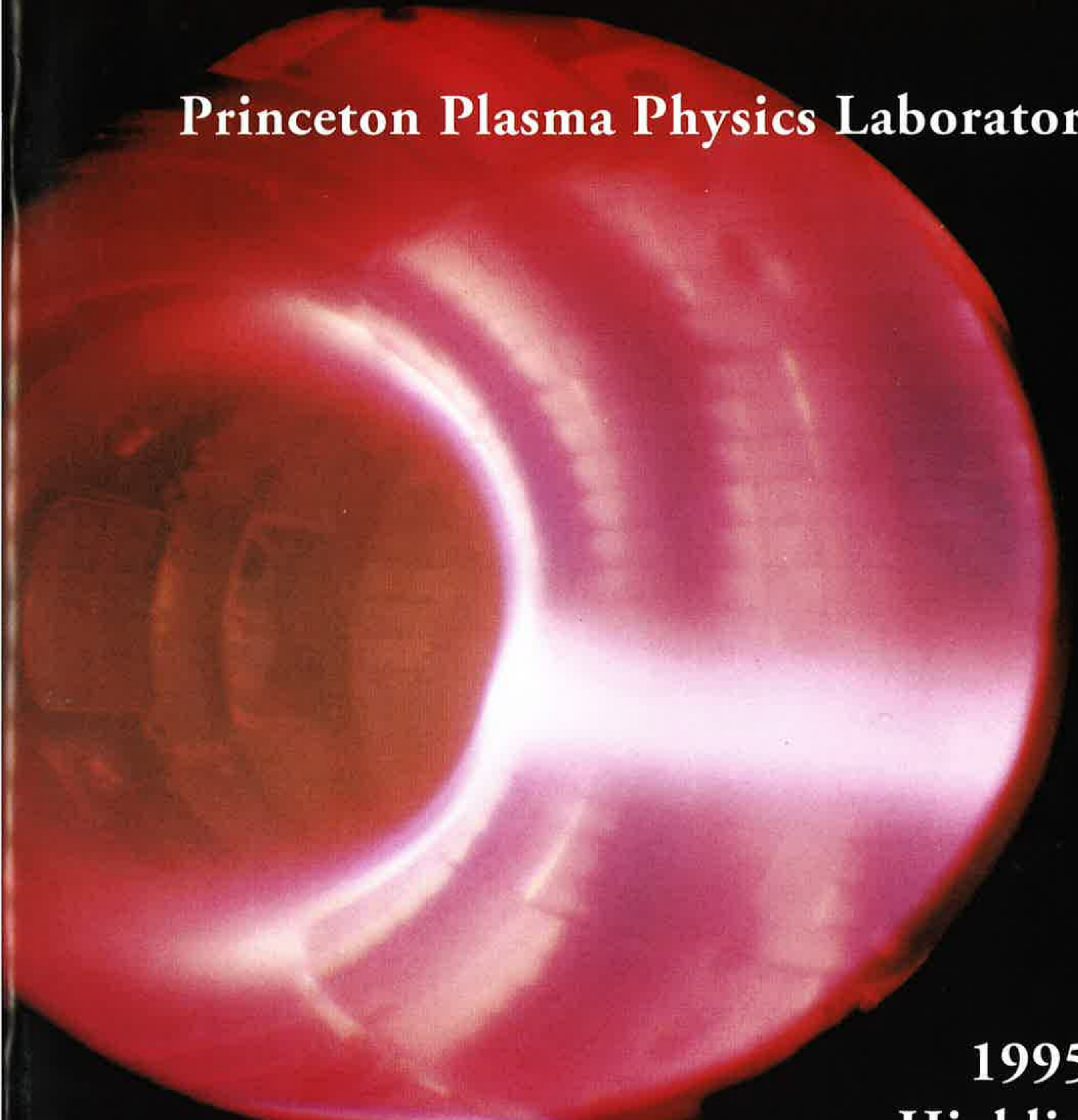
Princeton Plasma Physics Laboratory



1995
Highlights

About PPPL

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

PPPL is managed by Princeton University under contract with the U.S. Department of Energy. The fiscal year 1995 budget was almost $98 million. The average number of full-time employees for the fiscal year was about 720 with an additional 110 subcontractors, graduate students, and visiting research staff. The Laboratory is sited on 72 acres of Princeton University's James Forrestal Campus, about four miles from the main campus.

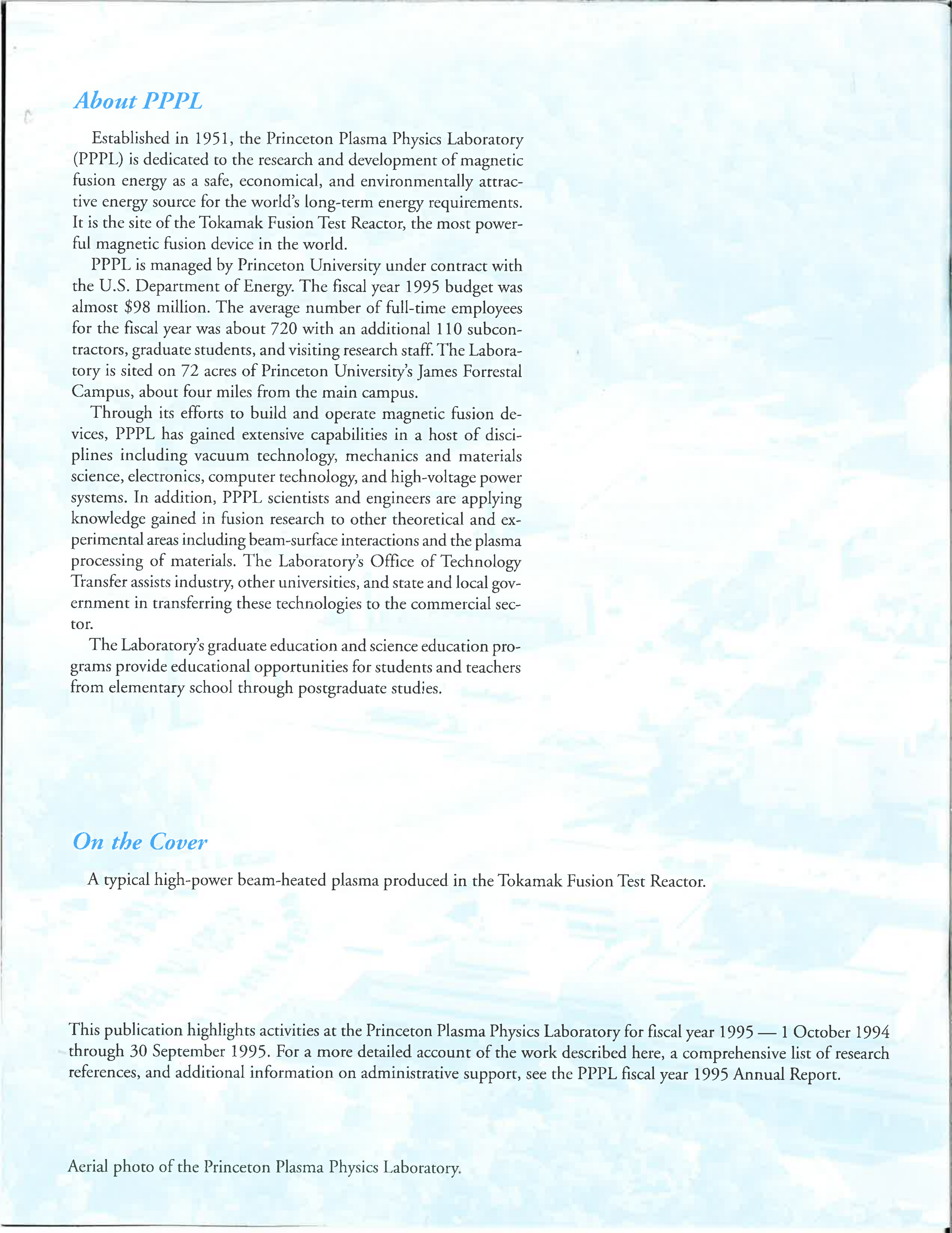
Through its efforts to build and operate magnetic fusion devices, PPPL has gained extensive capabilities in a host of disciplines including vacuum technology, mechanics and materials science, electronics, computer technology, and high-voltage power systems. In addition, PPPL scientists and engineers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

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

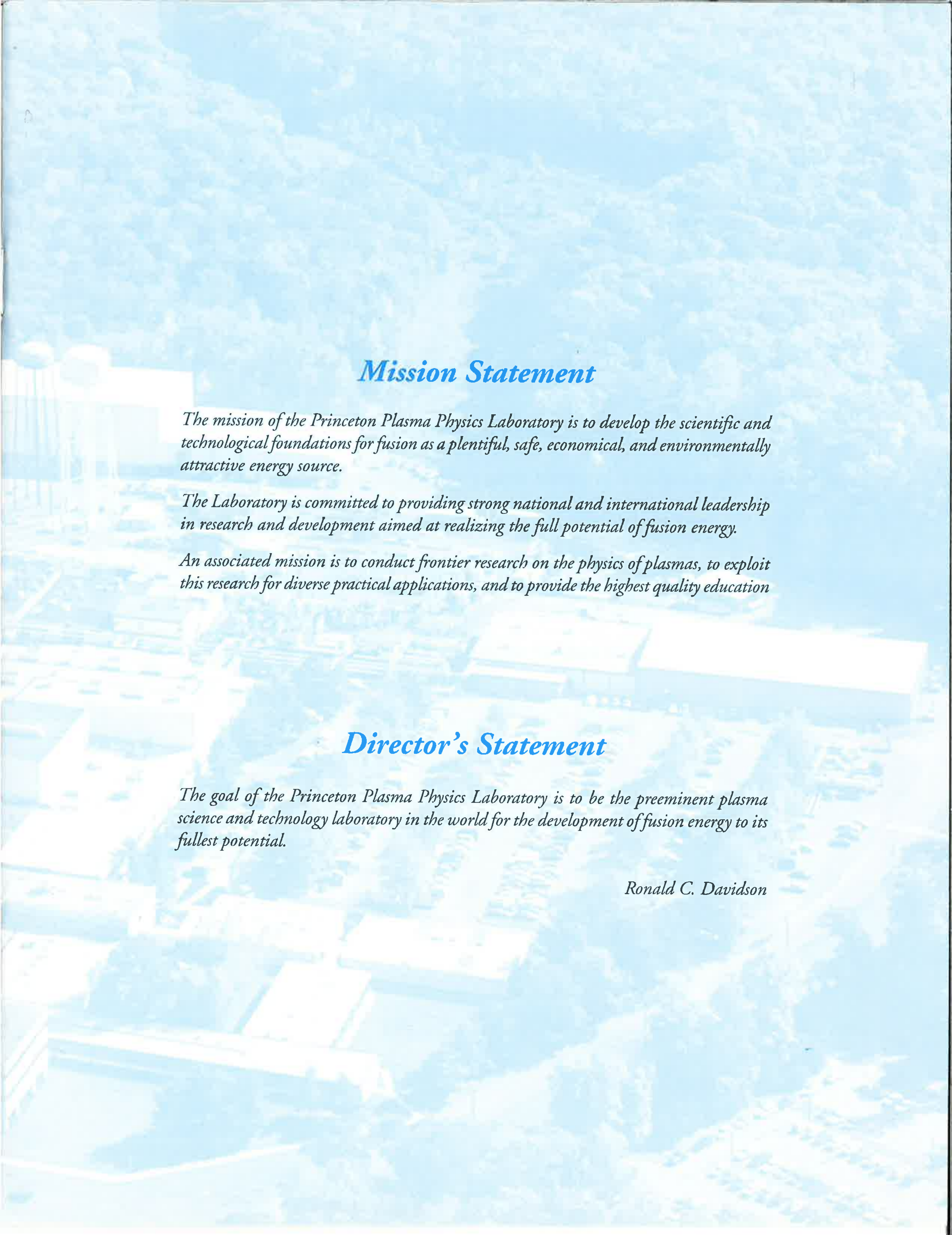
On the Cover

A typical high-power beam-heated plasma produced in the Tokamak Fusion Test Reactor.

This publication highlights activities at the Princeton Plasma Physics Laboratory for fiscal year 1995 — 1 October 1994 through 30 September 1995. For a more detailed account of the work described here, a comprehensive list of research references, and additional information on administrative support, see the PPPL fiscal year 1995 Annual Report.



Aerial photo of the Princeton Plasma Physics Laboratory.



Mission Statement

The mission of the Princeton Plasma Physics Laboratory is to develop the scientific and technological foundations for fusion as a plentiful, safe, economical, and environmentally attractive energy source.

The Laboratory is committed to providing strong national and international leadership in research and development aimed at realizing the full potential of fusion energy.

An associated mission is to conduct frontier research on the physics of plasmas, to exploit this research for diverse practical applications, and to provide the highest quality education

Director's Statement

The goal of the Princeton Plasma Physics Laboratory is to be the preeminent plasma science and technology laboratory in the world for the development of fusion energy to its fullest potential.

Ronald C. Davidson

Advantages of Fusion Energy

- Worldwide availability of inexhaustible low-cost fuel.
- No chemical combustion products contributing to acid rain or global warming.
- Materials and by-products unsuitable for weapons production.
- Radiological hazards thousands of times less than from fission.
- No runaway reaction possible.
- Estimated cost of electricity comparable to other long-term energy options.

Contents

From the Director

Ronald C. Davidson

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

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

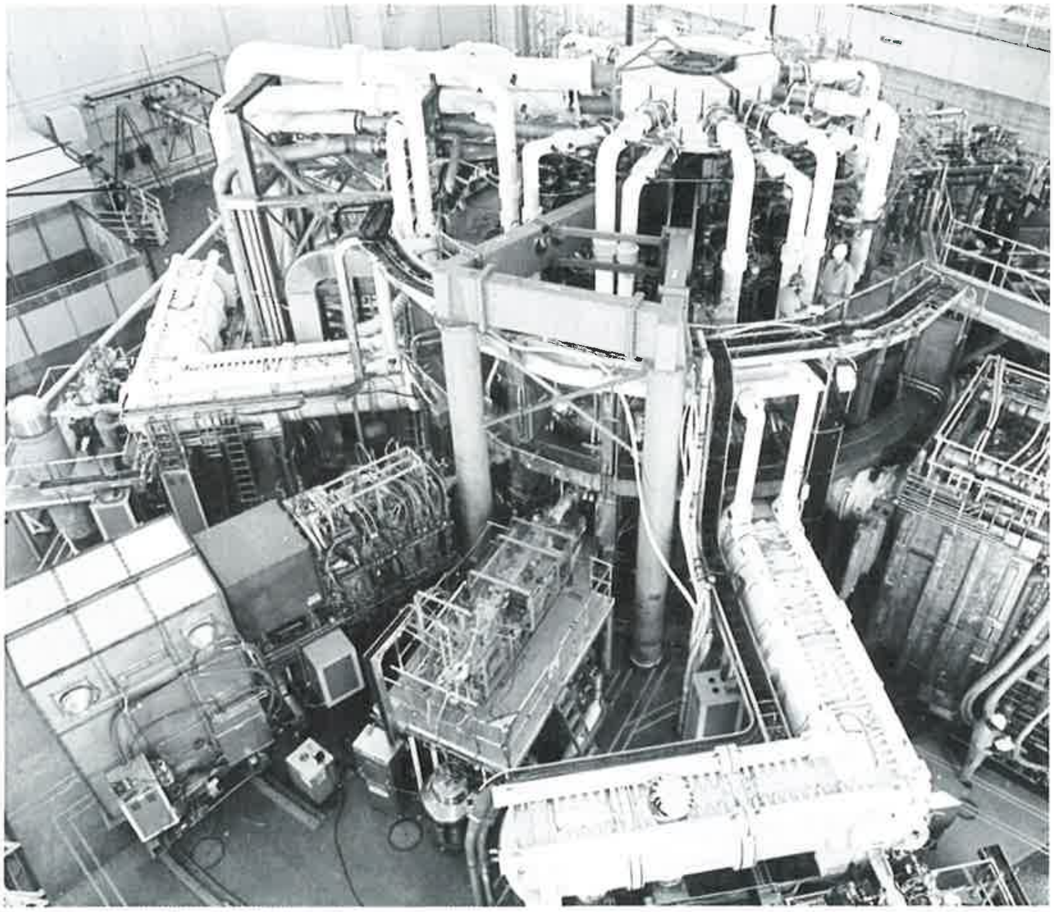
The purpose of this Highlights Report is to present a brief overview of the Laboratory's significant research accomplishments during the fiscal year 1995. The activities covered in this report include advances on the large projects, such as the discovery of the Enhanced Reversed Shear mode on the TFTR and the engineering design developments in the International Thermonuclear Experimental Reactor project, as well as the significant progress made in plasma theory, small-scale experiments, technology transfer, graduate education, and the Laboratory's outreach program in science education.

While the principal emphasis in this report is on recent significant advances in fusion science and technology, it is important to recognize that, historically, research on fusion has propelled the development of plasma physics as a scientific discipline, and the development of many related technologies that have widespread practical applications in other fields. The Laboratory's core competencies represent an outstanding capability of PPPL's scientific and engineering personnel to make world-class contributions in a wide variety of technical areas beyond traditional fusion science and engineering. These areas range from plasma processing for industrial applications, to advanced computing architectures, to theory and instrumentation techniques for space plasmas and the near-Earth environment, to advanced design capabilities for high-field magnet systems and coherent radiation sources, and to fundamental nonlinear dynamics, chaos, and turbulence in complex systems with many degrees of freedom, to mention a few examples. This is particularly important, both for the purpose of increasing U.S. industrial competitiveness in related technologies, and for the purpose of making an effective transfer of technical capability developed in the Department of Energy's fusion program to other government agencies and programs.

Ronald C. Davidson
Director

TFTR

Tokamak Fusion Test Reactor



Tokamak Fusion Test Reactor

The Tokamak Fusion Test Reactor (TFTR) continued with a second highly successful year of operation using deuterium-tritium fuel. Since the beginning of deuterium-tritium experiments in November, 1993, more than 600 deuterium-tritium plasmas have been studied, investigating fusion power performance, energy and particle transport, stability, and alpha-physics issues. During these experiments, world-record parameters for fusion power, ion temperature, and the Lawson triple product have been achieved. A major project milestone to produce at least ten million watts of fusion power was surpassed on November 2, 1994. The TFTR has been operated at and beyond its original specifications in magnetic field and neutral-beam heating power. Finally, a new approach, the enhanced reversed-shear mode, for producing high-performance plasmas that could lead to smaller and less expensive fusion power plants has been explored.

The TFTR physics program continues with high-priority deuterium-tritium physics experiments. Safe operation of the tritium processing system and successful machine and diagnostic performance in a high-radiation environment has permitted an extended deuterium-tritium experimental campaign on the TFTR tokamak.

Deuterium-Tritium Fusion Power

A world-record fusion power of 10.7 million watts was produced using 39.5 million watts of neutral-beam heating. This record was achieved in a "supershot" plasma, to date, the highest performance plasma in TFTR.

Supershots are produced when high-powered neutral beams are injected into a plasma after the walls of the confinement vessel have been scrupulously conditioned to remove absorbed deuterium and to inhibit the influx of carbon impurities. These plasmas are much denser at their center than their edge and are characterized by very high temperatures and an enhancement in confinement time.

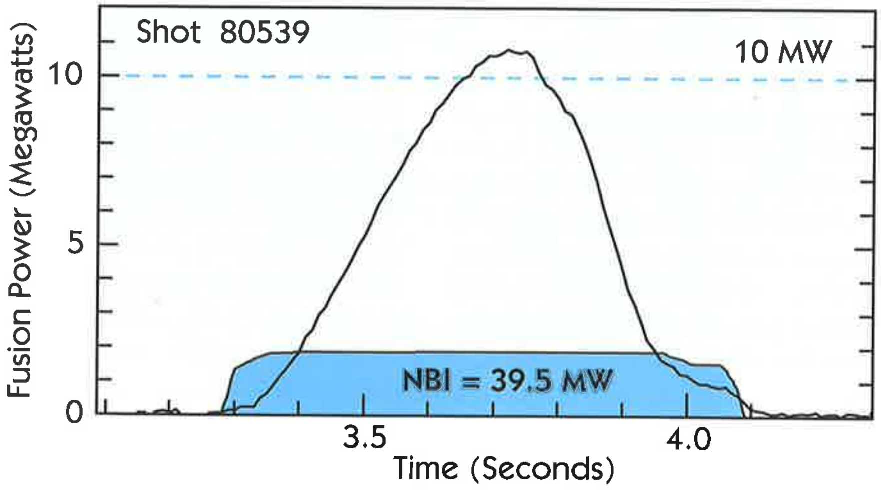
Supershot performance was improved in fiscal year 1995 because of two important developments: First, lithium-pellet conditioning of the graphite inner wall was increased, extending the range of high-performance operating modes of TFTR plasmas. Second, a 20% increase in energy confinement for deuterium-tritium plasmas with a 50/50 ratio of deuterium to tritium was obtained when compared to reference deuterium-deuterium plasmas. This was a result of a favorable isotope scaling of energy confinement with atomic mass of the plasma species.

With these high-performance deuterium-tritium plasmas, the central energy and fusion power densities are comparable to or greater than those expected on the International Thermonuclear Experimental Reactor. Thus, these experiments are providing scientists with unique information about the physics of the plasma core of a fusion reactor.

High Triple Product Experiments

A record central Lawson triple product (measurements of ion density and temperature taken at the center of a plasma) of 8.3×10^{20} m^{-3} sec keV was achieved as a result of extensive lithium-pellet conditioning and improved energy confinement with deuterium-tritium plasmas. The Lawson triple product is an important figure of merit related to the plasma's energy multiplication (how close plasma conditions are to achieving ignition). It is the product of the density, energy confinement time, and temperature.

The use of lithium conditioning increases the plasma current at which the supershot characteristics are obtained and has resulted in an energy confinement time of 0.33 seconds — the longest to date — in a plasma heated with 17 million watts of tritium neutral-beam injection. This plasma also had a "global value" for Q_{DT} (the ratio of fusion power to heating power) of 0.27 and a calculated "central value" for Q_{DT} (the ratio of the local fusion power density to the heating power density) of 0.75. Record ion temperatures of 510 million degrees centigrade were also achieved.



Record-setting 10.7 million watts of fusion power was achieved on November 2, 1994, surpassing a major milestone for the project.

Enhanced Reversed-Shear Mode

A new approach for producing high-performance plasmas that could significantly improve tokamak performance and lead to a smaller less expensive fusion reactor was explored in fiscal year 1995. In this approach, called the enhanced reversed-shear mode, the plasma's current profile, and hence the twist of the magnetic field (magnetic shear), is modified by adjusting how the plasma is initiated and the timing of the neutral-beam heating power. The resulting magnetic-field configuration has a region of reversed shear in the plasma core in which the shear decreases with minor radius prior to increasing.

Transitions to a new plasma regime of enhanced confinement have been observed in TFTR plasmas with reversed magnetic shear and near balanced co- and counter-tangential neutral-beam heating above about 20 million watts. These plasmas are characterized by a very rapid increase in density within the shear-reversed region: density $n_e(0) \sim 1.2 \times 10^{20}$ m^{-3} where the ion temperature $T_i(0) \sim 24$ keV, electron temperature $T_e(0) \sim 8$ keV, and the pressure peaking factor is about 7. After the transition, plasma transport, which can cause particles to "leak" out of the plasma and thus limit tokamak performance, is reduced by approximately a factor of 50. Particle transport in the enhanced reversed-shear mode is comparable with the values of neoclassical predictions; the ion-thermal transport is calculated to be significantly lower than neoclassical predictions.

The plasma is very quiescent in the reversed-shear region, even though the normalized pressure gradient is 3 to 5 times higher than in supershots. Analysis indicates that the plasma pressure can be substantially increased by optimizing the reversed-shear configuration and extending these experiments to higher toroidal field and plasma current. These simulations predict that substantial alpha-particle heating in the plasma core could be achieved, thus allowing alpha-particle studies on TFTR to be substantially extended.

Confinement in Deuterium-Tritium Plasmas

In the first deuterium-tritium experiments in the TFTR tokamak, it was immediately apparent that overall energy confinement in supershots is significantly better in deuterium-tritium plasmas than in comparable deuterium-only plasmas. The favorable scaling with atomic mass has been observed not only in enhanced-confinement supershots and high-confinement mode plasmas but also, recently, in low-confinement mode plasmas. Thus, transport models can now be more thoroughly benchmarked with these observations.

In the highest performance supershots produced so far, alpha-particle heating of the electrons amounts to only about 1 to 2 million watts out of a total of about 10 million watts, making its detection difficult. Nonetheless, an analysis of the TFTR database of deuterium, deuterium-tritium, and nearly tritium plasmas indicates the presence of alpha-particle heating in the plasma core. Extensions of these experiments to higher alpha-particle heating powers is important to assess the efficiency of alpha-particle heating.

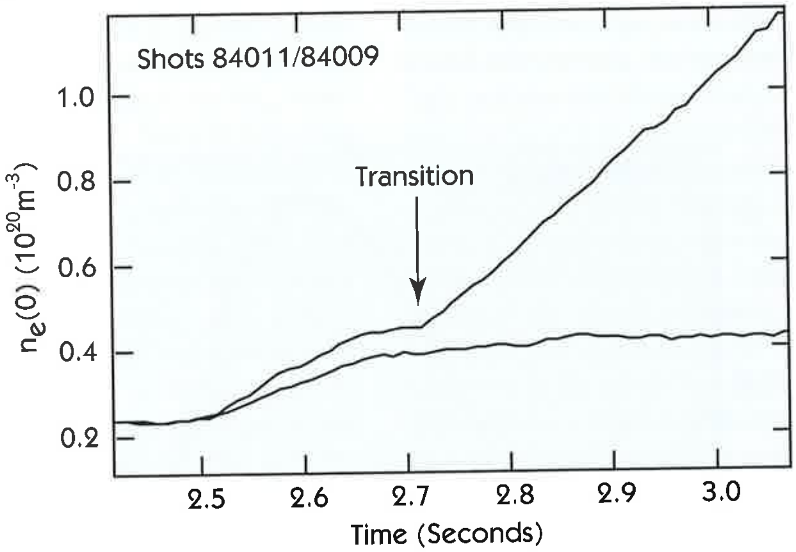
Confinement of Fusion Alpha Particles

Losses of energetic fusion alpha particles from deuterium-tritium plasmas have been measured by detectors mounted near the vacuum vessel wall. Scans of the plasma current have shown that in MHD-quiescent plasmas, the alpha loss rate at the 90° detector scales as expected for the prompt loss of particles born on unconfined orbits. Collisional and stochastic orbit losses in the toroidal-field ripple are being investigated.

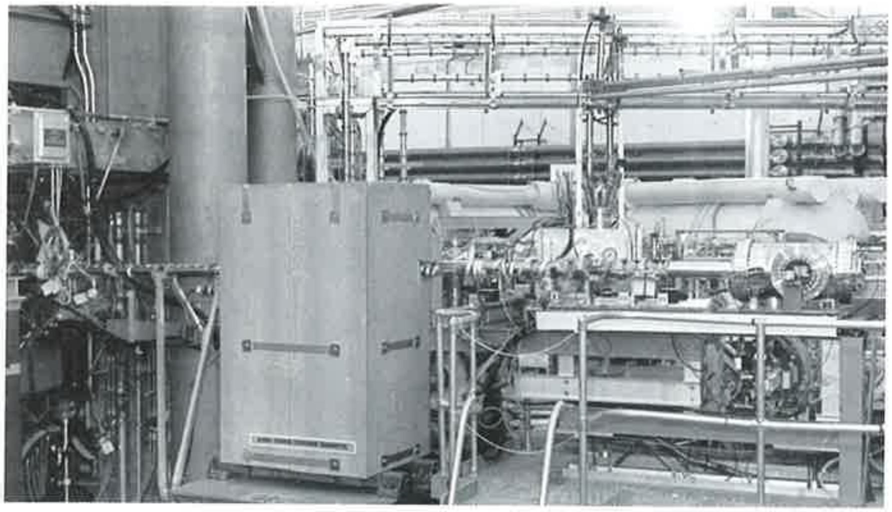
During major disruptions, which are instabilities of the plasma current column, losses of energetic alphas (estimated to be up to 10% of the alpha population) have been observed to occur in about two milliseconds during the thermal-quench phase while the total current is still unperturbed. Such losses, which are seen mainly by the 90° detector, could have a serious impact on first-wall components in a reactor.

The energy distribution of the alpha particles confined in the plasma has been measured for the first time in experiments on TFTR. Alphas in the range 0.5 to 2 million electron volts have been detected through conversion to neutral helium by double charge-exchange in the high-density neutral cloud surrounding an ablating lithium pellet. The measured spectrum has been compared with the transport code calculations and good agreement has been found. The alpha population in the lower energy range of 0.1 to 0.6 million electron volts has been detected by absolutely calibrated spectrometry of charge-exchange recombination emission. The intensities of the detected signals are within a factor two of calculations by the transport code.

The extent to which thermalized helium ash from the deuterium-tritium reactions accumulates in the plasma has a major impact on the size, and, therefore, the cost of future reactors. In TFTR, the radial profiles of helium ash have been measured by comparing charge-exchange recombination line emission from helium in otherwise similar deuterium-tritium and deuterium-only plasmas. Initial measurements have been found to be consistent with transport code mod-



In high-power reversed-shear plasmas, a transition to a regime of enhanced confinement and rapidly increasing density is observed at the core of the plasma. Shown above is a comparison of the evolution of electron density for a plasma that makes a transition into the reversed-shear mode and one that does not.



Lithium-pellet injector developed at the Massachusetts Institute of Technology for TFTR. The injector is used to inject lithium pellets to condition the limiter and vacuum vessel walls to extend the operating regime of TFTR plasmas.

eling for the helium profile based on transport coefficients that had been previously determined by using external helium gas puffs. With these same transport coefficients, helium-ash accumulation would not quench ignition in a thermalized deuterium-tritium fusion reactor such as the International Thermonuclear Experimental Reactor, provided the density of helium at the plasma edge can be controlled.

ICRF Heating and Current Drive of a D-T Plasma

Future fusion reactors such as the International Thermonuclear Experimental Reactor will need some form of auxiliary heating capabilities to heat the plasma to the temperatures necessary for ignition. Ion-cyclotron range-of-frequency (ICRF) heating is one of several candidates being studied at this time. Radio-frequency waves can be used also to drive the plasma current.

In fiscal year 1995, experiments on TFTR showed that radio-frequency heating using ion-cyclotron range-of-frequency waves is different in a deuterium-tritium plasma than in a deuterium plasma due to the additional resonance in the plasma. Ion-cyclotron range-of-frequency heating of deuterium-tritium supershot plasmas at the second harmonic of the tritium resonance resulted in good absorption (approximately 60% to ions), consistent with modeling. Electron heating and current drive was demonstrated, for the first time, using the mode-converted ion-Bernstein wave. This technique has been used successfully to drive 125 thousand amperes on axis with two million watts of radio-frequency power and 100 thousand amperes off axis with four million watts of radio-frequency power. It is planned to use ion-cyclotron range-of-frequency heating to increase the alpha-particle pressure and to investigate the possibilities for ion-cyclotron range-of-frequency current drive to attain "advanced" tokamak operating modes with improved confinement and stability of the core plasma.

Collaborations

Collaborations with other fusion researchers is vital to the TFTR experimental program. More than thirty universities, fusion laboratories, and industries, including several foreign institutions, actively participate in experiments on TFTR. These collaborations are performed in a variety of ways including hosting visiting researchers and through electronic communications. Major collaborations with universities include Columbia University, the Massachusetts Institute of Technology, the University of California at Irvine, and the University of Wisconsin. Fusion laboratories with substantial involvement in the TFTR program include the Oak Ridge National Laboratory, the Los Alamos National Laboratory, General Atomics, and the Ioffe-Physical-Technical Institute in St. Petersburg, Russian Federation.

Record-Setting Achievements

In a little more than two years, TFTR researchers have explored a wide range of physics issues in plasmas with high concentrations of tritium. Record fusion power production and ion temperatures have been achieved. The TFTR tokamak has been operated at and beyond its original specifications in magnetic field and neutral-beam heating power. The diagnostics have operated extremely well; a large amount of analysis has already been performed on the data and will be used to guide future experiments. Finally, the routine operation and maintenance of the Tokamak Fusion Test Reactor device in a high-radiation environment has demonstrated the safe operation of a tritium fusion facility.

PBX-M

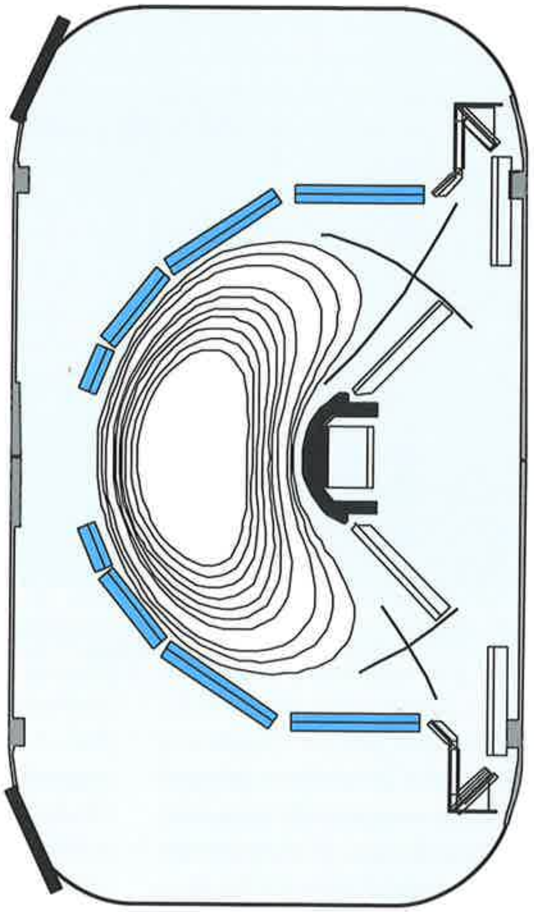
Princeton Beta Experiment-Modification

Princeton Beta Experiment-Modification

The Princeton Beta Experiment-Modification (PBX-M) is uniquely well configured to address certain key issues of advanced tokamak physics. As a consequence of constrained budgets and the higher-priority need to extend TFTR operations, the PBX-M has not been operated since late 1993, but would be ready to resume operation upon the conclusion of the TFTR extension phase.

The PBX-M program is targeted at studying control of magnetohydrodynamic (MHD) activity and the avoidance of plasma disruptions. These studies would be done in advanced tokamak plasmas, achieved with high-power auxiliary heating and current and pressure profile control. As higher beta values are achieved in all tokamak plasmas, kink-type instabilities and plasma disruptions are found to be more prevalent. This ubiquitous observation motivates a program focused on stabilization and/or avoidance of dangerous instabilities. Experiments on PBX-M will be used to develop techniques for avoiding plasma disruptions by using its unique combination of a highly conducting segmented thick aluminum shell, eddy-current sensors for feedback control, and active magnetic feedback coils, in concert with high-power auxiliary heating and specialized diagnostics. The PBX-M program will focus on:

- Exploitation of advanced current- and pressure-profile modification methods in order to achieve high-performance advanced tokamak operating modes.
- Stabilization of kink modes in these advanced tokamak plasmas using active magnetic coils integrated into the highly conducting close-fitting shell.
- Further plasma stabilization studies by ponderomotive force using radio-frequency waves, by



Simple schematic diagram of the Princeton Beta Experiment-Modification (PBX-M) showing the conducting shell (blue rectangles) which can match the shape of the plasma for improved plasma performance. A close-fitting conducting shell is unique to the PBX-M.

modulated neutral-beam injection, and by edge currents driven through nonaxisymmetric divertor biasing.

In order to access and sustain advanced tokamak operating modes, the toroidal current profile in PBX-M plasmas can be controlled by means of a 1.3-million-watt lower-hybrid current-drive system. In addition, PBX-M has a 2-million-watt ion-Bernstein-wave system which can be used to modify the pressure profile. The gradient in the pressure profile can lead to large self-generated ("bootstrap") currents. The pressure profile can be controlled by the 6-million-watt neutral-beam-heating system and by the generation of a high core confinement region using ion-Bernstein waves.

The unique close-fitting highly conducting shell, together with this advanced set of current and pressure profile modification methods, enables the study of MHD control and avoidance of plasma disruptions in advanced tokamak plasmas. The long resistive decay timescale of the PBX-M conducting shell, which simulates the long timescales expected in reactor systems, provides a unique opportunity to investigate feedback stabilization of plasma instabilities such as the resistive wall mode, with reasonable feedback gains and power levels.

Recent theoretical work, coupled with encouraging results from the PBX-M and the DIII-D tokamak in San Diego, California, has shown that a substantial improvement in plasma performance can be achieved by means of a close-fitting shell — but instabilities with growth times of the order of the shell time may need special techniques for feedback control and/or avoidance. Experiments on PBX-M will establish the foundation for control of such magnetohydrodynamic instabilities by means of the active control of the currents in the shell, by the use of ion-Bernstein waves for ponderomotive stabilization, by modulated neutral-beam injection, and by the nonaxisymmetric edge currents driven by divertor biasing.

Due to its independent shell structure, the PBX-M device has unique potential to control currents in the shell and test new concepts such as the "intelligent shell," which simulates a superconducting wall, or Fitzpatrick's recently proposed "fake rotating shell," which simulates a rapidly rotating resistive wall. The ion-Bernstein-wave system also provides unique capability for ponderomotive control. Development of more precise sensors to detect magnetohydrodynamic instabilities at low amplitudes, in order to facilitate low-power control, will be an important element in the program. Experimental results have already shown that the ability to measure the currents in the segmented conducting shell provides a sensitive measure of the onset of certain ("low-toroidal mode number") MHD instabilities and, therefore, it is a potentially important element in a feedback control system.

During the past year, in preparation for a resumption of operation, most of the effort on the PBX-M was devoted to facility upgrades and physics analysis.

Physics Analysis

Since the PBX-M is the only major tokamak with a conducting shell close to the plasma, it provides a unique environment for testing the recently developed theory of the resistive wall mode of ideal plasmas. This theory has been used in collaboration with the Federal Polytechnic Institute in Lausanne, Switzerland, to perform detailed calculations of the stability of plasmas that are strongly coupled to the shell. The results are in good agreement with the available experimental observations.

Lower-hybrid stabilizing effects, involving stabilization of sawtooth oscillations, were analyzed in collaboration with the Massachusetts Institute of Technology. They implied that in PBX-M plasmas, multipass lower-hybrid-wave absorption could lead to a positive gradient of the wave power density, and result in a controllable stabilizing lower-hybrid ponderomotive force. Linear stability analysis assuming this new phenomenon predicts the sawtooth suppression observed in these plasmas.

The effects induced on plasma electrons by an externally launched ion-Bernstein wave, in the presence of a lower-hybrid wave in the current-drive operating mode, was studied in collaboration with physicists from Frascati, Italy. The modeling correctly predicts the modification of the electron distribution by the ion-Bernstein wave during lower-hybrid current drive. This synergy between the ion-Bernstein and lower-hybrid waves results in improved current-drive efficiency and will be explored in future PBX-M synergy experiments.

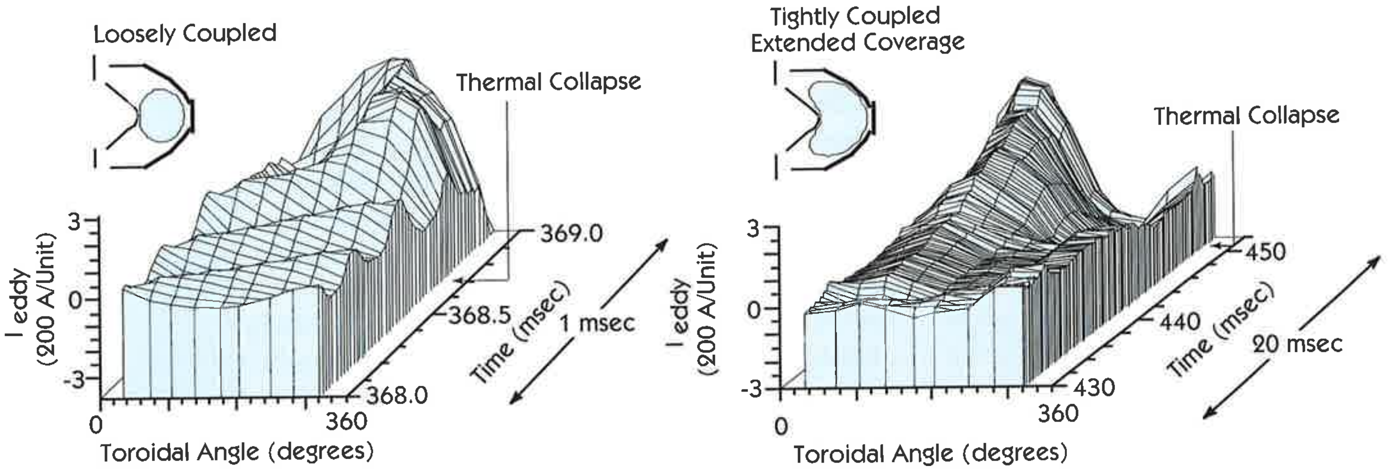
Two doctoral dissertations were completed. Sherrie Preische's thesis, "Radially Localized Measurements of Superthermal Electrons using Oblique ECE," was based on a new diagnostic that was successfully developed on PBX-M and used to measure the diffusion of energetic electrons during lower-hybrid current drive. For Keith Voss' thesis, "Pulse-Heated Vertical Electron Cyclotron Emission Diagnostic," he implemented a novel technique on PBX-M for determining plasma parameters from the transient response of the plasma to a pulse of lower-hybrid power.

Facility Upgrades

The PBX-M is presently the third embodiment of a tokamak in its large and versatile vessel (operations with the Poloidal Divertor Experiment and the Princeton Beta Experiment preceded PBX-M). In order to restore and improve the elastomer seals of the PBX-M vacuum vessel after 16 years of service, novel procedures and innovations were developed and applied to an upgrading of the vessel O-ring system. This work improved vacuum conditions and will enhance future performance and reliability.

During this upgrade, the transmission lines for the PBX-M ion-Bernstein-wave antenna systems were improved to facilitate high-power operation, and one of the antennae was relocated to allow the installation of a duct and gate valve for an Oak Ridge National Laboratory folded waveguide. The folded waveguide is a low-electric-field, all-metal coupler that, if successful, will permit the application of higher radio-frequency powers in the ion-cyclotron range of frequencies for the International Thermonuclear Experimental Reactor.

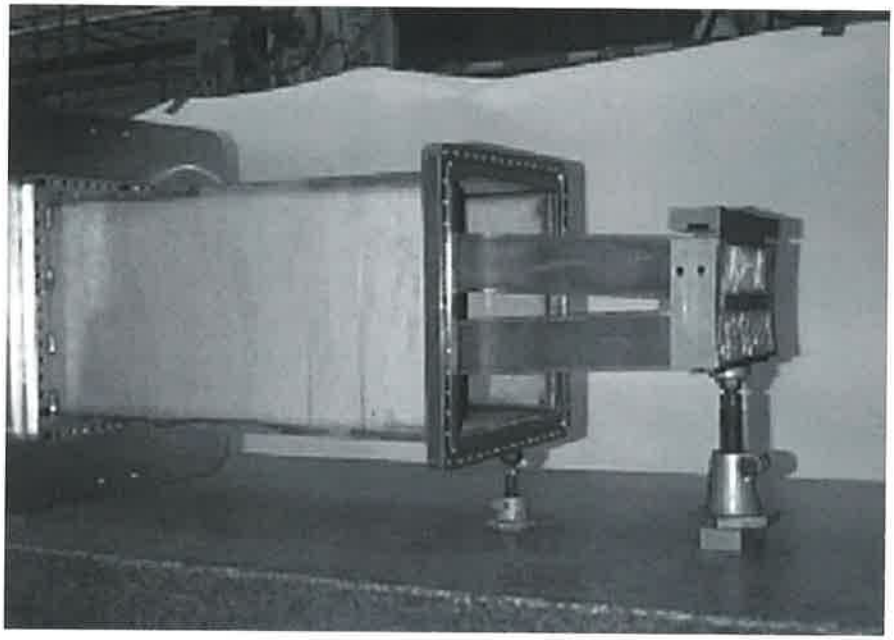
The PBX-M lower-hybrid current-drive system is coupled to the



A comparison of the eddy currents induced in the Princeton Beta Experiment-Modification conducting shell for plasmas which are (left) circular and far from the shell and (right) bean-shaped and close to the shell. Since the magnitude of the current is related to amplitude of the instability, these measurements show that the plasma instability growth rate slows with decreasing distance between the plasma and the shell.

plasma with a multi-waveguide phased array antenna. The lower-hybrid electrical systems were upgraded to facilitate operation at higher powers, and the antenna system was upgraded with an angled coupler configuration and coupler steering mechanism to give variable plasma coupling and minimize poloidal shape, resonance cavity, and particle effects.

A digital control system was developed for improved plasma control in advanced tokamak operating modes. The Phase I goal is to use a minimum hardware configuration to replicate the previous analog-based system that provided PBX-M plasma shape, current, and radial and vertical position control. Later work will expand the hardware configuration to include plasma profile controls to pursue topics in profile control, plasma disruption avoidance and amelioration, and other topics in advanced tokamak plasma control.



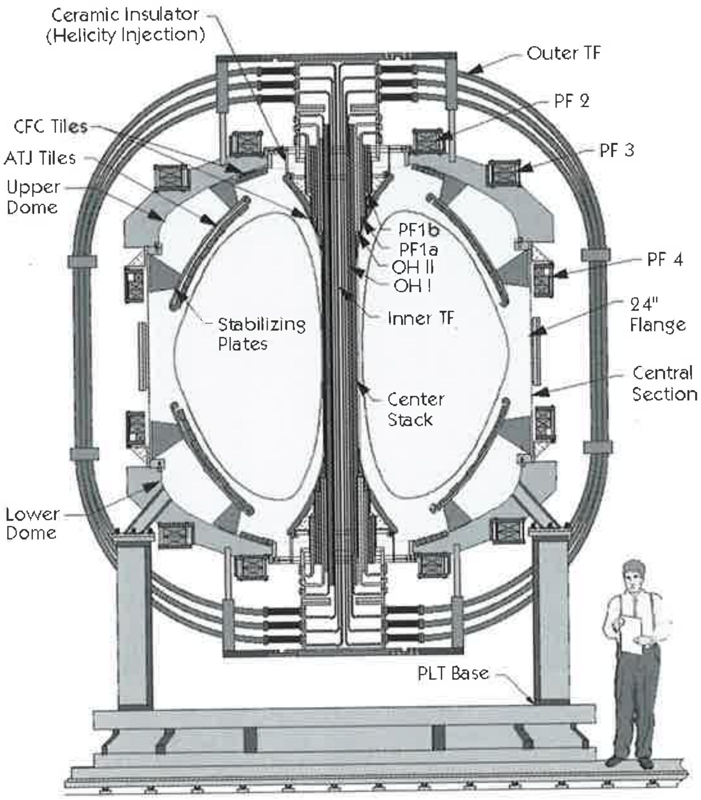
Side view of double-angled lower-hybrid coupler showing plasma-facing end. This lower-hybrid current-drive system is used to control the plasma current profile.

Status

Due to cuts in the fusion budget, all work on the PBX-M has been stopped and resources are focused on operation of the Tokamak Fusion Test Reactor. The PBX-M remains a uniquely flexible device to study important advanced tokamak physics issues. Resumption of PBX-M operation will depend on the outcome of the revised strategy for the U.S. fusion program.

NSTX

National Spherical Tokamak Experiment



Schematic of the National Spherical Tokamak Experiment

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

The NSTX design project is a national collaboration among several institutions including the Princeton Plasma Physics Laboratory (PPPL), the Oak Ridge National Laboratory, Columbia University, and the University of Washington at Seattle. PPPL has primary responsibility for the Project and the coordination of the design effort.

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

Theoretical Simulations

Fiscal year 1995 was a very productive year for the NSTX program. In particular, a computer modeling study of magnetohydrodynamic (MHD) equilibrium and stability of NSTX plasmas resulted in the simultaneous achievement of a stable high toroidal beta (the ratio of plasma pressure to the toroidal magnetic-field pressure) and a high bootstrap-current fraction (the ratio of internally generated pressure-driven currents to the total plasma current). Higher bootstrap-current fraction reduces the power requirements of externally applied current drive and thus enhances the attractiveness of the ST reactor concept. These plasma conditions were accomplished by optimizing plasma shaping, reducing the plasma aspect ratio (the ratio of the plasma's major radius to its minor radius) while maintaining sufficient plasma elongation, and using a stabilizing shell.

Mission

Reflecting the new "theoretical" findings and nationally based discussions, the NSTX research mission was enhanced. The enhanced mission is to evaluate the physics performance of spherical tokamak plasmas for:

- noninductive start-up, current maintained in the plasma, and current profile control;
- global plasma confinement and local transport physics;
- plasma beta-limit scaling; and
- plasma scrape-off-layer physics.

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

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

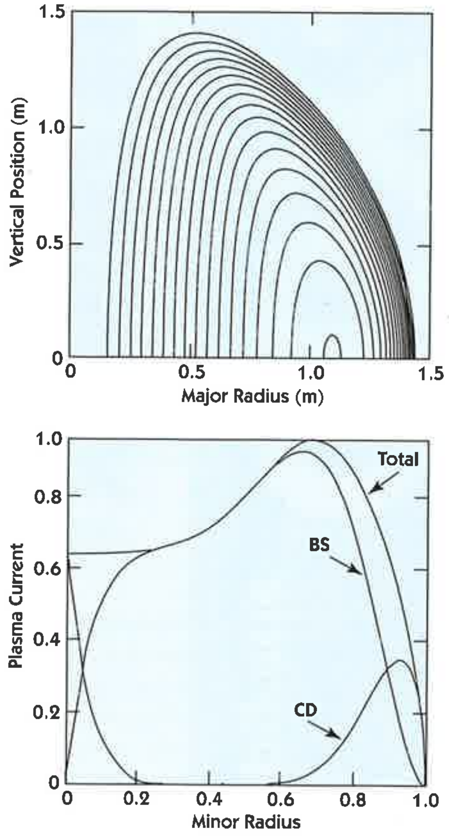
Design Improvements

As the NSTX design has evolved, it has undergone a number of changes and improvements. The center stack was redesigned to have ohmic-heating capability for a plasma with an aspect ratio of 1.25, compared to the original aspect ratio of 1.45. Because of the importance of plasma elongation, the maximum plasma elongation was increased from 1.8 to 2.2 and, accordingly, the height of the vacuum vessel was increased from 3 meters to 3.6 meters. The center-stack contour was reshaped to accommodate high-triangularity and high-elongation plasma discharges.

The use of auxiliary heating and current drive for current profile control has become an essential part of the NSTX base program. High-harmonic fast-wave heating was chosen as the primary auxiliary heating and current-drive tool because of its suitability to high-beta and high-bootstrap-current fraction plasma discharges and its low implementation cost, owing to available power supplies. Because of the importance of noninductive start-up and the possible need for edge current drive, the University of Washington's coaxial helicity injector design was incorporated into the base design for NSTX.

The plasma pulse length was increased from 0.5 second to 5.0 seconds to allow for full current-profile relaxation. The plasma facing components in the critical areas in the vacuum vessel were redesigned with continuous toroidal coverage by carbon tiles in order to handle the anticipated heat loads for the full 5-seconds plasma pulse. To minimize the vent recovery time with carbon tiles, the required bake-out temperature was increased from 100 °C to 350 °C. Finally, consideration was given to a 60-second long-pulse upgrade option.

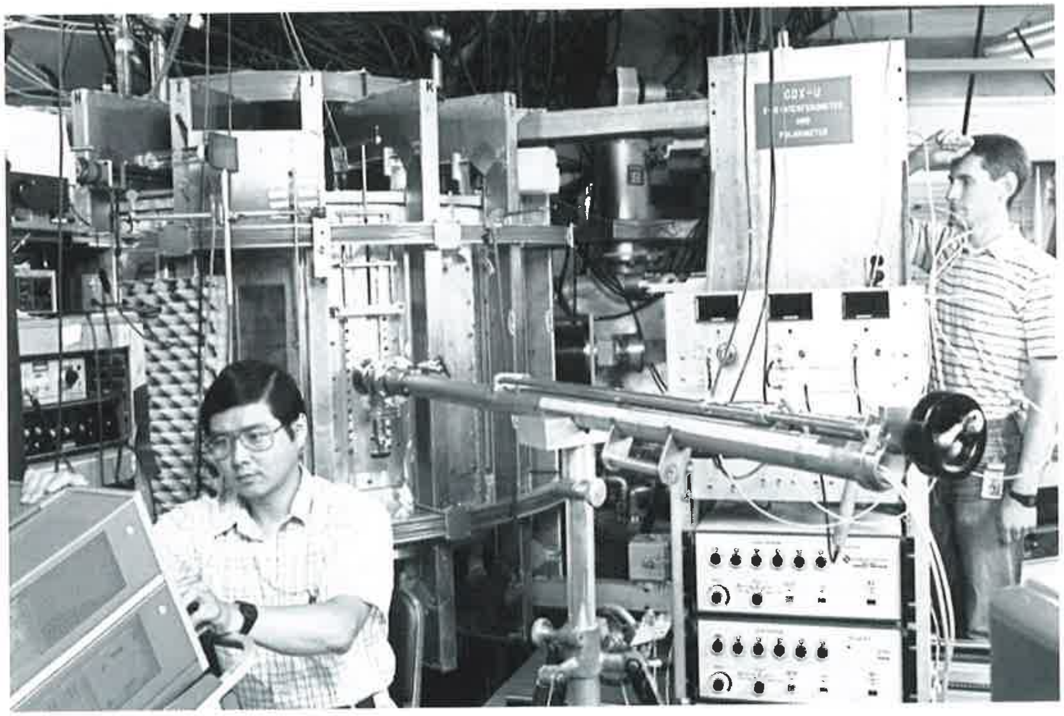
The NSTX design team made successful presentations at the NSTX Department of Energy Review in April, 1995, and the NSTX Department of Energy Physics Validation Review in July, 1995. The NSTX Project is now in the engineering design phase; construction is planned to begin in fiscal year 1997.



A computer simulation of an "optimized" plasma scenario where stable high toroidal beta and high bootstrap-current fraction are achieved simultaneously, and the external current-drive requirements are kept to a minimum. In this scenario, the plasma current I_p = 1 MA, toroidal beta β_t = 44%, and the bootstrap current fraction = 81%. The top figure shows the magnetic flux contours. Note the large magnetic axis shift (distance between inner most flux contour and the middle of the plasma), which is characteristic of these high beta-high bootstrap fraction equilibria. The bottom figure shows profiles of the bootstrap current (BS), external current drive (CD), and total plasma current (Total) for this simulation. Keeping the bootstrap-current fraction high reduces the external current-drive requirements, thus reducing power productions costs — important in the development of smaller, more economical tokamak power plants.

CDX-U

Current Drive Experiment-Upgrade



Current Drive Experiment-Upgrade

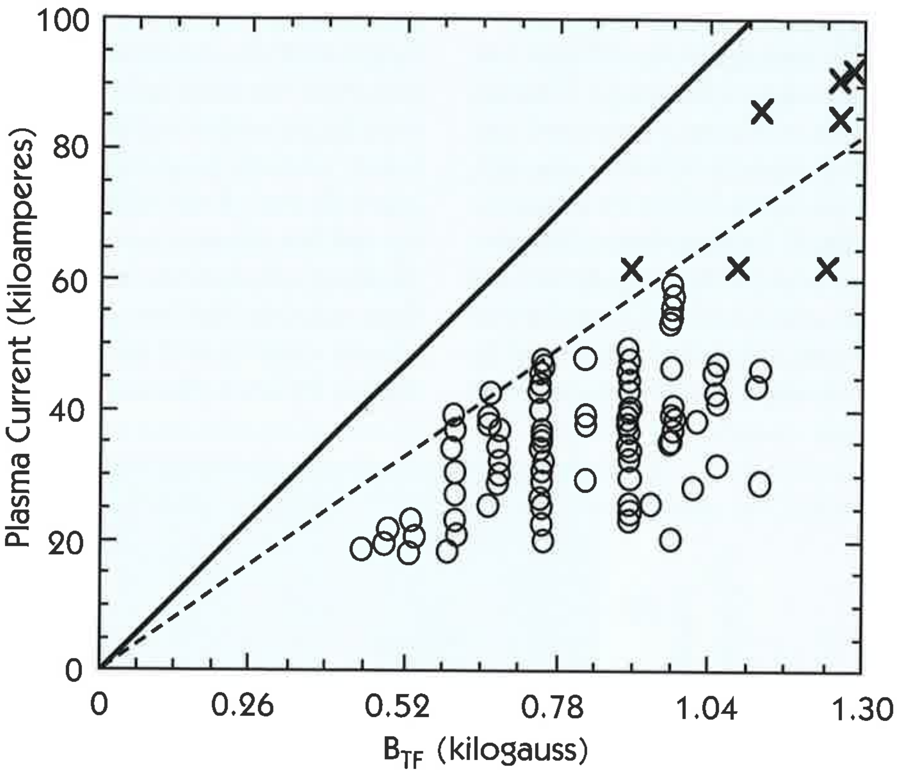
The Current Drive Experiment-Upgrade (CDX-U) is the first U.S. fusion facility to conduct experiments on the spherical tokamak concept — an alternative approach to the conventional tokamak for achieving fusion energy. The spherical tokamak mode of operation is achieved when the plasma's aspect ratio (the ratio of the plasma's major radius to its minor radius) is reduced to well below two — as compared to a conventional tokamak plasma with an aspect ratio of about 3. The name "spherical tokamak" comes from the shape of the plasma. As the plasma's aspect-ratio becomes smaller, the plasma elongates naturally and takes on a spherical shape instead of the donut-shape of standard tokamak plasmas. An important characteristic of the spherical tokamak (ST) plasma is that it is predicted to sustain a higher pressure for a given magnetic field. If the ST works as predicted, it could lead to a smaller, more economical fusion power system.

As a prototype for future ST devices such as the proposed National Spherical Tokamak Experiment (NSTX), the CDX-U serves as an ST test bed, providing information necessary for the design and future operation of these devices. The CDX-U achieved two important ST-related milestones in fiscal year

1995: The attainment of 100,000 amperes (or 100 kilo amperes) of current in the plasma and the successful collaboration with the A.F. Ioffe Physical-Technical Institute (Russian Federation) to install the first operational multipass Thomson scattering system in the U.S. This diagnostic is used to measure the plasma's electron temperature and density.

Plasma Current Experiments

Spherical tokamak reactor performance will depend heavily on the amount of current the plasma can support. Therefore, it is important to explore the plasma current limit of ST plasmas. Early in fiscal year 1994, an ohmic transformer capable of delivering the highest ohmic-heating and current-drive power to date to an ST plasma was installed on CDX-U. This capability along with optimization of the plasma has allowed scientists to study ohmically heated ST plasmas with currents of up to 100 kilo amperes.

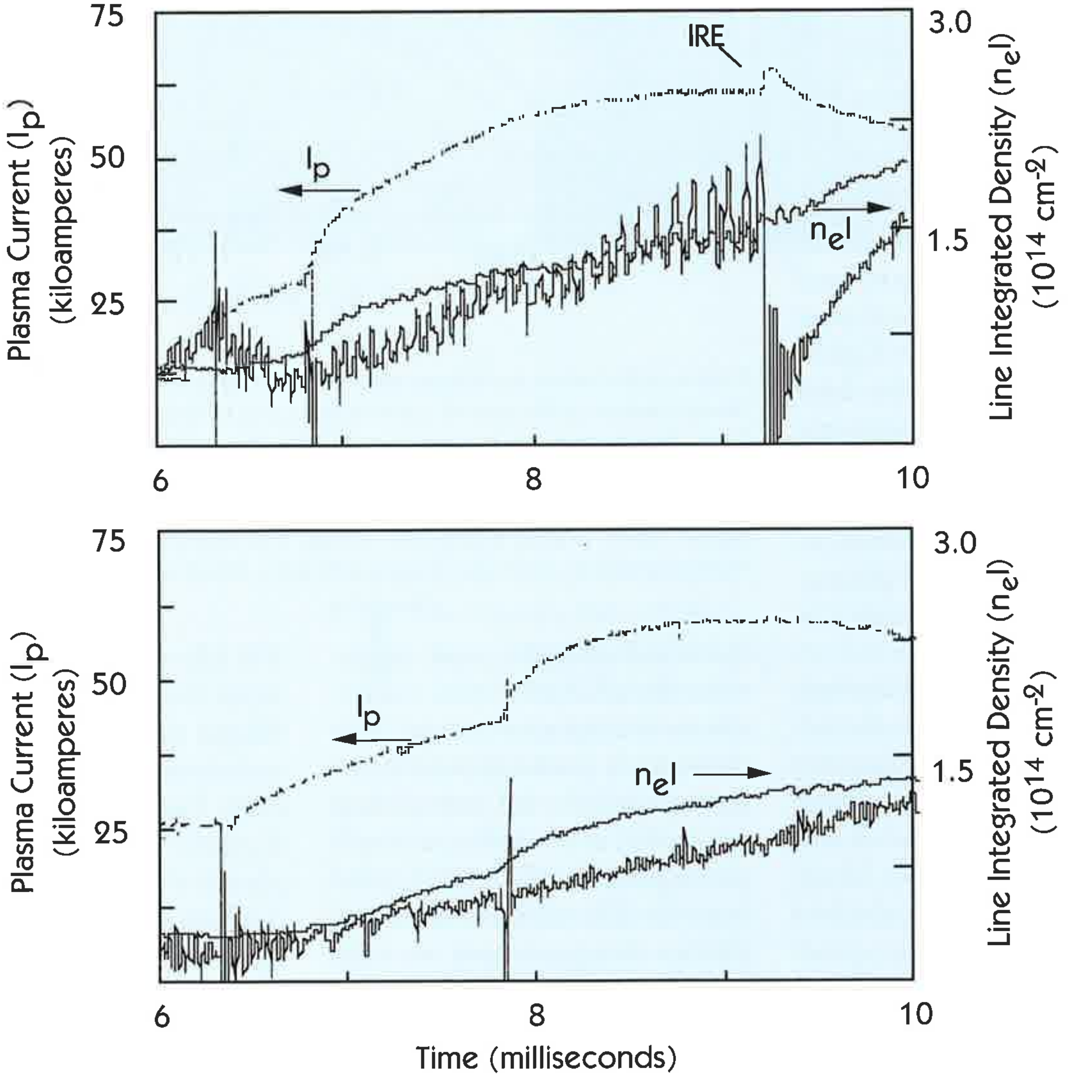


Plasma optimization techniques and ohmic-heating capability have allowed CDX-U researchers to study plasma current limits and to test methods to increase their limits. This graph compares experimentally achieved plasma current values (circles and crosses) and theoretically predicted plasma current values (dashed and solid lines) as a function of the toroidal magnetic field for CDX-U plasmas of different aspect ratios, plasma elongation values, and an edge safety factor of 3.5. The crosses are for an optimized plasma and show about a 30% gain in plasma current.

Generally, the plasma current limit is proportional to a device's toroidal magnetic field, but experimentally in the CDX-U the plasma current limit is reached when the plasma edge safety factor is about 3.5 and a resistive magnetohydrodynamic (MHD) mode (a type of instability in the plasma) develops causing current saturation. It has been predicted theoretically and shown experimentally (see graph below) that the CDX-U plasma current limit can be increased substantially (about 40%) with modest (about 5%) changes in plasma aspect ratio and elongation (plasma optimization). In the graph, experimentally achieved plasma current values (circles and crosses) and theoretically predicted plasma current values (solid and dashed lines) are plotted as a function of toroidal magnetic field for CDX-U plasmas with different aspect ratios and plasma elongation and an edge safety factor of 3.5. The circles are for a nonoptimized plasma with an aspect ratio of 1.62 and plasma elongation of 1.49 and the crosses are for an optimized plasma with an aspect ratio of 1.55 and plasma elongation of 1.60. The crosses show about a 30% gain in plasma current from 60 kilo amperes to 100 kilo amperes, taking into account the toroidal magnetic field. Plasma optimization techniques and advanced ohmic-heating capability have allowed CDX-U researchers to begin to investigate ST plasma current limits and to test methods to increase this limit, a crucial element in the development of an ST fusion reactor alternative.

Multipass Thomson Scattering Diagnostic

The existence of a hot plasma core of well above 100 electron volts (1 million °C) was confirmed with the installation and operation of the multipass Thomson scattering diagnostic system. Interestingly, two distinctly different sets of plasma conditions for identical values of plasma current and toroidal magnetic field were observed. In the figure below, the time evolution of the two plasmas is shown. The first plasma (top figure) has sawtooth-like MHD oscillations (plasma instabilities) followed by an internal reconnection event (IRE) and a low central electron temperature of only about 65 electron volts. The second plasma (bottom figure), with a slightly different current ramp-up rate, is relatively free of the MHD activity and has a central temperature of about 140 electron volts, more than twice the first case. Since the plasma current and density are similar for both plasmas, the difference in plasma behavior may be attributed to the plasma current profiles (current ramp-up rate). It is encouraging that the plasma's MHD behavior may be controlled by plasma programming, resulting in a significant improvement in plasma confinement. Also, with the higher temperatures, ST plasmas on CDX-U are now in a reactor-relevant collisionless regime.



With "plasma programming," researchers on CDX-U have been able to increase plasma confinement time and temperature. In the graphs above, the time evolution of two plasmas with distinctly different plasma behavior but with identical plasma current and toroidal magnetic field values are shown. The top graph shows a plasma discharge with sawtooth-like MHD oscillations, or instabilities, followed by an internal reconnection event (IRE) and a central electron temperature of only about 65 electron volts. The bottom graph shows a plasma discharge relatively free of MHD activity and a central electron temperature of about 140 electron volts, more than twice that of the first plasma. The difference in behavior may be due to the rate at which the current is "ramped up" in the plasma.

Other Activities

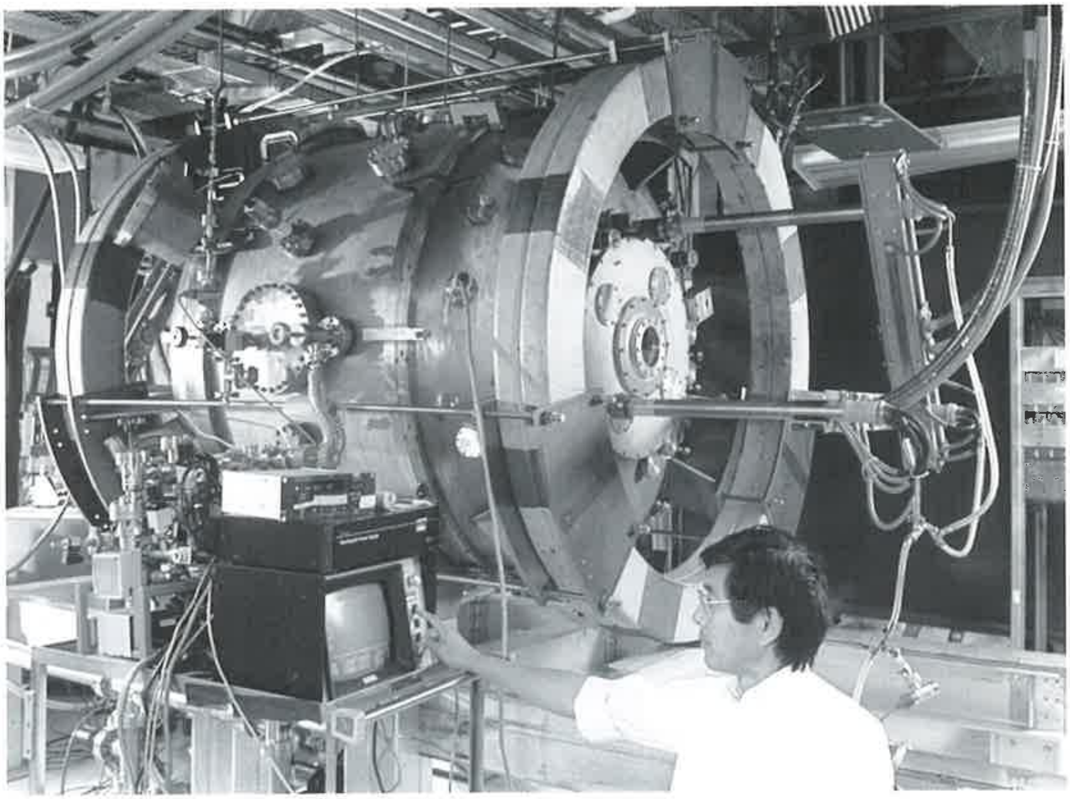
Other fiscal year 1995 activities for CDX-U include the development of an electron-ripple-injection concept for plasma transport control, design of a phase-contrast-imaging system for plasma fluctuation studies, the carrying out of preliminary experiments for a soft X-ray line emission tomography system, and work on a high-harmonic fast-wave heating concept for heating and current drive of future ST plasmas.

CDX-U researchers collaborate actively with the A.F. Ioffe Physical-Technical Institute, St. Petersburg, Russian Federation, and the Johns Hopkins University, Baltimore, Maryland. In addition, CDX-U welcomed visiting researchers from several institutions, including the Culham Laboratory in England [Small Tight Aspect Ratio Tokamak (START) experiment], the University of Tromso in Norway, and the National Institute of Fusion Studies in Japan.

Finally, the CDX-U is an excellent experimental plasma physics facility for graduate student training. First-year graduate students play active roles in the research activities on CDX-U, and many go on to write their doctoral dissertations on their work. In fiscal year 1995, Theodore G. Jones was awarded a Ph.D. based on his research on the CDX-U. His thesis was entitled "Low-Aspect Ratio Tokamak Start-Up and Operational Current Limits in CDX-U."

MRX

Magnetic Reconnection Experiment



Magnetic Reconnection Experiment

A new basic plasma physics research facility at the Princeton Plasma Physics Laboratory (PPPL), the Magnetic Reconnection Experiment or MRX, is scheduled to begin operation early in fiscal year 1996. Experiments on MRX will study the physics of magnetic reconnection — the topological breaking and rapid reconnection of magnetic field lines in plasmas. PPPL scientists hope to develop a basic understanding of this important plasma physics process, how it occurs, and how it determines plasma characteristics such as confinement and heating.

The Magnetic Reconnection Experiment is an example of the Laboratory's efforts to broaden its research base. Gaining an understanding of magnetic reconnection will have relevance to solar physics, astrophysics, magnetospheric physics, and the physics of laboratory plasmas. Because magnetic reconnection is regarded as a key phenomenon in solar flares, MRX results could play an important role in interpreting data from satellites such as Yohkoh. Magnetic reconnection also occurs as one of the relaxation processes in fusion research plasmas; it often plays a dominant role in determining the confinement characteristics of high-temperature fusion plasmas. Its small size and rich plasma physics make the MRX an ideal facility for studying basic plasma physics and educating graduate student.

Finally, the MRX represents a diversity of funding sources for the Laboratory, with support from the National Science Foundation, the National Aeronautics and Space Administration, the Office of Naval Research, and the U.S. Department of Energy.

The MRX

The design and construction of the MRX facility was done entirely at PPPL. To save money, components from earlier experimental devices were used. In particular, part of the vacuum vessel from Proto S-1 and the equilibrium field coils from S-1 were recycled.

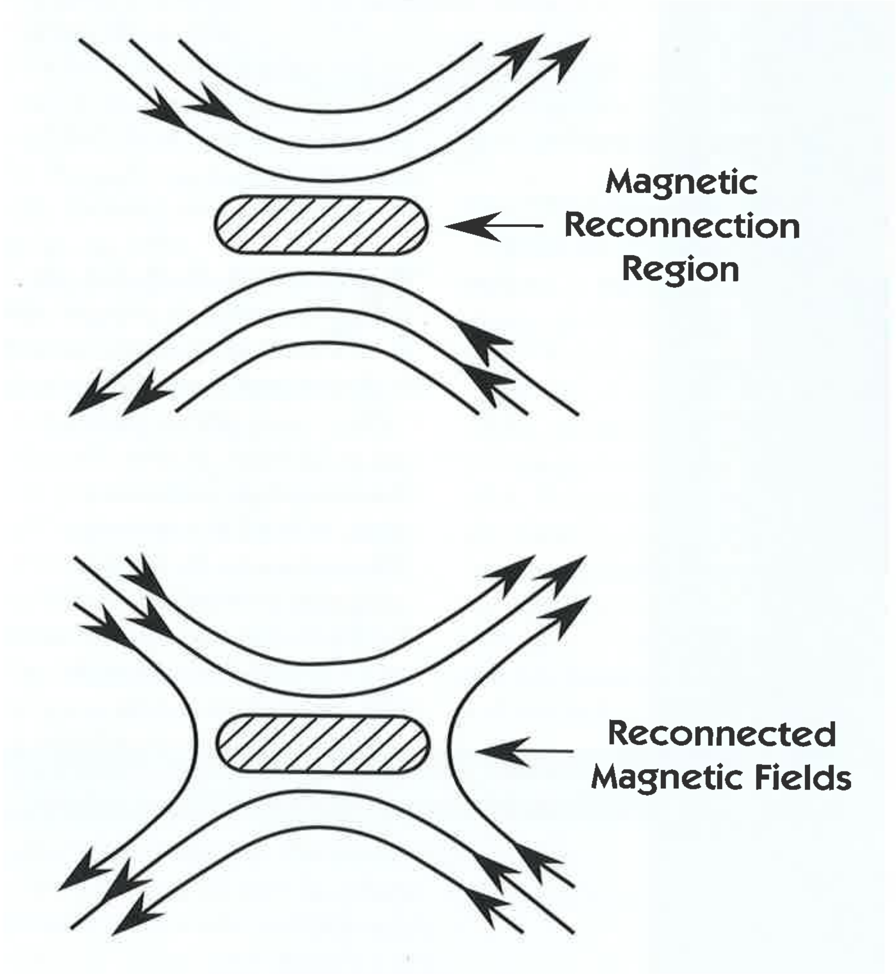
In an MRX experiment, two rings of plasmas with identical toroidal currents will be created. Initially, the two plasmas are kept apart by the external magnetic field, but eventually the attractive force created by the toroidal currents in the plasmas dominates and the plasmas merge. The merging plasmas induce magnetic reconnection. Understanding this interplay between plasma and magnetic field is fundamental to the development of magnetic fusion as an energy source. This is because the magnetic field bottles, which are used to confine the plasma, can "open up" or "tear" when they interact with the plasma and cause a loss in confinement, which is essential for fusion energy production.

A primary objective of experiments on MRX will be the comprehensive analysis of the physics of magnetic reconnection both locally and globally within an MHD plasma. This will be accomplished by investigating the coupling between microscale reconnection layers for local reconnection and global forcing and MHD flows for global reconnection issues. Fully three-dimensional magnetic reconnection experiments are now possible on this device.

A set of carefully chosen diagnostics will be used to measure and view the plasmas created in the MRX device. These include Langmuir probes for measuring electron density and temperature, Faraday cups, spectroscopy for measuring ion and electron temperature and impurity concentration, and laser-induced fluorescence for measuring local ion dynamics and temperature. These diagnostics will provide insight into the physics of magnetic reconnection and real-time monitoring of MRX plasmas.

Future Experiments

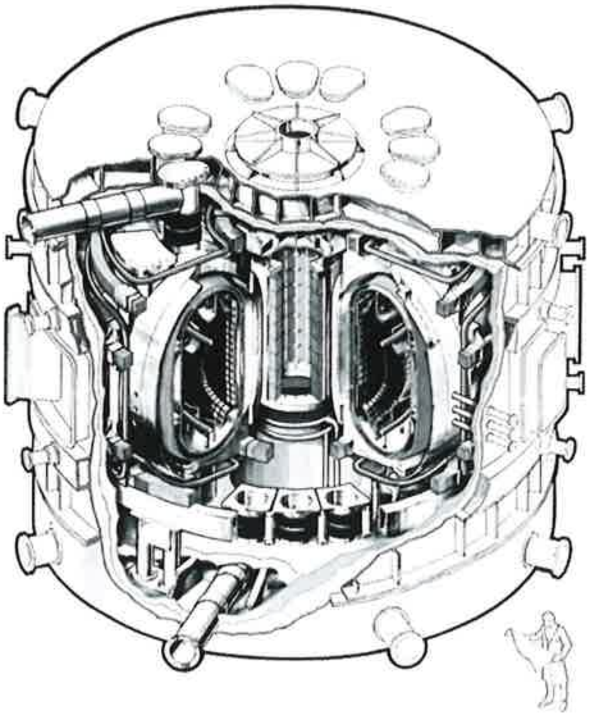
Future experiments on the MRX device could include a comparative study of plasma characteristics of compact toroids such as the spheromak, the field-reversed configuration, and the ultra-low-aspect-ratio tokamak. Studying these alternative concept configurations is important for developing and understanding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



The top figure shows typical magnetic-field topology before magnetic reconnection. The bottom figure shows magnetic-field topology during magnetic reconnection. This fundamental plasma physics process plays a key role in the evolution of solar flares and fusion plasmas.

TPX

Tokamak Physics Experiment



Tokamak Physics Experiment

Nineteen ninety-five was a year of great promise and extreme disappointment for the Tokamak Physics Experiment (TPX) Project. With a specific mission to "develop the scientific basis for a compact and continuously operating tokamak fusion reactor," the TPX's role in the United States fusion program was to help determine whether the tokamak approach could evolve smaller, less expensive, and more attractive fusion reactors than are presently forecast using "conventional" physics assumptions. Accordingly, the TPX was designed to extend the advanced tokamak operating modes of high beta, confinement time, and bootstrap current fraction to the steady-state regime. An additional benefit of the Project would have been the extension of the tokamak technology base. Unfortunately, as part of the budget reduction actions of Congress, the TPX Project was canceled in September, 1995.

Notwithstanding the disappointing end of the TPX Project, the Project represented a milestone in the successful management of complicated and geographically dispersed projects in the Department of Energy. The TPX was a focused national effort that involved the resources of a large part of the United States Department of Energy's national fusion program. Although the Princeton Plasma Physics Laboratory was responsible for the overall management and eventual operation of the TPX, the Project included many of the U.S. plasma physics research laboratories, universities, and industrial firms as participants. These participants are listed in detail in the PPPL Fiscal Year 1994 Annual Report. They share the credit for the technical achievements of the Project as report in this Highlights Report. One of the successes of the Project for the U.S. fusion program was the early involvement of industry in the design phase.

Technical Highlights

Significant technical progress was made in fiscal year 1995 by the national team despite the uncertain future of the Project. One of the most challenging areas, the design and research and development associated with the magnet systems, received highest priority based on schedule considerations. Technical achievements included the successful completion of the preliminary designs for both the toroidal-field and poloidal-field magnet components assigned to the industrial partners, the completion of a full-scale model of a poloidal-field solenoid coil to demonstrate fabrication techniques, the completion of a large portion of the research and development on the niobium-tin superconductor, and the modeling and measurement of the properties of the insulation material for the magnet systems. In addition, significant progress was made in the design of the vacuum vessel and plasma facing components, including the determination of the technique for welding vacuum vessel materials and evaluation of the properties of the candidate materials for the plasma facing components.

Contracts

An important legacy of the TPX Project will be the establishment of the active involvement of industry early in the life of a Project. With the exception of the design and fabrication of the cryostat, which was planned for 1996, all other stages of the Industrial Involvement Plan (developed in late 1993) were completed in the spring of 1995 when the Systems Integration Support Contract and the Tokamak Construction Management Contract were awarded. With these awards, the industrial contracts shown in the Table below were in place. Although these initial contracts only totaled approximately $70 million, the expected industrial involvement was to be about 75% of the total of the TPX Project estimated costs of $742 million.

Project Assessment

A Department of Energy technical, cost, schedule, and management review was held in early February, 1995. The status of the Project and its readiness to proceed with construction and its ability to identify problem areas and to make recommendations was assessed. This was the third major review of the TPX Project (the first was in early 1994 and the second in mid-1994) by the Department of Energy Office of Energy Research. Because of outyear budget uncertainties, the focus of the review was on 1995 fiscal year activities and the Project's readiness to proceed with construction as scheduled in fiscal year 1996.

The overall conclusion of the review was that the TPX Project was "functioning well and was clearly ready to proceed with construction." In addition to the Department of Energy Office of Energy Research team, representatives from the Department of Energy Office of Field Management attended the review and concurred in the Review Committee's assessment. Furthermore, the Office of Field Management indicated the intention to validate the fiscal year 1997 budget request at the level planned. Unfortunately, the decisions of Congress obviated these actions.

TPX Major Parameters.

Parameter	Baseline	Maximum*
Toroidal Field, B_t	4.0 T	—
Plasma Current, I_p	2.0 MA	—
Major Radius, R_o	2.25 m	—
Aspect Ratio, R/a	4.5	—
Elongation, κ_x	2.0	—
Triangularity, δ_x	0.8	—
Configuration	Double-Null Poloidal Divertor	Double or Single-Null Poloidal Divertor
Heating & Current Drive:		
Neutral Beam	8 MW	24 MW
Ion Cyclotron	6 MW	18 MW
Lower Hybrid	3 MW	3.0 MW
Electron Cyclotron	—	10 MW
Plasma Species	Hydrogen or Deuterium	Tritium
Pulse Length	1,000 sec	>>1,000 sec

*Upgrade capabilities accommodated by the baseline design.

The TPX Legacy

While the TPX Project will not go forward, it has had a strong impact on the vision of the "Advanced Tokamak." This has resulted in dramatic redirection of research activities on TFTR and other experimental devices worldwide with very positive results. Theoretical work in this area has blossomed as well. Finally, the TPX Project has demonstrated a positive management model for national collaboration among national laboratories, universities, and industry in fusion research.

Tokamak Physics Experiment Project Industrial Contracts.

Contract	Date	Industrial Team Leader
Design & Fabrication of the Vacuum Vessel	June 1994	Ebasco Division of Raytheon Engineers & Constructors
Design & Fabrication of the Plasma Facing Components	June 1994	General Atomics
Preliminary Design of the Toroidal-Field Magnets	July 1994	Babcock & Wilcox
Preliminary Design of the Poloidal-Field Magnets	July 1994	Westinghouse Electric
Systems Integration Support Contract	April 1995	Missile Systems Division of TRW, Incorporated
Tokamak Construction Management Contract	June 1995	Stone & Webster Engineering Corporation

ITER

International Thermonuclear Experimental Reactor

International Thermonuclear Experimental Reactor

The International Thermonuclear Experimental Reactor (ITER) is a collaboration between the governments (referred to as Parties) of the European Union, Japan, the Russian Federation, and the United States. The overall objective of the ITER is to demonstrate the scientific and technological feasibility of magnetic fusion energy. The ITER would accomplish this by demonstrating controlled ignition and extended burn of deuterium-tritium plasmas, with steady-state operation as an ultimate goal; by demonstrating technologies essential to a fusion reactor in an integrated system; and by performing integrated testing of the high-heat-flux and nuclear components required to utilize fusion energy for peaceful purposes.

Following a successful Conceptual Design Activity from 1988–90, the second phase of the ITER Project — the Engineering Design Activities — began in 1992 and is planned to extend through mid-1998. The organizational structure of the Engineering Design Activity involves a Joint Central Team located at three Joint Work Sites

(Garching, Germany; Naka, Japan; and San Diego, United States) and drawn approximately equally from each of the four ITER Parties, together with four Home Teams working within their respective Parties. The combined organization reports through a Director to the ITER Council, which is representative of the responsible governmental agencies of the four Parties.

Joint Central Team

During fiscal year 1995, the Joint Central Team completed the ITER Interim Design Report, which was reviewed by the Technical Advisory Committee and presented to and accepted by the ITER Council. The Joint Central Team also worked with the Home Teams to assign and continue the Technology Research and Development plan, which defines the research and development to be carried out during the Engineering Design Activity.

The Princeton Plasma Physics Laboratory (PPPL) provided four members of the Joint Central Team in fiscal year 1995: the Head of the Physics Integration Unit (at San Diego), a senior physicist developing plasma scenarios and divertor physics concepts (at San Diego), a senior diagnostics physicist (also at San Diego), and a senior tritium engineer with experience on the Tokamak Fusion Test Reactor's tritium system and previously from the Savannah River Plant (at Naka). The Laboratory is also prominently represented on the physics side within the U.S. Home Team, providing the overall U.S. Physics Manager, as well as the Task Area Leaders of the Divertor Physics and Plasma Diagnostics Task Groups. The Chair of the Technical Advisory Committee is also from PPPL.

Major progress was made in 1995 in the PPPL contributions to the ITER Voluntary Physics Research and Development program. Research activities of the TFTR and PPPL Theory and Modeling groups contributed information in virtually all the ITER Physics Research and Development areas.

Physics Expert Groups

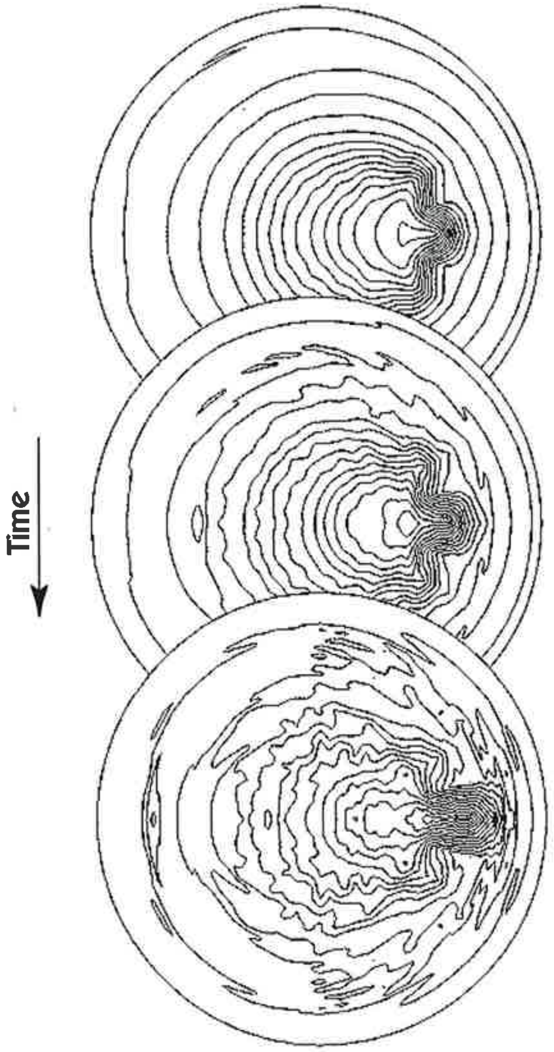
There are seven ITER Physics Expert Groups responsible for defining and monitoring so-called "voluntary" physics research and development within the national programs of the four Parties. The Laboratory provides the Chair of one of the Physics Expert Groups (Diagnostics) and has a staff member serving on five of the other six (Divertor Physics; Divertor Modeling and Database; Confinement Modeling and Database; Disruptions, Plasma Control, and Magnetohydrodynamics; and Energetic Particles, Auxiliary Heating, and Current Drive). The PPPL-provided Physics Manager on the U.S. Home Team facilitates the coordination of this activity with the Division Directors for Confinement Systems and for Applied Physics and Technology within the Department of Energy's Office of Fusion Energy. The Expert Group structure provides a focus for the national experimental and theoretical programs on the physics needs of ITER; it also permits the development and analysis of international databases and the joint understanding of ITER-relevant physics.

As part of the funded-ITER physics design effort, Laboratory scientists performed a number of tasks in areas such as plasma scenario development, plasma control, magnetohydrodynamic stability analyses, and divertor physics design.

Interim Design Machine Parameters for the International Thermonuclear Experimental Reactor.

Parameter	Value
Major Radius (R)	8.1 m
Minor Radius (a)	3.0 m
Elongation	1.6
Toroidal Field (B)	5.7 T
Plasma Current (I_p)	~21 MA
Power and Particle Control	Single-Null, Poloidal Divertor
Auxiliary Power	0.1 GW
Fusion Power	1.5 GW

Theoretical Studies



The time evolution of plasma pressure by a numerical simulation is shown in the above figure. The local bulging of the pressure causes the plasma to disrupt. This theoretical result compares well with experimental data. Work like this has led to the first successful interpretation of the physics behind high-beta plasma disruption phenomena.

The Princeton Plasma Physics Laboratory (PPPL) Theory Division is generally recognized as the leading center of excellence in plasma theory research. Its primary mission is to help achieve the physics knowledge required to produce economic and environmentally attractive fusion reactors. Theoretical staff members contribute to the development of this body of knowledge by involvement in the conception, design, and interpretation of experiments and by generally assessing the implications of the laws of physics.

The fundamental laws that determine the behavior of fusion-relevant plasmas are embodied in the well-known Maxwell's equations and the equations of classical and statistical mechanics. However, even the most basic forms of these nonlinear equations applied to the simplest real geometry can produce very complex and unexpected behavior. Hence, a significant effort in fundamental theoretical research is necessary to gain a proper understanding of the physics associated with magnetically confined plasmas. Many of the advances in the fusion program have resulted from an appreciation for the implications of these laws and not just from the development of empirical rules for scaling.

Recent improvements in operational reproducibility and in diagnostic techniques have made possible realistic comparisons of experimental results from the leading confinement devices, such as tokamaks, with theoretical models. This has led to significant advances in scientific understanding and to the development of innovative methods for improving performance. The PPPL Theory Division has a lead role not only in the essential long-range work providing the basic understanding to develop new analysis techniques and tools but also in the actual applications of state-of-the-art theoretical codes to the interpretation and design of key experiments. Endorsements from the national and international fusion communities for these activities have been stimulated by seminal scientific contributions, national and international collaborations, and exciting prospects for future impact.

Scientific Contributions

Princeton Plasma Physics Laboratory's theoretical work has provided major contributions to the development of analysis techniques and computational tools for the magnetic fusion research program. This work has involved the innovative development and integration of state-of-the-art analytic and numerical analysis capabilities, which have helped provide the first-rate fusion science needed to effectively develop an economical reactor. High-impact contributions have come from applications of the best existent computer codes to interpret and design experiments. Some examples include:

- The first successful interpretation has been made of the physics behind the high-beta plasma disruption phenomena which have limited performance in the world-record fusion power-producing deuterium-tritium experiments on TFTR.
- New kinetic calculations have predicted, for the first time, that under certain accessible conditions all prominent microinstabilities can be suppressed in plasmas with reversed magnetic shear, leading to neoclassical levels of confinement. These exciting positive results have subsequently been found to correlate well with favorable trends observed in recent TFTR and DIII-D (a tokamak at General Atomics) experiments.
- Excellent correlations have been found between theoretical predictions and experimental observations in comprehensive studies of toroidicity-induced Alfvén eigenmodes (a type of plasma instability) in TFTR deuterium-tritium plasmas. Understanding these instabilities is generally recognized to be a key issue for performance in planned ignition devices such as the International Thermonuclear Experimental Reactor (ITER).
- Highly visible progress has been demonstrated in the challenging area of turbulent transport by the successful application of the Institute for Fusion Studies-Princeton Plasma Physics Laboratory (IFS-PPPL) computer model to interpret many of the important thermal confinement properties in TFTR plasmas.
- Creative new methods have been suggested for a possible experimental demonstration of the viability of channeling energy from alpha particles to ions, which could in turn dramatically enhance the plasma reactivity.

External Collaborations

Collaborations between the PPPL Theory Division and national and international fusion institutions such as General Atomics, the Japanese Atomic Energy Research Institute, and the Institute for Fusion Studies, to name a few, as well as individuals from university programs at, for example, the Massachusetts Institute of Technology and the University of California at San Diego, have continued to be highly productive and visible. This is clearly evident from the number of refereed journal publications, International Atomic Energy Agency and American Physical Society oral presentations, and completed, as well as planned, experimental proposals on devices such as DIII-D and JT-60U (Japan). An example is the success of the aforementioned IFS-PPPL transport model. In addition, the key role of PPPL Theory Division in helping to provide the tools and concepts for ITER research and development needs is well recognized (e.g., membership on ITER expert groups and letters of endorsement with requests for enhanced activity).

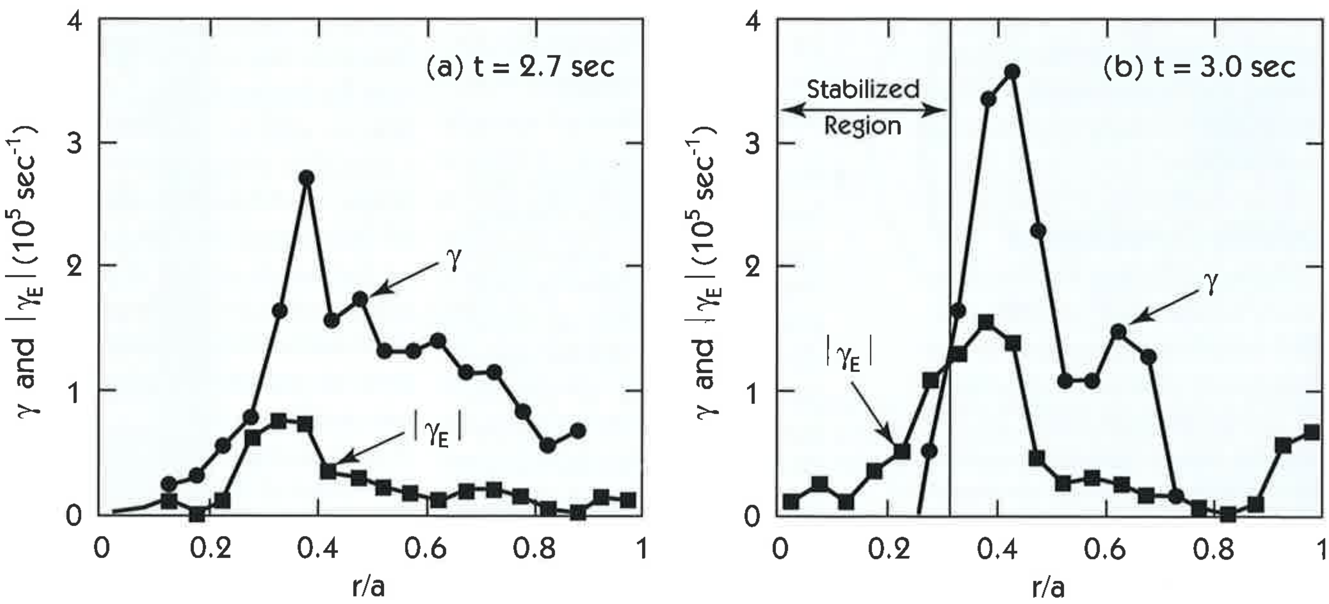
Future Impact

In addition to its demonstrated leadership and productivity highlighted in the preceding discussion, PPPL Theory Division work has a high potential for future impact on the fusion program. Prominent "site credits" include: (i) excellent coupling to an outstanding experimental program at PPPL; (ii) integral part of the premier academic program in plasma sciences; and (iii) general acknowledgment from the international fusion community as having the "best array of computational and analytic talent in the world."

Diversification

In order to enhance the creative environment by diversification of research activities, theoretical efforts in non-fusion areas such as space physics, X-ray lasers, and industrial applications of particle simulations have been undertaken. This has included contributions on the influence of energetic particles in the magnetosphere with applications of the associated theory to the interpretation of data from satellite observations. With regard to X-ray laser research, an excellent example of creativity is the proposal for a device capable of achieving recombination-pumped gain at very short lasing wavelengths (approaching ten Angstroms).

New research initiatives have involved non-fusion applications of powerful particle simulation methodology developed in fusion research. Investigations of the behavior of low-energy electron beams in air have been carried out to support the industrial development of improved electrostatic sprayers with relevance to fire suppression systems, ink-jet printers, paint sprayers, and fuel injectors. Charge transport modeling ("dusty plasma" simulations) of the xero-



New kinetic calculations have predicted that under certain accessible conditions all prominent microinstabilities can be suppressed in plasmas with reversed magnetic shear. This is illustrated in the above graphs. When the toroidal drift mode is unstable, with linear growth rate $\gamma > 0$, it can cause anomalous transport. Reversed magnetic shear reduces γ, and when the shearing frequency $|\gamma_E|$ is greater than γ, the mode is considered to be nonlinearly stabilized. At time t = 2.7 sec, Graph (a), before the enhanced reversed shear transition, γ is larger than $|\gamma_E|$ everywhere, and normal anomalous transport is expected. At time t = 3.0 sec, Graph (b), after the enhanced reversed shear transition, $|\gamma_E|$ is greater than γ inside r/a = 0.3, so the mode is stabilized there, reducing the anomalous transport, as seen in the experiment.

graphic recharge processes is presently being pursued in collaboration with Xerox Corporation. Other important non-fusion initiatives involve novel particle simulation studies of collective effects on accelerator performance with Fermi Lab and theoretical support for the new multi-agency (National Science Foundation, National Aeronautics and Space Administration, Office of Naval Research, Department of Energy) funded Magnetic Reconnection Experiment sited at the Laboratory.

Graduate Education

Motivated by the need to help attract, train, and assimilate the best and brightest young talent into the field, Theory Division personnel actively participate in the education program at Princeton University. The PPPL Theory Division has continued in its role of being a primary contributor to the maintenance of the leading program for graduate studies in plasma physics. In addition to those serving on the teaching faculty, many members of the theory group provide support to the program by serving as thesis research advisors. This has been a mutually beneficial relationship in that the high quality of students in the graduate program has been a valuable and stimulating source of youthful energy, enthusiasm, and creativity for the Theory Division.

Engineering and Technology Development

The Engineering and Technology Development Department is primarily responsible for managing PPPL's engineering resources and for developing applicable technologies for fusion and fusion-related technologies that may be candidates for transfer to the commercial and industrial sectors. Brief summaries of the major activities for fiscal year 1995 are given below.

Tokamak Fusion Test Reactor

All TFTR systems achieved high levels of availability and reliability at operating parameters equal to or exceeding original design criteria during the extended TFTR experimental program in fiscal year 1995. More than 12,000 plasma discharges, including more than 500 with deuterium-tritium, were produced. Additional maintenance capability for tritium-contaminated equipment was required also during this period. The high air purity clean room was integrated into TFTR site tritium cleanup systems and an annex to the decontamination facility was designed and built to provide refurbishment capability for the neutral-beam ion sources. Five ion sources were refurbished to maintain full neutral-beam potential for TFTR.

The design and operation of engineering upgrades to TFTR systems continued. The TFTR toroidal magnetic field was successfully increased to 6 tesla, a 15% increase above the original design value of 5.2 tesla. A design to convert four of the radio-frequency power sources and two radio-frequency launchers to 30-MHz operation was completed to support investigation of new radio-frequency heating techniques to enhance plasma heating and current drive. Development of the Tritium Purification System progressed to full-scale operations in deuterium, providing operating experience in this new technology before it is introduced into the TFTR tritium systems. The Tritium Purification System utilizes a specialized cryogenic distillation process developed by the Canadian Fusion Fuels Technology Project that should reduce TFTR's tritium shipping and disposal costs.

Princeton Beta Experiment-Modification

An upgrade of the Princeton Beta Experiment-Modification (PBX-M) vacuum vessel O-ring system to improve vacuum conditions and enhance future performance and reliability was done. The lower-hybrid current-drive coupler was remanufactured to a new angular geometry and the entire splitter-coupler support assembly was replaced with a new design that provides a larger degree of coupler position adjustment during

The tritium-contaminated long-pulse neutral-beam ion source is refurbished.

machine operation. Equipment that will provide real-time digital control of the PBX-M plasma was specified, purchased, and tested.

National Spherical Tokamak Experiment

The National Spherical Tokamak Experiment (NSTX) is a proposed mega-amp-level spherical tokamak facility designed to investigate physics issues related to spherical-shaped plasmas. A comprehensive finite-element model for the NSTX was developed and preliminary stress analyses were completed for the vacuum vessel and the toroidal and poloidal magnetic-field coils in support of the upcoming engineering conceptual design review. An engineering organizational structure was established for the design and construction phases of the Project.

Magnetic Reconnection Experiment

The Magnetic Reconnection Experiment (MRX) is the first new device at PPPL in nearly a decade. Design of the MRX was completed, and flux cores for the machine were built. Facility construction was completed at the end of the fiscal year and first plasma is scheduled for November, 1995.

Tokamak Physics Experiment

Engineering support was provided for the preliminary design of the Tokamak Physics Experiment (TPX). Emphasis was placed on design optimization and the analysis and improvement of systems performance. Designs for the internal coils for plasma control were completed. Design of the shielding to ensure radiological safety for the auxiliary systems was completed also. A coil systems code was constructed which combined the interaction of thermal, electromagnetic, mechanical, and nuclear effects in a parametric formulation to assess the performance of the design. The computer code, IVBRAN, was developed to account for the effects of "halo" currents during a plasma disruption. The spatial and time dependence of the eddy currents induced in the complex structure due to the plasma disruption can now be fully analyzed using the SPARK and IVBRAN computer codes.

Computer Systems

Tools and technologies that enhance the ability of remote collaborators to participate in physics planning and experimental operation were introduced. A three-year initiative to expand the main PPPL network backbone to a 100-Megabytes fiber distribution data interface ring was completed. This capability, which supports faster data communications, provides increased network-based audio and video communications. The use of the World Wide Web at PPPL also was enhanced to provide desktop access to and archives of important project information.

Environmental Restoration and Waste Management personnel measure groundwater level and prepare to collect samples using the new groundwater sampling system.

Environmental Restoration and Waste Management

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

In fiscal year 1995, field sampling and analysis required under the site-wide Remedial Investigation Program was completed. A new state-of-the-art groundwater sampling technology, expected to save as much as $62,000 per year in costs, was adopted. Remediation of the remaining contamination associated with former underground fuel oil storage tanks was completed, including the removal of contaminated soil beneath the floor of the boiler room.

"Type A" disposable molecular sieve beds, which are integral to the TFTR tritium-handling systems, were redesigned to provide better operational efficiency, greater water-loading capacity, and a reduction in fabrication costs to less than half that of the present design. A silver recovery project was started with the Photo Lab to reduce the discharge of silver into the sanitary sewer, thus avoiding the necessity of a costly sanitary sewer sampling program.

Collaborations

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

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

There was also considerable activity associated with the Tokamak Physics Experiment design and in new initiatives in Cooperative Research and Development Agreements and Work for Others and participation in education programs.

The Laboratory presently collaborates with the following organizations:

Laboratories

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

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

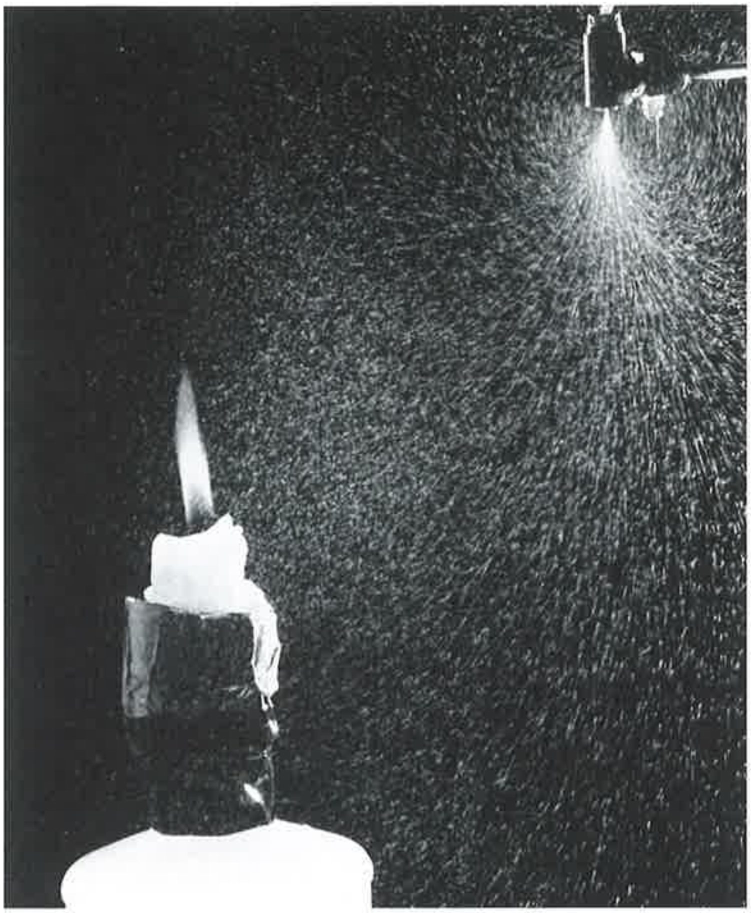
Industries

ABB, North Brunswick, NJ
Applied Physics Technologies, Inc., Stonybrook, NY
Armand Engineering Corporation, Marlton, NJ
ATT Bell Laboratories, Murray Hill, NJ
AT&T, Hopewell, New Jersey
Babcock and Wilcox, Lynchburg, VA
Bristol-Myers Squibb, Lawrenceville, NJ
Burns and Roe Company, Oradell, NJ
CBI Services, Newcastle, DE
Canadian Fusion Fuels Technology Project, Canada
Charged Injection Corporation, Monmouth Junction, NJ
DuPont Chemical Corporation, Wilmington, DE
Dynamic Research Corporation, Hillsboro, OH
Everson Electric Company, Bethlehem, PA
Exide Corporation, PA
Fusion Physics and Technology, Inc., Torrance, CA
General Atomics, San Diego, CA
Lodestar, Boulder, CO
McDonnell Douglas Missile Systems, St. Louis, MO
Millitech Corporation, South Deerfield, MA
Mission Research Corporation, Newington, VA
Northrop Grumman Aerospace and Electronics Corporation, Bethpage, NY
Plasma Technology, Inc., Santa Fe, NM
Princeton Research Instruments, Princeton, NJ
Princeton Electronic Systems, Inc., Princeton, NJ
Radiation Science, Inc., Belmont, MA
Raytheon Engineers and Constructors, Inc., Ebasco Division, New York, NY
Rocketdyne Division of Rockwell International Corporation, Canoga Park, CA
Roy F. Weston, Inc., West Chester, PA
Stone and Webster Engineering Corporation, Boston, MA
TRW, Incorporated, San Bernardino, CA
Xerox Corporation, N. Tarrytown, NY

Universities and Educational Organizations

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

Technology Transfer



The design of novel fire sprinklers is just one of the many applications in the field of electrostatic atomization. The photo shows electrically charged water mist attracted to the flame of a candle. Being able to focus the water at the fire source eliminates the need to deluge an entire area thus preventing unnecessary water damage to materials not directly involved in the fire.

The Technology Transfer Office at the Princeton Plasma Physics Laboratory (PPPL) actively promotes transfer of technology developed at the Laboratory to the private sector. This is accomplished through a variety of technology transfer mechanisms including Cooperative Research and Development Agreements, Work for Others, Personnel Exchanges, Technology Maturation Projects, Licensing Agreements, and Patents.

CRADAs

A Cooperative Research and Development Agreement (CRADA) is a contractual agreement between a federal Laboratory and one or more industrial or university partners. A CRADA enables industry and Laboratory researchers to work on programs of mutual interest. The following CRADAs have been developed recently through the PPPL Technology Transfer Office.

Tokamak-Based Lithography Concept

This CRADA is a joint effort with PPPL, the Plasma Fusion Center at the Massachusetts Institute of Technology, and Applied Physics Technologies Inc., to investigate the possibilities of using tokamak plasma X-ray radiation for the purpose of X-ray lithography. Through this CRADA, a series of experiments will be conducted on Versator II, a small tokamak at the Plasma Fusion Center, to evaluate and determine the optics and plasma conditions that produce the most useful radiation for X-ray lithography.

Low-Energy Electron Beams in Air

This CRADA, with Charged Injection Corporation in Monmouth Junction, New Jersey, is for the investigation of low-energy electron-beam behavior in air. Techniques developed will be used for the manufacture of electrostatic atomizer technology, with applications in the automotive industry for increased combustion efficiency and reduced over spraying during painting that will yield substantial environmental benefits. Applications also exist in other industries.

Plasma Chemical Synthesis

Through this CRADA, the potential for synthesizing chemicals with commercially viable purity and yields of interest to the industrial sector will be explored. A proof-of-principle study will be conducted using a small-scale reactor to create "synthesized" chemicals from plasmas initially composed of feedstock chemicals.

Advanced Computer Modeling Environment Project

This CRADA is with Dynamic Research Corporation. It is for the development of a high-level computational environment that allows diverse computational modules to be rapidly and easily integrated into a computer model by the end user.

On-line Processing Control of Fiber Morphology for the American Textile Partnership

This CRADA, with the Princeton Textile Research Institute, is for the development of an on-line, real-time measurement tool based on noncontact optical and spectroscopic techniques. This tool will be used during textile production to monitor and measure fiber characteristics. This CRADA supports the long-term online process control goal to increase the competitiveness of the U.S. textile fiber manufacturers by providing quality improvement through state-of-the-art fiber production technology.

Chemical Synthesis and Waste Treatment

This CRADA is with the Center for Plasma Processing of Materials at Drexel University (Philadelphia, Pennsylvania) and Plasma Technology, Inc., a small business in Santa Fe, New Mexico. Through this CRADA, chemical waste processing by induction-coupled plasmas will be investigated. This novel technique for breaking down waste promises to be an alternative to the more conventional method (incineration) because the by-products are environmentally benign or even usable. Investigators will use spectroscopic diagnostics developed at PPPL to identify and measure the concentrations of the key chemical molecules useful for waste processing present in induction-coupled plasmas. Using these measurements, a computer simulation will be generated to identify the formation processes of the molecules and to suggest ways to improve the chemical waste processing efficiency.

Photo Cathode Electron Projection Lithography

This CRADA with AT&T Bell Laboratories, Murray Hill, New Jersey, addresses photo cathode electron projection lithography, an electron lithography technique that could be used to pattern semiconductors at the deep submicron level using the concept of magnetic compression. This CRADA supports research to verify the concept, by direct numerical simulations of the electron trajectories, and to design a system with the desirable magnetic and electric field qualities.

Work for Others

In Work for Others agreements, industry supports work performed at PPPL. This past year, Laboratory scientists helped Princeton Electronic Systems to develop and characterize detectors to be used in monitoring systems for nuclear nonproliferation. The Laboratory is presently in discussions with Asea Brown Boveri (ABB) for a Work for Others arrangement to support plasma arc research to improve the performance of ABB's electric arc furnace performance.

Personnel Exchanges and Technology Maturation Projects

The Laboratory also collaborates with industry through the Personnel Exchange program where researchers from industry assume a work assignment at the Laboratory or PPPL staff work in the industrial setting. The Laboratory also provides limited help to industry through the Technology Maturation Program, where PPPL staff members work on the development of a technology to help move it closer to commercial practicability. In the past, PPPL staff have collaborated with Asea Brown Boveri, AT&T Bell Laboratories, and the David Sarnoff Research Laboratory on projects of mutual interest.

Licensing Agreements

Licensing agreements of PPPL technology is through Princeton University's Technology Transfer Office. Laboratory licensing agreements include those for XMACRO (software developed at PPPL for the transmission of documents in which many equations are embedded) and for the Chemical Waste Management and Report Generating System software.

Patent Awareness Program

The Laboratory supports and encourages innovation through its Patent Awareness Program. Through this program, PPPL staff receive monetary compensation when a disclosure is filed and additional compensation when a patent is issued. In fiscal year 1995, three patents were issued, one patent was applied for, and sixteen invention disclosures were filed.

Graduate Education

The first-year graduate students in the Program in Plasma Physics.

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 advanced degrees through the Department of Astrophysical Sciences.

With more than 174 graduates since 1959, the Program in Plasma Physics has provided many of today's leaders in the field of plasma physics. At the beginning of fiscal year 1995, there were forty graduate students in residence in the Program in Plasma Physics holding between them one Department of Energy Computational Fellowship, two Department of Energy Magnetic Fusion Science Fellowships, one Hertz Fellowship, two Princeton/Hertz Fellowships, three National Science Foundation Fellowships, one Office of Naval Research Fellowship, and one Natural Sciences and Engineering Research Council (Canadian) Fellowship.

Five new students were admitted to the Program in fiscal year 1995, two from the Russian Federation. Nine students graduated. All graduating students found positions. Three graduates received postdoctoral positions in plasma physics: one at the Los Alamos National Laboratory, one at the University of British Columbia, Canada, and one at the Naval Research Laboratory. Two graduates took positions in the private sector: one at MKS, Inc., in Andover, Massachusetts, and the other at The Lawrenceville School in New Jersey. Three graduating students won prestigious postdoctoral research fellowships from the Department of Energy: two are at the Princeton Plasma Physics Laboratory and one is at the University of California, Irvine. One graduate won a postdoctoral fellowship to Centre d'etude de Cadarache in France.

Students Admitted to the Plasma Physics Program in Fiscal Year 1995.

Student	Undergraduate Institution	Major Field
Joshua Breslau	Massachusetts Institute of Technology	Physics
Troy Carter	North Carolina State University	Physics and Nuclear Eng.
Andrei Litvak	University of Nizhniy, Russia	Physics
Alexander Schekochihin	Moscow Institute of Physics and Technology	Applied Math
Sean Strasburg	Benedictine College, Kansas	Physics and Math

Graduate students in the Program in Plasma Physics, Department of Astrophysical Sciences, Princeton University, in fiscal year 1995.

Recipients of Doctoral Degrees in Fiscal Year 1995.

Julian C. Cummings

Thesis: Gyrokinetic Simulation of Finite-beta and Self-generated Sheared-flow Effects on Pressure-gradient-driven Instabilities
Advisor: Wei-li Lee
Employment: Los Alamos National Laboratory

Michael A. Beer

Thesis: Gyrofluid Models of Turbulent Transport in Tokamaks
Advisor: Gregory W. Hammett
Employment: Princeton Plasma Physics Laboratory

Gordon S. Chiu

Thesis: Studies of Magnetized Plasmas Interacting with Neutral Gas
Advisor: Samuel A. Cohen
Employment: University of British Columbia, Canada

David A. Moore

Thesis: Pressure Measurement using a Pure Electron Plasma
Advisor: Ronald C. Davidson
Employment: MKS, Inc., Andover, MA

Sherrie A. Preische

Thesis: Radially Localized Measurements of Superthermal Electrons using Oblique ECE
Advisor: Philip Efthimion and Stanley Kaye
Employment: Centre d’etude de Cadarache, France

Theodore G. Jones

Thesis: Low-aspect-ratio Tokamak Start-up and Operational Current Limits in CDX-U
Advisor: Masayuki Ono
Employment: Naval Research Laboratory

Qian Qian

Thesis: Nonlinear Dynamics of an Intense Nonneutral Ion Beam Propagating Through an Alternating-gradient Focussing Lattice
Advisor: Ronald C. Davidson
Employment: Princeton Plasma Physics Laboratory

Keith E. Voss

Thesis: Pulse-heated Vertical Electron Cyclotron Emission Diagnostic
Advisor: Robert Kaita
Employment: The Lawrenceville School, New Jersey

Genze Hu

Thesis: Statistical Theory of Resistive Drift-wave Turbulence and Transport
Advisor: John A. Krommes
Employment: University of California, Irvine

Science Education

PPPL women researchers discussed careers in science with participants of "Women and Girls in Math and Science Day" when they visited the Laboratory.

The Princeton Plasma Physics Laboratory's (PPPL) Science Education Program enjoyed a great deal of success during fiscal year 1995. The National Teacher Enhancement Project was launched, as were several new programs offering research opportunities to students from underrepresented minority groups. The Science Education Program's existing programs continued to grow. The five-year-old Trenton Partnership received the National Center for Public Productivity's New Jersey Exemplary State and Local Award in recognition of its significant innovations and achievements.

New Programs in 1995

The U.S. Department of Energy's Office of Fusion Energy provided funding for the Research Opportunity Program for Underrepresented Groups which includes students and faculty from Historically Black Colleges and Universities, other minority-serving institutions, and women's colleges. The program was designed to give outstanding undergraduates from these institutions an opportunity to spend a summer participating in projects at the forefront of research and development in plasma physics and controlled fusion. The goals of the program are to stimulate the interest of members of underrepresented groups in science and engineering, and to expose those students to state-of-the-art research equipment and facilities in an environment that is both challenging and supportive.

During the summer of 1995, ten students participating in this program and three students participating in the Department of Energy's Historically Black Colleges and Universities Visiting Faculty and Student Research Program spent the summer at PPPL. The students spent two weeks working in small groups with scientists in the graduate laboratory to conduct experiments that covered the basic elements of plasma physics and provided an introduction to fusion technology. The students were paired with a mentor and spent the next eight weeks conducting research in the mentor's field. For many students this program provided them with an opportunity to be exposed to material and equipment not available at their home institutions.


Students from underrepresented minority groups took part in PPPL research activities under programs sponsored by the U.S. Department of Energy.

Students and Faculty who Participated in Research Activities at PPPL in Fiscal Year 1995 under the Research Opportunity Programs for Underrepresented Groups and the Historically Black Colleges and Universities Visiting Faculty and Student Research Program.

Research Opportunity Programs for Underrepresented Groups

Name	School	Project	Mentor
J. Edson	Hampton University	Development of a Fusion Education Web Site	R. Holt
M. Gaillard	South Carolina State	Analysis of Groundwater	S. Larson
H. Horton	Southern University	Groundwater Detection and Analysis	S. Larson
F. Hunte	Florida A&M	Study of Recycling of Tritium in TFTR Supershots	R. Budny
C. Roberts	Elizabeth City State	Magnetic Reconnection Experiment	M. Yamada
R. Powell	Florida A&M	Ground Fault Detection for TPX	C. Neumeyer
A. Sen	Mt. Holyoke College	Magnetohydrodynamic Stability	J. Manickam
S. Upshaw	Hampton University	Code Development of Factors Affecting the Interchange Stability for Tokamaks	M. Chance
J. Vela	Florida A&M	Magnetic Reconnection Experiment	H. Ji
V. Walker	Southern University	Magnetic Reconnection Experiment	M. Yamada

Historically Black Colleges and Universities Visiting Faculty and Student Research Program

Name	School	Project	Mentor
U. Farrukh (Dr.)	Hampton University	Lower-Hybrid Current Drive	D. Ignat
T. Huang (Dr.)	Prairie View A&M	Nonneutral Plasma (Theory and Simulation)	H. Okuda
I. Smith	Prairie View A&M	Electrostatic Atomization	H. Okuda
K. Storr	Prairie View A&M	Electrostatic Sprays	H. Okuda
X. Yu	Prairie View A&M	Analysis of Charged Octoil Sprays	H. Okuda

New Jersey middle school science and mathematics teachers learned about the scientific research process through the National Teacher Enhancement Project.

Teacher Enhancement

The summer of 1995 also marked the beginning of the National Teacher Enhancement Project at PPPL. This U.S. Department of Energy and National Science Foundation-sponsored project is taking place at eight other national laboratories around the country. Thirty middle school science and mathematics teachers from New Jersey spent three weeks at the Laboratory during the summer receiving an introduction to the scientific research process, to the research being conducted at the Princeton Plasma Physics Laboratory, and to teacher leadership issues, such as alternative assessment and organizational change. The teachers will return to the Laboratory for three weeks during each of the next two summers and for four days of school year follow-up during each of the next three school years to continue working in these areas.

Internet Training

Almost ninety teachers visited the Laboratory to receive basic Internet training during fiscal year 1995 as a part of the Science Education Program's involvement in the National Science Foundation's Networking Infrastructure for Education Project undertaken with the Center for Improving Science and Engineering Education at Stevens Institute of Technology. During the first of this three-year project, Princeton Plasma Physics Laboratory personnel worked with the Stevens Institute, New Jersey's Statewide Systemic Initiative, the New Jersey Intercampus Network, Bellcore, and the New Jersey Department of Education to provide teachers throughout the state with eight hours of basic Internet training, including the use of e-mail, Telnet, Gopher, Lynx, and Mosaic. The training also included a visit from the instructor to each teacher's school to answer his or her specific connectivity questions. Also during 1995, Science Education and Computer Systems Division staff began working with Research Physicists at the Laboratory to develop physical science curriculum modules that utilize PPPL experimental data to illustrate basic concepts, such as heat, electricity and magnetism, spectroscopy, and radiation safety. The development of these modules will continue in collaboration with middle school teachers throughout 1996.

Long-Term Programs for Teachers and Students

Nineteen ninety-five was also an exciting year for many of PPPL's existing Science Education programs. The PPPL-Trenton Partnership, in its fifth year, continued to provide assistance to the Trenton Public School District in implementing hands-on science activities in the elementary school designed around the district's newly adopted science curriculum. Scientists and engineers from the Laboratory served as Science Advisors to all of the schools in the Trenton Public School District. The Partnership was recognized by the National Center for Public Productivity when it received the New Jersey Exemplary State and Local Award in recognition of its significant innovations and achievements. The Partnership was recognized as having produced exceptional cost savings, measurable increases in quality and productivity, and improvements in the quality and effectiveness of government services.

Fellowship Program

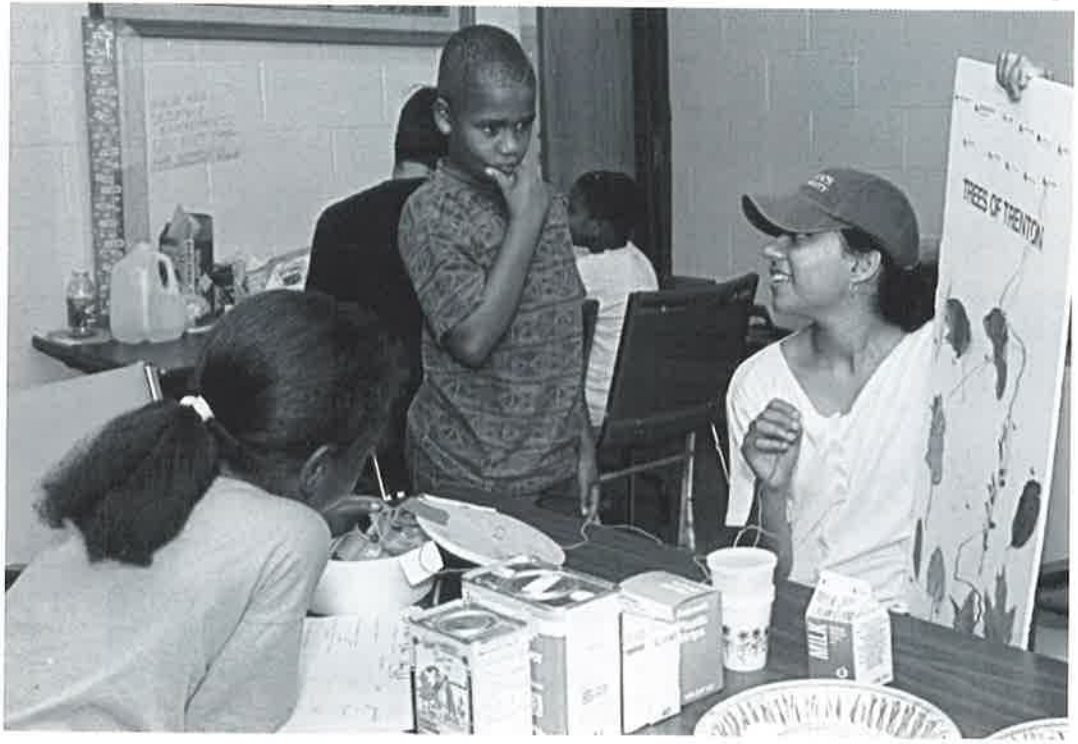
The Office of Fusion Energy's National Undergraduate Fellowship Program in Plasma Physics and Fusion Engineering and the Laboratory's popular summer research programs for high school students and teachers and local undergraduates enjoyed another successful year. These programs, in combination with the new Research Opportunity Program for Students from Underrepresented Groups, provided summer research opportunities for over fifty students and teachers at the Princeton Plasma Physics Laboratory.

Under the Princeton University Student Volunteers Program and PPPL's Summer Internships in Trenton Program, Princeton University students served as mentors and tutors to Trenton inner-city youth.

Symposium

World-renowned professors and researchers in the field of fractals returned to Princeton to present "Fractals, Chaos, and Dynamics III." This week-long symposium was attended by forty high school mathematics teachers from across the United States and built on material covered in the first two symposia offered during the summers of 1993 and 1994. Several of the fractals presenters conducted a three-day mathematics workshop for twenty middle-school teachers in New Jersey.

The Science Education Program welcomed hundreds of other visitors of all ages to the Laboratory for a variety of programs aimed at science literacy and community outreach. These programs included the nine-week Science on Saturday lecture series, New Jersey-Pennsylvania regional Science Bowl competition, and the Women and Girls in Math and Science Day Program.



Young persons from inner-city Trenton learn about the "Trees of Trenton" from a student volunteer.

Laboratory Awards

New Jersey Exemplary State and Local Award

National Center for Public Productivity (at Rutgers University)

In recognition of the "PPPL/Trenton Science Education Partnership for producing exceptional cost savings, measurable increases in quality and productivity, and improvements in the quality and effectiveness of government services."

Corporate Award of Excellence

Mercer Chapter of Professional Secretaries International (PSI)

In recognition of PPPL's continued support and encouragement of office professionals.

United Way Silver Award

United Way

For PPPL's contributions to the Greater Mercer United Way 1994/1995 Campaign.

Individual Honors

Bobbie Forcier
Certificate of Accomplishment
Princeton University Women's Organization

Harold Furth
1995 Distinguished Career Award
Fusion Power Associates

Richard Hawryluk
Distinguished Associate Award
U.S. Department of Energy

Suzanne Homer
Certificate of Accomplishment
Princeton University Women's Organization

Jerry Levine
1995 Energy Research NCO Quality Award for Preparation of Quality NEPA Documents
U.S. Department of Energy

Donald Monticello
Fellow
American Physical Society
Division of Computational Physics


Harold Furth

Jack Mount, Jr.
PPPL Area Safety Coordinator of the Year
Princeton Plasma Physics Laboratory

Masayuki Ono
PPPL Distinguished Research Fellow
Princeton Plasma Physics Laboratory

Phyllis Schwarz
Certificate of Accomplishment
Princeton University Women's Organization

Lynne Yager
Certificate of Accomplishment
Princeton University Women's Organization

Michael Zarnstorff
Fellow
American Physical Society
Division of Plasma Physics

PPPL Distinguished Research Fellow
Princeton Plasma Physics Laboratory


Michael Zarnstorff


Richard Hawryluk


Masayuki Ono


Donald Monticello


Jack Mount, Jr.


Jerry Levine (left) with PPPL Director Ronald Davidson.


Phyllis Schwarz, Suzanne Homer, and Bobbie Forcier.

The Year in Pictures

The TFTR generated 10.7 million watts of fusion power on November 2, 1994 — the highest ever achieved by magnetic confinement. Here, Richard Hawryluk, TFTR Project Head, prepares to cut cake at the Lab-wide celebration held on November 28 to commemorate the milestone achievement.

New Jersey Governor Christine Todd Whitman, shown shaking hands with PPPL employees, visited the Lab in February, 1995. During her short visit, Whitman met and talked with employees, toured the TFTR, and talked with reporters.

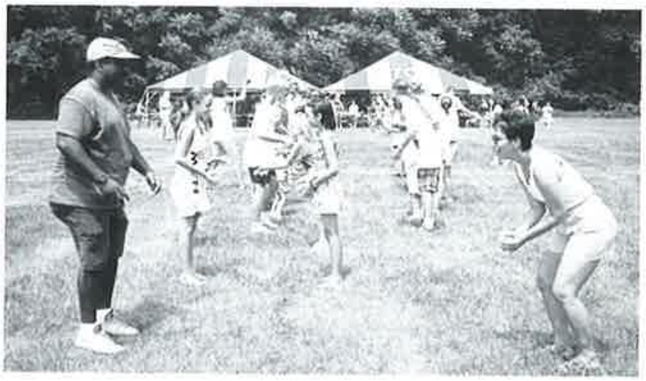
A "Letter of Intent for Research Cooperation" was signed between PPPL and the Korea Basic Science Institute in June, 1995. Laboratory Director Ronald C. Davidson (front right) shakes hands with Korea Basic Science Institute President Duk-In Choi after the signing. Behind Davidson is Milton Johnson, Manager of the U.S. Department of Energy's Princeton Area Office and behind Choi is Jong Chul Kyung, Director-General of Korea's Ministry of Science and Technology.

N. Anne Davies, Associate Director for Fusion Energy at the U.S. Department of Energy's Office of Energy Research, visited the Laboratory in April, 1995. During her visit she discussed the status and plans of the Laboratory's various projects, lunched with a group of employees, visited Princeton University and talked with University officials, and toured the Laboratory. Here, Davies is shown with Principal Research Physicist Samuel Cohen discussing the Princeton Divertor Simulator.

Daughters, granddaughters, friends, and relatives of PPPL employees visited the Laboratory in April, 1995, for the second "Take Our Daughters to Work Day." Creatively solving problems are, clockwise from left, Nadia Hasan, Amaryllis Gonzales, Stephanie Wise, Monica Zimmer, Science Education employee Helene Tinkel, and Becca Holcombe.

At the thirteenth annual Patent Awareness Program Dinner in May, 1995, forty-six PPPL inventors were recognized and honored for their inventiveness. Among those who attended the ceremony are, front row left to right, Jan Wioncek, Holt Murray, Mounir Awad, Martha Redi, Bill Persely, Ramon Pressburger, and Ronald Hatcher. In the back row are, left to right, John Desandro, Roland Snead, Rich Rossmassler, Nathaniel Fisch, Jean Rax, Shoichi Yoshikawa, Charles Skinner, Roscoe White, D. Kingston Owens, Geoff Gettelfinger, Szymon Suckewer, Alan Ramsey, and Sylvester Vinson.

During the summer, the Laboratory hosted a "Free Lunch" for staff. Employee volunteers manned the grills and distributed food. Clockwise from left are: Rod Templon, Lew Meixler, Margaret Young, Angelo Candelori, John Bavlish, and Steve Iverson.



As temperatures soared to a record-breaking 101 °F on July 15, nearly 350 employees, retirees, family members, and friends braved the heat and humidity and gathered for a barbecue, music, games, pony rides, and a host of ad libbed activities. Here, contestants prepare for the water balloon toss.

PPPL Advisory Council

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

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

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[1] Lawrence Livermore National Laboratory

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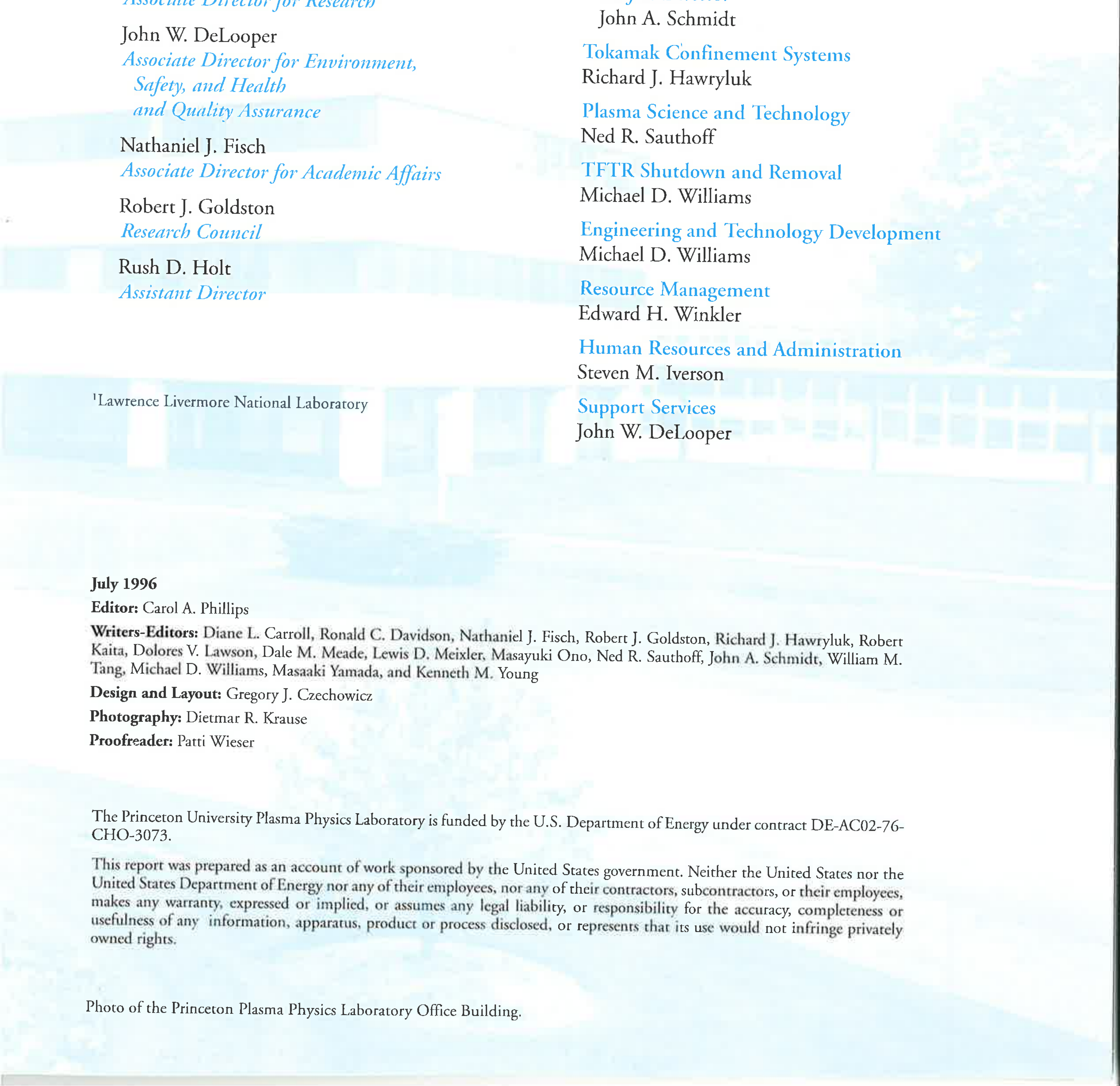

Photo of the Princeton Plasma Physics Laboratory Office Building.

The Princeton Plasma Physics Laboratory is operated by Princeton University under contract with the U.S. Department of Energy. For additional information contact: Information Services, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08543. Phone: (609) 243-2750; Fax: (609) 243-2751; e-mail: pppl_info@pppl.gov; Internet Address: http://www.pppl.gov/ .