Undergraduate Laboratory Fellowship Program at PPPL.***

| **Name** | **School** | **Mentor/ Group** | **Project** |
|---|---|---|---|
| Melissa Cheng | Brown University | Computer Division | Microcomputer Specialist |
| Abinidab Dieter | Harvey Mudd College | Robert Kaita | Upgrade of CDX-U Soft X-Ray Diode Array |
| Kevin Ertmer | Princeton University | Computer Division | Microcomputer Specialist |
| Hans Gangwar | NJ Institute of Technology | Computer Division/ Mechanical Engineering | CADD Designer |
| Austin Grisham | Purdue University | Douglas McCune | |
| Al-Khalique Hamilton | Georgia Tech | Geophysical Fluid Dynamics Laboratory | 3-D Modeling |
| Blaise Kapombe | Morgan State University | Andrew Post-Zwicker | Predicting the Impact of Fusion Energy on Global Climate |
| Gregory Lampkin | Fisk University | Robert Kaita | Laser-induced Fluorescence Study of Poloidal Shear Rotation |
| Benita Lee | Southern University | Charles Gentile | Real Time and Passive Measurements of the Distribution of Tritium in TFTR |
| Gregory Larchev | Stanford University | Raki Ramakrishnam | Coil Protection Calculation for NSTX |
| Michael Obland | University of Montana | Zihong Lee | Orbit Topologies of Plasma Particles in a Tokamak |
| Carver Page | NJ Institute of Technology | Andrew Post-Zwicker | Updating the Virtual Tokamak using Object-oriented Modeling |
| Sekhon Sunitinder | University of Pennsylvania | Douglas McCune | Visualization Research in the CPPG |
| Neshana Shaw | Southern University | Geophysical Fluid Dynamics Laboratory | Statistical Analysis of Associations Between Temperature Anomalies and Occurrences |
| Sterling Windsor | Southern Missouri State University | Ronald Hatcher | Simulation of a Plasma Start-up Scenario |

Energy Research Undergraduate Laboratory Fellowship Program. The Fellowships are designed to provide educational training and research experiences for academically talented, undergraduate students. By reinforcing and influencing career choices of students, the Program assists in developing a technically trained workforce. PPPL was one of ten DOE laboratories selected to participate. The appointments are for 10 weeks during the summer or for 16 weeks during the fall term. During the summer of 1998, fifteen students from 13 different colleges and universities, including three Historically Black Colleges and Universities, participated in the Program at PPPL. Students were selected based on their academic ability, potential to do research work, and interest in graduate study. A list of the students is found in the table above.

Undergraduate students from both programs joined members of the American Physical Society Division of Plasma Physics in presenting the results of their summer research at the Division of Plasma Physics Annual Meeting held in New Orleans, Louisiana, in November 1998.

# Awards and Honors

## Individual Awards

### Michael Bell
Fellow
American Physical Society
Division of Plasma Physics

### Stanislav Boldyrev
Porter Ogden Jacobus Fellowship
Princeton University

### Mary Ann Brown
Gayle B. Crews Memorial Award
United Way

### Ronald C. Davidson
President's Standing Committee on
the Status of Women Award
Princeton University

### Gregory Hammett
Fellow
American Physical Society
Division of Plasma Physics

### Pamela Lucas
President's Standing Committee on
the Status of Women Award
Princeton University

### Susan Murphy-LaMarche
President's Standing Committee on
the Status of Women Award
Princeton University
and
Executive of the Year
Professional Secretaries International
Mercer County Chapter

### Jon Menard
Best Student Paper Award
American Nuclear Society
Fusion Energy Division

### Wonchull Park
Fellow
American Physical Society
Division of Computational Physics

### Paul Rutherford
Distinguished Career Award
Fusion Power Associates

## Laboratory Awards

### Turquoise Award for Commitment in EEO/Diversity
U.S. Department of Energy

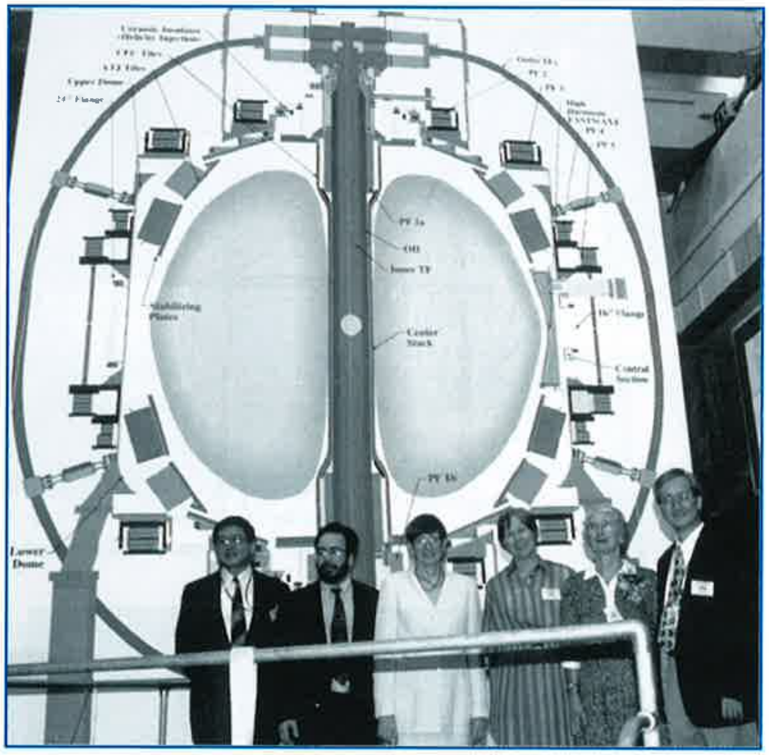
### EEO/Diversity Best Practices Award
U.S. Department of Energy

### Best Poster Design Award
Pollution Prevention
U.S. Department of Energy

### *1998 PPPL Employee Recognition Award Recipients*

***Honored by their co-workers for their "personal qualities and professional achievements," nineteen PPPL employees received Employee Recognition Awards in 1998. The recipients are, from left, Al von Halle, John Boscoe, Masayuki Ono, Rosemarie Fuchs, Tom Meighan, Charles Karney, Tom Egebo, John Bennevich, Andy Carpe, Sharon Warkala, Carl Szathmary, John Gennuso, Gregory Rewoldt, Joyce Bitzer, and Ernest Valeo. Not pictured are Keith Chase, Marie Iseicz, Steve Langish, and James Morgan.***

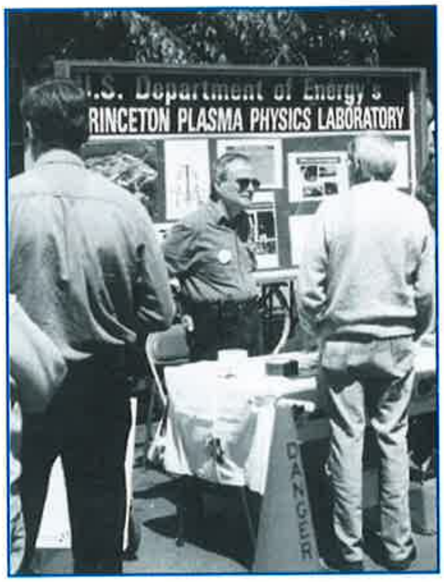
# The Year in Pictures



***PPPL celebrated the dedication of the Lyman Spitzer Building and the groundbreaking of the National Spherical Torus Experiment (NSTX) on May 18, 1998. Standing in front of a full-scale drawing of NSTX at the groundbreaking ceremony are (from left) Masa Ono, NSTX Project Director; Rob Goldston, Director of PPPL; Martha Krebs, Director of the U.S. Department of Energy's Office of Science; N. Anne Davies, Associate Director, U.S. Department of Energy Office of Fusion Energy Sciences; Doreen Spitzer, widow of Lyman Spitzer, Jr.; and Martin Peng, NSTX Program Director.***

***PPPL's Laboratory Office Building was renamed in honor of Laboratory founder Lyman Spitzer, Jr., who died in 1997. Mrs. Spitzer (right) and Martha Krebs, Director of the U.S. Department of Energy's Office of Science, view the building plaque after the unveiling at the building dedication.***

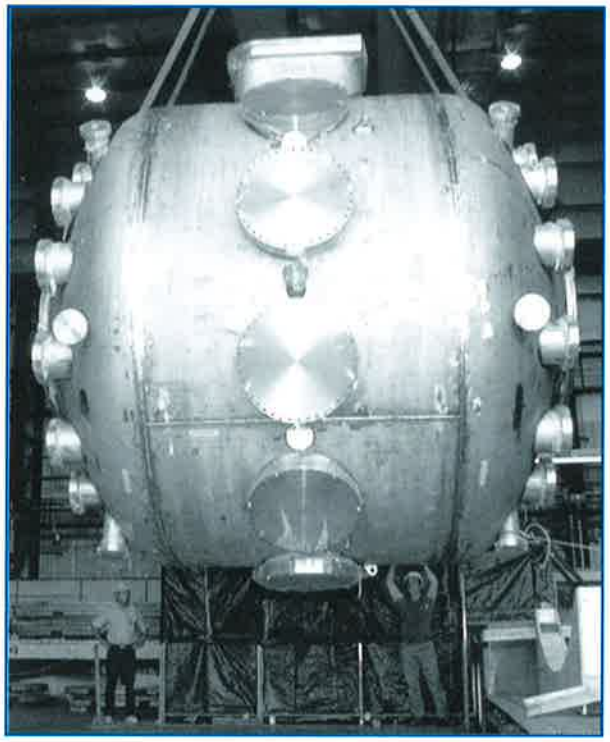
*In April, PPPL participated in Communiversity, an annual springtime celebration that joins Princeton University with the community of Princeton. In photo above, PPPL Associate Director for External Affairs John DeLooper (left) demonstrates turbulence with a flowing bubble apparatus to the sons of PPPL Deputy Director Richard Hawryluk as Hawryluk (in sunglasses) watches.*



*Information Services Head Anthony DeMeo fields questions about the Lab.*

*PPPL received $700,000 in fiscal year 1998 under a Cooperative Research and Development Agreement (CRADA) between the Laboratory and the Princeton Textile Research Institute. The agreement is part of the American Textile Partnership (AMTEX) — a government-industry consortium which includes many of the nation's leading textile and apparel manufacturers. Under the terms of the CRADA, Laboratory staff will develop state-of-the-art optical techniques for the on-line characterization of synthetic fibers during production. PPPL staff involved in the AMTEX project are (from left) Dennis Mansfield, Hideo Okuda, Mark Cropper, Phil Efthimion, and Stewart Zweben. The laser device is on the table in front of Efthimion.*

*The Laboratory honored twenty-two inventors for Fiscal Year 1997 during the sixteenth annual Patent Recognition Dinner on June 16 at Princeton University's Prospect House. Those attending the dinner and receiving awards included (from left) Don Weissenburger, Joseph Cecchi, Charles Skinner, Nathaniel Fisch, Robert Woolley, Samuel Cohen, Gennady Shvets, Tobin Munsat, Jan Wioncek, Enoch Durbin, Szymon Suckewer, and Hironori Takahashi.*



*Construction of the National Spherical Torus Experiment (NSTX) progressed rapidly. The 23,000-pound vacuum vessel for NSTX arrived at the Laboratory on August 5, marking a major step in the construction of the new device. Earlier in the summer, the world's tallest ohmic-heating solenoid was delivered to PPPL and lowered over the inner toroidal field coils of NSTX, which were also major milestones in the assembly of the project.*

*PPPL Nobel Laureate Russell Hulse and Plainsboro Public Library Director Jinny Baeckler spearheaded a project called "Contact Science," which will create, disseminate, and support small-scale traveling science exhibits in public libraries. The prototype exhibit would be located at the Plainsboro, New Jersey library and travel to other libraries from there. Procter & Gamble, Inc. is funding the Phase I scoping and program development studies. The Contact Science team includes, from left, former PPPL Associate Director Dick Rossi, consultant Barbara Graham, Hulse, and Baeckler.*

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

| | FY94 | FY95 | FY96 | FY97 | FY98 |
|---|---|---|---|---|---|
| **Operating Costs** | | | | | |
| Fusion Energy Sciences | | | | | |
| TFTR Physics | $17,331 | $14,207 | $13,004 | $13,607 | $4,955 |
| TFTR Operations | 50,646 | 46,938 | 33,792 | 13,497 | — |
| TFTR DT Systems | 1,041 | — | — | — | — |
| TFTR Shutdown/Caretaking | 4,503 | 2,047 | 8 | 12,368 | 3,292 |
| Subtotal TFTR | $73,521 | $63,192 | $46,804 | $39,472 | $8,247 |
| NSTX | — | — | $1,163 | $1,441 | $3,241 |
| TPX | $15,550 | 43,145 | (1,255) | (1,062) | (224) |
| Advanced Projects/Stellarator | — | — | 1,073 | 702 | 2,524 |
| Theory and Computation | 3,142 | 3,295 | 2,683 | 2,929 | 4,003 |
| ITER | 2,146 | 2,138 | 2,981 | 3,546 | 3,677 |
| Off-site Collaborations | 430 | 2,279 | 1,253 | 4,028 | 9,241 |
| Off-site University Research Support | — | — | — | — | 985 |
| PBX-M | 3,913 | 4,138 | 9 | — | — |
| CDX-U | 677 | 758 | 699 | 479 | 802 |
| Science Education Programs | 271 | 429 | 301 | 440 | 691 |
| Other Fusion | 519 | 1,710 | 1,232 | 1,469 | 2,385 |
| Change in Inventories* | (1,915) | (76) | (90) | (35) | (50) |
| Total Fusion Energy Sciences | $98,254 | $121,008 | $56,853 | $53,409 | $35,522 |
| Environmental Restoration and Waste Mgt | $4,811 | $5,728 | $3,581 | $4,066 | $3,735 |
| Computational and Technology Research | 66 | 300 | 391 | 157 | 101 |
| Basic Energy Sciences | — | — | — | — | 302 |
| High Energy Physics | — | — | — | — | 73 |
| University and Science Education | 406 | 331 | 279 | 92 | — |
| Energy Management Studies | 65 | 124 | 136 | 13 | 3 |
| Total DOE Operating | $103,602 | $127,491 | $61,240 | $57,737 | $39,736 |
| Work for Others | | | | | |
| Korea Basic Science Institute | — | — | $186 | $1,837 | $2,039 |
| All Other | 490 | 797 | 693 | 1,199 | 2,218 |
| Total Operating Costs | $104,092 | $128,288 | $62,119 | $60,773 | $43,993 |
| **Capital Equipment Costs** | | | | | |
| TFTR | $373 | $469 | $546 | $241 | — |
| NSTX Fabrication | — | — | — | 3,412 | 12,268 |
| All Other Fusion | 390 | 458 | 71 | 32 | — |
| Environmental Restoration and Waste Mgt | 67 | 127 | 125 | 75 | (1) |
| Total Capital Equipment Costs | $830 | $1,054 | $742 | $3,760 | $12,267 |
| **Construction Costs** | | | | | |
| General Plant Projects - Fusion | $1,875 | $2,066 | $2,158 | $473 | $454 |
| General Plant Projects - ERWM | 310 | 163 | — | — | — |
| Safety and Fire Protection Improvements | 1,014 | 817 | 332 | 34 | — |
| Radioactive Waste Handling Facility | — | 1,066 | 560 | 1 | — |
| Energy Management Projects | 11 | 71 | 66 | 255 | 45 |
| Total Construction Costs | $3,210 | $4,183 | $3,116 | $763 | $499 |
| TOTAL PPPL | $108,132 | $133,525 | $65,977 | $65,296 | $56,759 |

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

# PPPL Organization

## Directorate

Robert J. Goldston
**Director**

Richard J. Hawryluk
**Deputy Director**

William M. Tang
**Chief Scientist**

Nathaniel J. Fisch
**Associate Director for Academic Affairs**

John W. DeLooper
**Associate Director for External Affairs**

Steven M. Iverson
**Head, Human Resources**

Susan E. Murphy-LaMarche
**Deputy Head, Human Resources**

## PPPL Director's Cabinet

Robert J. Goldston
**Director**

Richard J. Hawryluk
**Deputy Director**

William M. Tang
**Chief Scientist**

William Happer
**Chair, Princeton University Research Board**

## Departments

**Advanced Projects**
John A. Schmidt, Head
G. Hutch Neilson, Deputy

**Off-Site Research**
Ned R. Sauthoff

**Plasma Science and Technology**
Stewart J. Zweben

**National Spherical Torus Experiment**
Martin Peng, Program Director*
Masayuki Ono, Project Director
Michael D. Williams, Deputy

**Theory**
William M. Tang, Head
Stephen C. Jardin, Deputy

**Experiment**
Joel C. Hosea

**Engineering and Technical Infrastructure**
Michael D. Williams

**Business Operations**
Edward H. Winkler

**Environment, Safety, and Health and Infrastructure Support**
John W. Anderson

**from Oak Ridge National Laboratory, residing at PPPL.*

# PPPL Staffing Summary by Fiscal Year

| | FY94 | FY95 | FY96 | FY97 | FY98 |
|---|---|---|---|---|---|
| Faculty | 7 | 7 | 7 | 6 | 6 |
| Physicists | 97 | 91 | 89 | 88 | 87 |
| Engineers | 156 | 118 | 105 | 76 | 74 |
| Technicians | 306 | 215 | 198 | 137 | 136 |
| Administrative | 121 | 91 | 81 | 66 | 68 |
| Office and Clerical Support | 57 | 37 | 28 | 19 | 18 |
| Total | 744 | 559 | 508 | 392 | 389 |

## PPPL Advisory Council

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

Dr. Norman R. Augustine
Princeton University

Dr. David E. Baldwin
General Atomics

Dr. Robert W. Conn
University of California, San Diego

Dr. Andrea Dupree
Harvard University

Professor Jerome Friedman
Massachusetts Institute of Technology

Professor Edward A. Frieman
Scripps Institution of Oceanography

Professor Robert A. Gross
Chapel Hill, North Carolina

Mr. Edwin E. Kintner
Norwich, Vermont

Dr. William L. Kruer
Lawrence Livermore National Laboratory

Dr. Jerry D. Mahlman
Geophysical Fluid Dynamics Laboratory

Dr. Richard A. Meserve
Covington and Burling

Dr. John Nuckolls
Lawrence Livermore National Laboratory

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

Dr. Burton Richter
Stanford Linear Accelerator Center

## PPPL University Oversight Committee

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

Professor Jeremiah P. Ostriker (Chair)
Provost

Mr. Raymond J. Clark
Treasurer

Mr. Robert K. Durkee
Vice President for Public Affairs

Mr. Howard S. Ende
General Counsel

Professor William Happer
Chair, University Research Board

Mr. Eugene J. McPartland
Vice President for Facilities

Mr. Allen J. Sinisgalli
Associate Provost for Research
and Project Administration

Professor A.J. Stewart Smith
Chair, Department of Physics

Dr. Richard R. Spies

Professor Joseph Taylor
Dean of the Faculty

Professor Sam B. Treiman
Department of Physics

Professor James Wei
Dean, School of Engineering
and Applied Science

Professor John F. Wilson
Dean of the Graduate School

Professor Robert J. Goldston
Director
Princeton Plasma Physics Laboratory

Dr. Richard J. Hawryluk
Deputy Director
Princeton Plasma Physics Laboratory

Mr. Steven M. Iverson
Head, Human Resources
Princeton Plasma Physics Laboratory

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