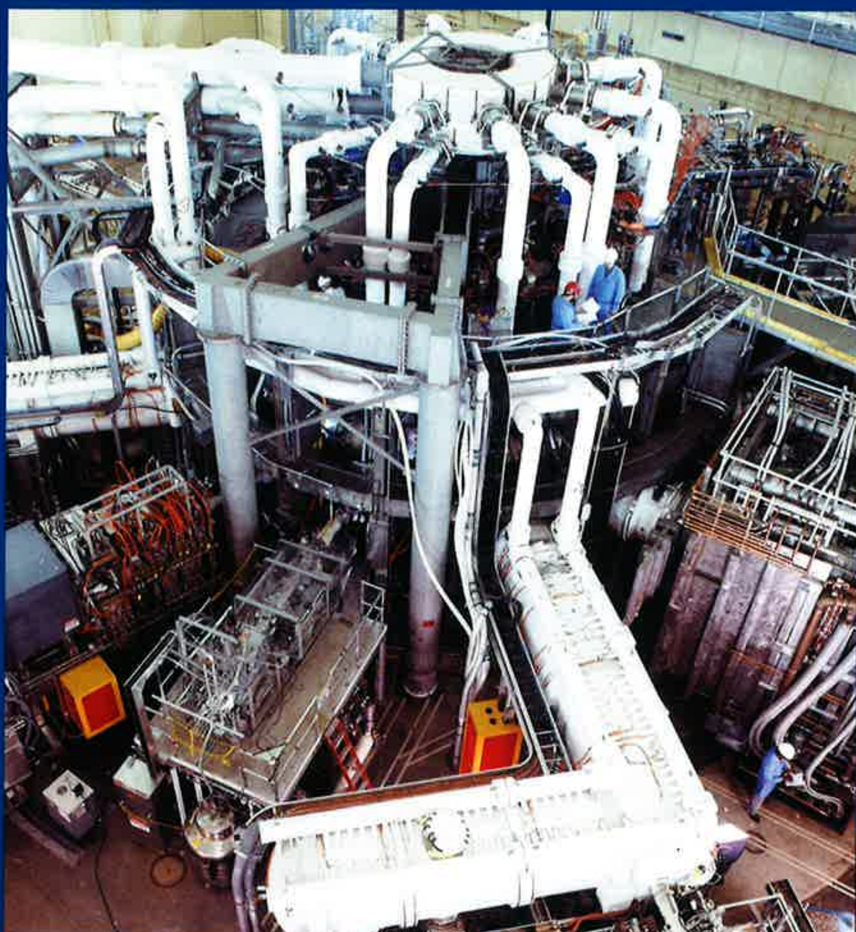
Princeton University Plasma Physics Laboratory



1994 Highlights

About PPPL

Established in 1951, the Princeton University 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, and the site of the proposed Tokamak Physics Experiment.

PPPL is managed by Princeton University under contract with the U.S. Department of Energy. The annual budget is more than $100 million. Full-time employees number about 745 with an additional 150 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

In fiscal year 1994, scientists at the Princeton University Plasma Physics Laboratory conducted experiments on the Tokamak Fusion Test Reactor (TFTR), top, using, for the first time, a 50-50 deuterium-tritium fuel; the mixture needed for a commercial fusion power plant. In the small photo at the bottom, scientists are shown in the TFTR Control Room on December 9, 1993, as they waited for data from the initial experiments to appear on computer monitors. These first experiments produced 3.0 to 6.0 million watts of fusion power. In subsequent experiments during the year, TFTR produced 9.3 million watts of fusion power. (Group photo courtesy of the *Trenton Times.*)

This publication highlights activities at the Princeton University Plasma Physics Laboratory for fiscal year 1994 — 1 October 1993 through 30 September 1994. 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 1994 Annual Report.

Aerial photo of the Princeton University Plasma Physics Laboratory.

Mission Statement

The mission of the Princeton University 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 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 in plasma science and related technologies.

Director's Statement

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

Ronald C. Davidson
Director

Princeton University

Plasma Physics Laboratory
James Forrestal Campus
P.O. Box 451, Princeton, New Jersey 08543

May 1995

The historic deuterium-tritium experiments on TFTR, which began in December 1993, are marking one of the most exciting periods in the U.S. magnetic fusion program. The major advances in a wide range of program areas would have been impossible without the hard work and dedication of the Laboratory staff.

The enclosed *1994 Highlights Report* presents a summary of PPPL's significant research accomplishments for fiscal year 1994. In addition to the major fusion projects, the report describes the progress that has been made in plasma theory, small-scale experiments, and in the efforts to transfer technology developed at PPPL to applications in other fields.

Please accept the *1994 PPPL Highlights Report* with my sincere thanks for your superb efforts in making this one of the most successful years for the Princeton Plasma Physics Laboratory.

Sincerely,

Ron Davidson

Ronald C. Davidson
Director

RCD/ksf
Enclosure

Advantages of Fusion Energy

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

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From the Director

The goal of the Princeton University Plasma Physics Laboratory (PPPL) is to be the preeminent plasma physics 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.

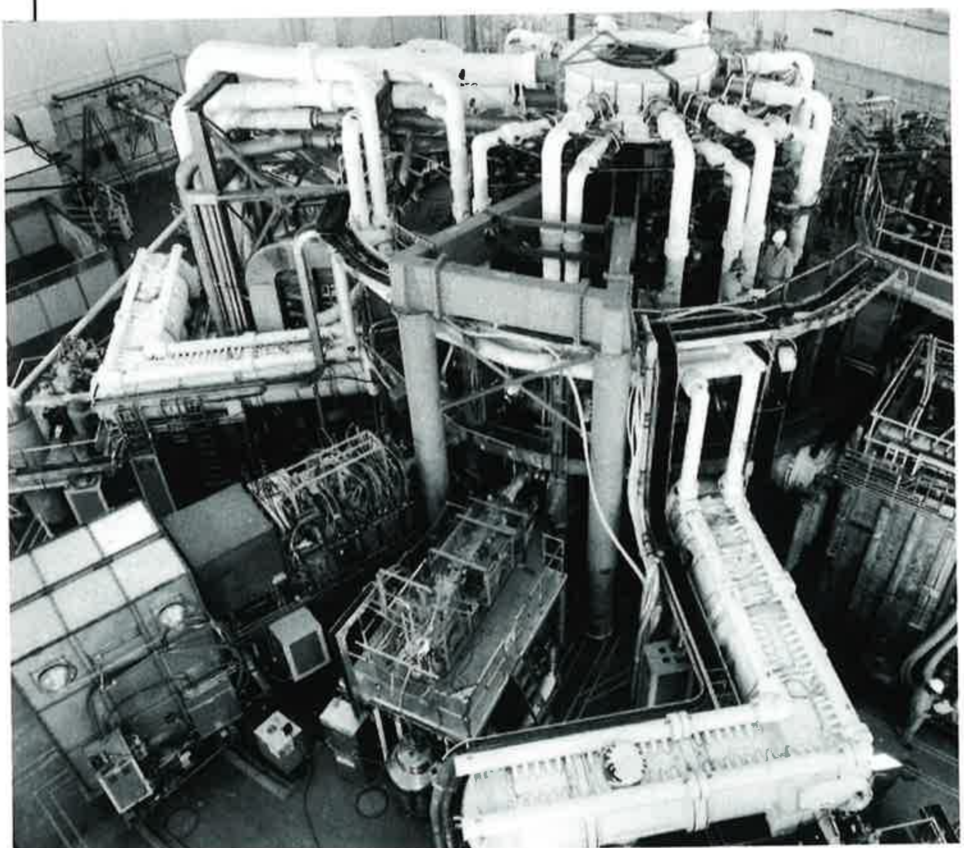
Operated by Princeton University, the Princeton Plasma Physics Laboratory is the only single-program laboratory funded by the U.S. Department of Energy for the development of magnetic confinement fusion as an abundant and environmentally attractive energy source for the future and for research in the 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 advanced, superconducting tokamak, the Tokamak Physics Experiment (TPX), to be operated as a national facility, 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 1994. The activities covered in this report include advances on the large projects, such as the historic deuterium-tritium experiments on the TFTR and the engineering design developments in the Tokamak Physics Experiment and International Thermonuclear Experimental Reactor projects, 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

Tokamak Fusion Test Reactor



Tokamak Fusion Test Reactor

The Tokamak Fusion Test Reactor (TFTR) produced a world record 9.3 million watts (MW) of controlled fusion power in fiscal year 1994. This is nearly 90 million times the amount possible in 1974 when the TFTR was proposed and about five times that produced in 1991 by the larger Joint European Torus. These experiments used, for the first time ever, a fuel mixture composed of equal amounts of deuterium and tritium (D-T) — the fuel mixture required for a commercial fusion reactor.

Record fusion power production in TFTR came from "supershot" plasmas. Supershots are plasma discharges produced by intensive neutral-beam heating after the walls of the confinement vessel have been conditioned to remove absorbed deuterium and to inhibit the influx of carbon impurities. These conditions provide a plasma that is much denser at its center than at its edge.

Tritium fueling and heating was accomplished by operating six of TFTR's twelve neutral-beam injectors with pure tritium. The neutral-beam injectors provided up to 33.7 MW of heating power in the D-T experiments.

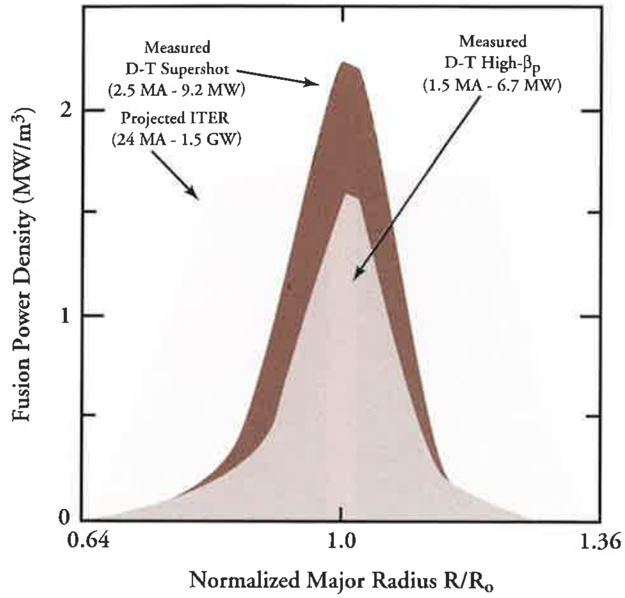
To date, the highest performance discharges, i.e., high fusion power, have been in the supershot regime. These discharges are characterized by very high temperatures and enhancements in the confinement time. Another approach to achieve high performance discharges is to modify the current profile in the plasma by adjusting the current at the plasma's edge. This technique, which has been studied in collaboration with Columbia University, Oak Ridge National Laboratory, and the Massachusetts Institute of Technology, has also resulted in a very high fusion power but at a lower value of plasma current. High fusion power performance at lower values of plasma current and magnetic field can result in a more cost effective tokamak reactor.

In TFTR, plasmas produced by either approach have fusion power densities in their core comparable to that of the proposed International Thermonuclear Experimental Reactor (ITER). Thus, these experiments are providing experimental information about the physics of the plasma core of a fusion reactor, enabling scientists to examine directly many of the critical physics issues for ITER.

Two-hundred and fifty-three D-T experiments were successfully and safely performed this past year. Important information that has been gained so far includes:

- Stored energy and energy confinement time for a deuterium-tritium plasma is greater than in a deuterium-only plasma.
- Heat confinement of the plasma ions is better for a deuterium-tritium plasma than in a deuterium-only plasma.

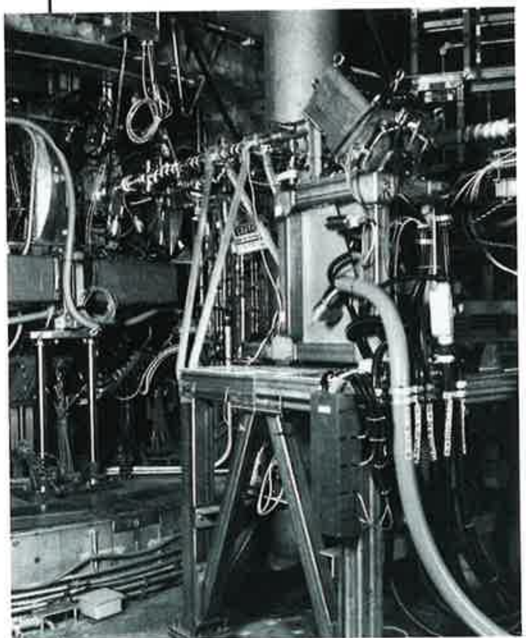
(continued)



Measured deuterium-tritium (D-T) fusion power density profiles for the TFTR supershot and high-β_p plasma discharges given in the Table (below), and a projected profile for the International Thermonuclear Experimental Reactor (ITER). The D-T fusion power density in TFTR is based on neutron emission profile measurements with an uncertainty of ±15% in the plasma core. This comparison shows that the fusion power density in the core of TFTR plasmas is comparable to that projected for ITER.

Plasma Parameter	D-T Supershot	D-T High-β_p
Plasma Current (MA)	2.5	1.5
Neutral-Beam Power (MW)	33.7	30.9
Electron Density	8.5×10^{19} m^{-3}	8.0×10^{19} m^{-3}
Central Hydrogenic Density	6.3×10^{19} m^{-3}	5.8×10^{19} m^{-3}
Electron Temperature (keV)	11.5	10.0
Ion Temperature (keV)	44.0	30.0
Confinement Time (sec)	0.24	0.21
Confinement Time Enhancement	2.4	3.2
P_{fusion} (MW)	9.3	6.7
Triple Product	5.5×10^{20} m^{-3} · sec · keV	3.7×10^{20} m^{-3} · sec · keV

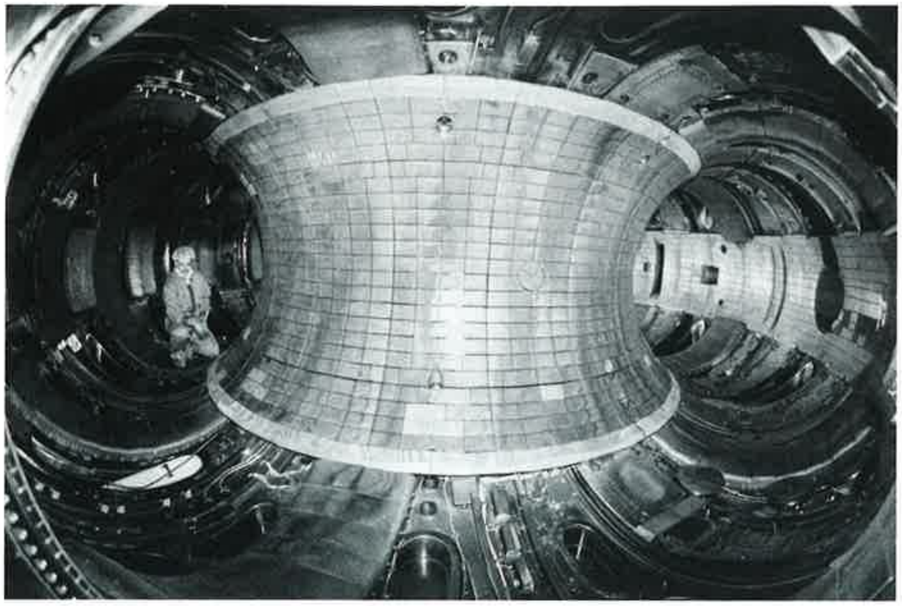
High performance deuterium-tritium (D-T) plasmas can be created with intense neutral-beam heating (supershots) and modification of the current profile (high-β_p).



The first-ever measurements of confined alpha particles were made with the Alpha Charge-Exchange Diagnostic shown above.

TFTR (continued)

- Ion-cyclotron range-of-frequencies heating of a D-T plasma has been demonstrated. This is important for the design for ITER radio-frequency heating systems employing the ion-cyclotron range of frequencies.
- Measurements of fusion power are in good agreement with calculations based on the measured plasma parameters.
- The first-ever measurements of confined alphas in the plasma core show that the alpha particles are well confined in the core. These measurements were made in collaboration with the University of Wisconsin, General Atomics, and A.F. Ioffe Physical-Technical Institute (Russian Federation).
- The first-ever measurements of alpha ash from D-T fusion reactions were made. They indicate that the alpha ash transport in the plasma core will not be a fundamental limiting factor for alpha exhaust in a reactor with supershot-like transports.
- Measurements of the flux of alpha particles escaping to the bottom of the vessel are in good agreement with calculations for normal plasma discharges. However, very large and rapid increases in the flux of alpha particles are observed in discharges which disrupt (undergo a sudden termination due to a plasma instability). These are important considerations for the design of vacuum vessel and divertor components for the ITER.
- Fractional loss of alpha particles does not increase with fusion power. This indicates that alpha particles do not adversely affect plasma stability.
- Wall conditioning using lithium pellets improves the confinement in supershot plasmas.
- Operational experience in the safe handling and processing of tritium has been documented.



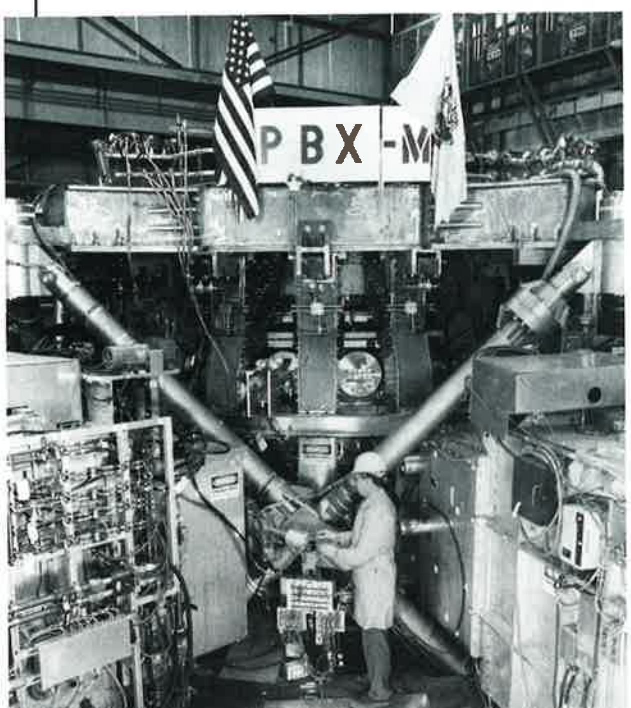
Interior view of the TFTR vacuum vessel. At the center, on the inner wall of the vessel, is the bumper limiter composed of graphite and carbon-fiber-composite tiles. Graphite tiles, which protect the vessel from neutral beams, can be seen to the right along the middle of the outer wall of the chamber. Arrays of carbon-fiber-composite tiles are also visible at the top and bottom of the vessel. Ion-cyclotron radio-frequency launchers are seen at the left of the vacuum vessel near the shoulders of the technician.

Fiscal year 1994 has been a very exciting year for TFTR. Realization of the mission goals first defined for TFTR in 1976 was achieved. The first-ever series of comprehensive experiments to study deuterium-tritium plasmas were conducted. Record amounts of fusion power were produced and the first glimpses of alpha heating were seen. Long-standing theoretical predictions were confirmed.

Experiments during fiscal year 1995 will focus on studying alpha-particle physics, confinement in a D-T plasma, and ion-cyclotron range-of-frequencies heating of a D-T plasma. Further increase of fusion power production will be possible by operating at higher values of toroidal-field and neutral-beam power. During the past year, the scientific and technical capability for forming deuterium-tritium plasmas has been demonstrated. In fiscal year 1995, the scientific potential of operation with deuterium and tritium will be realized.

The TFTR is scheduled to cease operation at the end of September, 1995, and Shutdown and Removal Operations will begin.

Princeton Beta Experiment-Modification

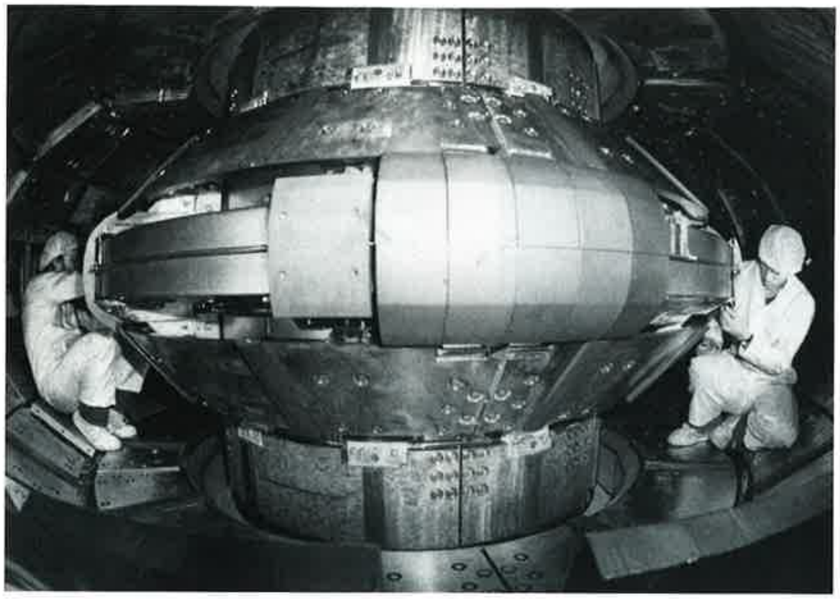


Princeton Beta Experiment-Modification

The goal of the Princeton Beta Experiment-Modification (PBX-M) Project is to improve the attractiveness of the tokamak as a fusion reactor concept. Its approach is to show the practicality of controlling the plasma current and pressure distribution to achieve stable advanced operating regimes and to avoid plasma disruptions. The PBX-M tokamak is particularly well-suited for this task because it can explore concepts which are prototypes for the Tokamak Physics Experiment and other future devices.

The experiments on PBX-M during the past year have demonstrated the modification of the plasma current profile with lower-hybrid waves. These radio-frequency waves transfer energy to electrons at very specific locations inside the plasma, and they are thus able to drive local currents which alter the overall current distribution. For the first time, it was shown that such changes could be maintained as the plasma discharges were heated by neutral-beam injection to increase the plasma pressure or "beta." This is a critical step toward obtaining advanced tokamak plasma regimes.

New plasma diagnostics were also developed to assess the effectiveness of current drive with lower-hybrid waves. Very energetic electrons are created when the lower-hybrid power is absorbed by the plasma, and they emit hard X-rays. Information about the power deposition, the confinement of these electrons, and their diffusion across the plasma can be determined by measuring the hard X-rays. A special "pinhole" camera with a lead aperture was installed on PBX-M to obtain such data. The PBX-M was the first tokamak to use such an instrument, and detailed, two-dimensional pictures of the hard X-ray distributions can be generated after every plasma discharge.



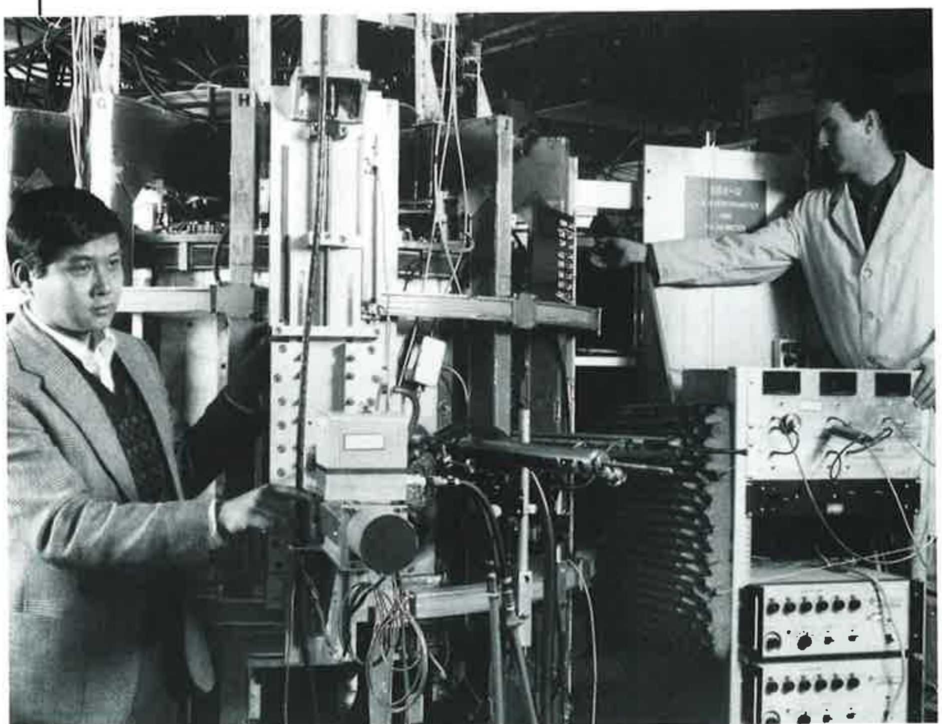
Interior view of the Princeton Beta Experiment-Modification vaccum vessel. The large horizontal ring in the center of the picture is the "pusher" magnetic field coil for controlling the plasma shape. The plates above and below this coil and in the foreground are part of the metal "shell" which surrounds the plasma and reduces instabilities.

Ion-Bernstein radio-frequency wave heating has been added to neutral-beam heating to create plasma discharges with a high central density. The plasmas have good confinement like the so-called H-mode (for high-confinement mode), where there is a "barrier" to energy loss at the edge. With ion-Bernstein wave heating, however, this barrier is closer to the center of the plasma. This new operating regime, first discovered on PBX-M, has thus been labeled the CH-mode (for core H-mode). As a means of improving the performance of the hot plasma core, it could be an attractive possibility for future fusion reactors.

The PBX-M plasma discharge is surrounded by an aluminum and stainless steel "shell," and the currents that are induced in it generate a force that can reduce plasma instabilities. The focus of the next experiments will be to study further the effect of the shell on plasma stability. Theoretical predictions indicate that the presence of a particular kind of instability, called the "resistive wall mode," depends on the gap between the plasma and the shell. The PBX-M tokamak has the unique capability of tailoring the shape of the plasma to make it fit closely to the shell and then varying the separation distance. These experiments are especially interesting for the Tokamak Physics Experiment since its design also includes a conducting shell.

Imaging tube for the hard X-ray "pinhole" camera being inserted into shielding assembly. The lens and optical conduit for coupling the tube output to the image processing computer can be seen on the lower left side of the picture.

Current Drive Experiment-Upgrade



Current Drive Experiment-Upgrade

A unique feature of the Laboratory's Current Drive Experiment-Upgrade (CDX-U) tokamak is its low aspect-ratio (major plasma radius divided by minor plasma radius). For CDX-U, this can be as low as 1.4 compared to a typical tokamak with a value of about 3. Low-aspect-ratio tokamaks, or LARTs, such as CDX-U promise to have several advantageous features, a major one being a high plasma pressure stability limit which is important for the development of smaller and more economical tokamak fusion reactors. The unusual geometry of LARTs allows the study of an interesting new regime of tokamak physics caused by strong toroidicity.

Ohmic LART Operation

Early in fiscal year 1994, an ohmic transformer with the highest power capability of any LART to date was installed on CDX-U. With this transformer providing ohmic heating and current drive power, various outstanding issues related to ohmic LART operation are now being investigated for plasma currents of up to 60 kA.

Plasma Initiation in LARTs

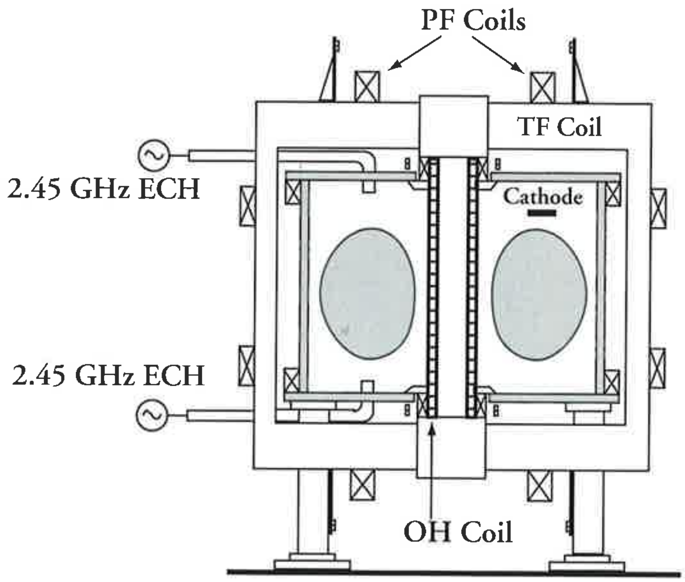
With the assistance of electron cyclotron resonance radio-frequency heating, plasma initiation has been possible with almost arbitrarily low ohmic transformer power. This is important in the LART geometry where the transformer size and power are limited. Low-aspect-ratio tokamak plasmas also have been initiated with a wide range of toroidal-field strength, with the toroidal-field coil current being as low as 70 kA-turns. This demonstration of starting up tokamak plasmas with arbitrarily low toroidal-field coil currents is an important step toward future high plasma pressure experiments in LARTs and ultra-low-aspect-ratio tokamaks (ULARTs).

Plasma Current Limits in LARTs

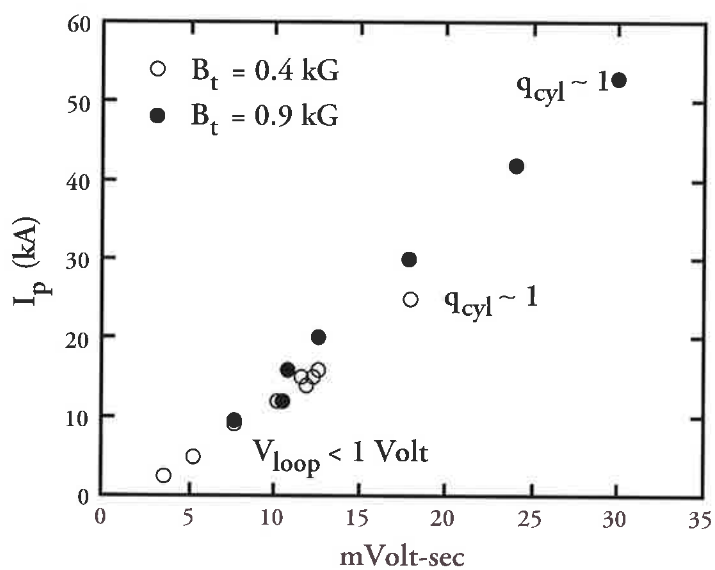
Since tokamak performance depends strongly on the amount of plasma current that can be supported, it is important to explore the plasma current limit for LARTs. One measure of the current limit is the cylindrical safety factor q_{cyl} which is inversely proportional to magnetic field line pitch and plasma current. In CDX-U, q_{cyl} is lowered to a value of 1, which is the lowest thus far achieved in a LART. As the average magnetic field line pitch is increased, low mode-number, long wavelength MHD instabilities are observed. Preliminary estimates of plasma conditions show that the plasma is relatively hot and collisionless, with an electron temperature near 100 eV.

Medium-sized LART/ULART

To explore LART physics at higher performance levels than is possible in small-sized LART devices such as CDX-U, a conceptual design study for a new, medium-sized LART/ULART (major radius R = 80 cm, minor radius a = 55–65 cm, and plasma current I_p = 1 MA) named the National Spherical Tokamak Experiment (NSTX) has begun. This device aims to test the spherical tokamak concept as a basis for a volumetric neutron source and/or advanced fuel fusion reactor. Design and operational experience with the CDX-U tokamak (which is similar but smaller in size by a factor of 2.5) significantly benefits the NSTX design effort.

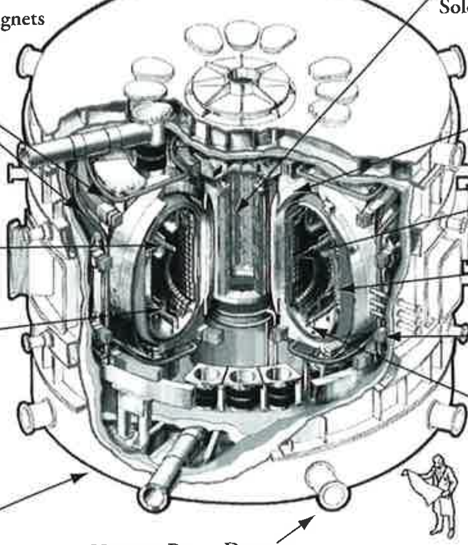


Schematic cross-sectional view of the Current Drive Experiment-Upgrade tokamak.



Ohmic heating efficiency in CDX-U plasma start-up. At the highest plasma current (I_p) for a given toroidal magnetic field (B_t), the cylindrical safety factor q_{cyl} has reached a value of 1, the lowest obtained in a low-aspect-ratio tokamak to date.

Tokamak Physics Experiment



Tokamak Physics Experiment

The Tokamak Physics Experiment (TPX) will play the important role in the U.S. fusion program of determining whether the tokamak approach can evolve smaller, less expensive, and more attractive fusion reactors than are presently forecast using "conventional" physics assumptions. The specific mission for TPX is "to develop the scientific basis for a compact and continuously operating tokamak fusion reactor."

The TPX is being designed to extend advanced tokamak operating modes with high beta, confinement, and bootstrap current fraction to the steady-state regime. While the TPX would be built primarily to explore advanced physics regimes in the steady-state, doing so will have the added benefit of expanding the tokamak technology base. Key technology information is expected to be gained in the use of superconducting magnets, in steady-state power handling in the divertors, in low-activation material usage to allow access to in-vessel components during early phases of operation, and in remote maintenance techniques.

The TPX Project is a focused, national effort involving the coordinated resources of a large part of the United States Department of Energy's (DOE) fusion program. Although the Princeton University Plasma Physics Laboratory (PPPL) is responsible for the Project, the Project includes, as participants, many of the U.S. plasma physics research laboratories, universities, and industrial firms.

The TPX will be operated as a national research facility. It will be sited at PPPL in the Test Cell now occupied by the Tokamak Fusion Test Reactor (TFTR). This will allow the use of existing TFTR hardware such as power supplies, neutral beams, radio-frequency heating systems, diagnostics, and water cooling capabilities.

Contracts

During the early part of 1993, an Industrial Involvement Plan for the TPX Project was developed. It allows for industrial involvement in the Project through industrial contracts for the design and fabrication of the Magnets, the Vacuum Vessel, the Plasma Facing Components, the Cryostat, and two management support contracts for Systems Integration Support and Tokamak Construction Management.

Contracts for the Vacuum Vessel and Plasma Facing Components for TPX were awarded in June 1994 to the Ebasco Division of Raytheon Engineers and Constructors and General Atomics, respectively. These contracts totaled $34.3 million. Mc-

Donnell-Douglas Corporation and General Atomics are lower tier contractors as part of the Raytheon Team, and McDonnell-Douglas Corporation, the Rocketdyne Division of Rockwell International, and the Ebasco Division of Raytheon Engineers and Constructors, are lower tier contractors as part of the General Atomics' Team.

The first phase (preliminary design) of the Toroidal Field and Poloidal Field Magnet design was awarded in July 1994 to Babcock and Wilcox and Westinghouse, respectively. These contracts totaled $7.25 million. General Atomics is the lower tier contractor to Babcock and Wilcox, and Northrop Grumman Aerospace & Electronics and Everson Electric Company are lower tier contractors to Westinghouse.

Proposals are in the evaluation phase for the System Integration Support and Tokamak Construction Management contracts. Award of these contracts is expected early in 1995. A contract for the design and fabrication of the cryostat is expected to be awarded in fiscal year 1996.

Major Parameters of the Tokamak Physics Experiment

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 and Current Drive:		
Neutral Beam	8 MW	24 MW
Ion Cyclotron	8 MW	18 MW
Lower Hybrid	1.5 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.

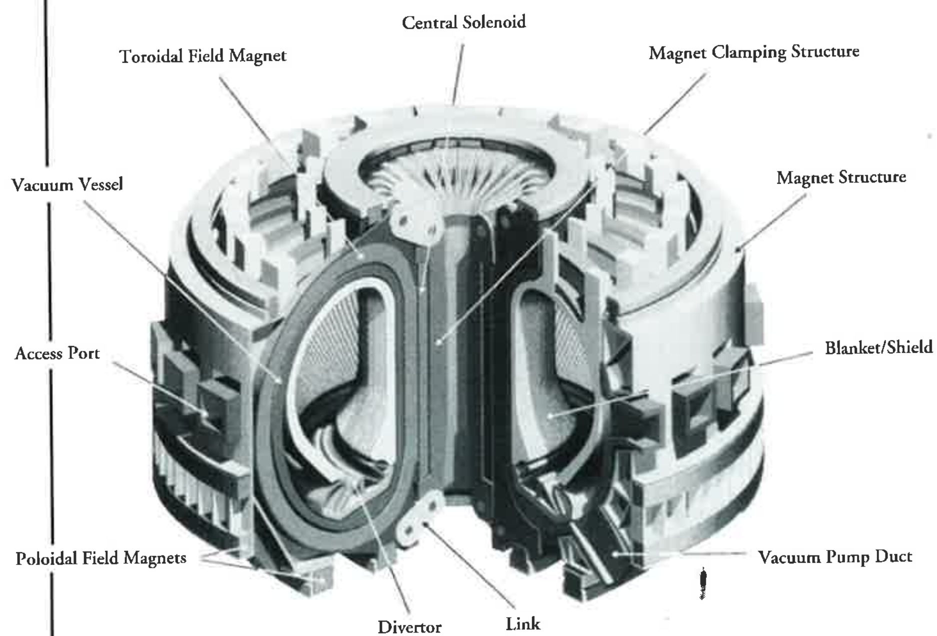
TPX Management Review

A TPX Management Review to assess the status of business management systems supporting the Project was conducted in the early part of 1994. The specific lines of inquiry used for the review were selected by DOE with special consideration given to avoiding system deficiencies observed at the Superconducting Super Collider. General findings drawn from the review are as follows:

- "PPPL is organized appropriately to support the TPX Project with a good balance between permanent and matrix staff.
- The project management roles and responsibilities of the various participants are well understood, and a strong industrial systems-integration contractor and a construction manager are planned to ensure physics requirements are integrated and controlled.
- Taken as a whole, the TPX Project has fundamentally sound management systems and practices which should enable it to complete construction on schedule and within budget. Furthermore, the Project is sensitive to avoiding the shortcomings experienced in the SSC and has productively taken steps to avoid them.
- In conclusion, the leadership of Department of Energy's Princeton Area Office and PPPL, and their staffs, should be complimented on the overall quality of their management systems and their cooperation in the conduct of the review."

Environmental Assessment

The Environmental Assessment for "TFTR D&D/TPX" encompasses the shutdown and removal of TFTR and the construction and operation of TPX. The review process has been completed for the Environmental Assessment and a Finding of No Significant Impact has been published in the Federal Register.



International Thermonuclear Experimental Reactor

The International Thermonuclear Experimental Reactor (ITER) is a collaboration between the governments of the European Communities, 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 practical purposes.

Following a successful Conceptual Design Activity (1988–90), the second phase of the ITER Project — the Engineering Design Activity (EDA) — began in 1992. The organizational structure of the EDA involves a Joint Central Team (JCT) located at three Joint Work Sites (Garching, Germany; Naka, Japan; 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.

During fiscal year 1994, the JCT completed the ITER Outline Design, which was reviewed by the Technical Advisory Committee and presented to the ITER Council in January, 1994. The JCT also developed a draft Work Program, which defines the research and development to be carried out during the EDA, and performed a Sensitivity

Study, which examines variations in the basic physics models and machine parameters. Both of these were also reviewed by the Technical Advisory Committee. Following a careful assessment of the results of the Sensitivity Study, the Outline Design was accepted by the ITER Council in July, 1994.

The Princeton University Plasma Physics Laboratory (PPPL) provided four members of the JCT in fiscal year 1994: the Head of the Physics Integration Unit (at San Diego), a senior physicist developing plasma scenarios and divertor physics concepts (also at San Diego), a senior magnet engineer (at Naka), and a senior tritium engineer with experience on the Tokamak Fusion Test Reactor's tritium system and previously from the Savannah River Plant (also at Naka). The Laboratory is also prominently represented on the physics side within the U.S. Home Team, providing the overall Physics Manager, as well as the Task Area Leaders of the Divertor and Disruption Physics and Plasma Diagnostics Task Groups. The Chair of the Technical Advisory Committee is also from PPPL.

A major step forward in 1994 was the formation of a (four-Party) Physics Committee, supported by seven Physics Expert Groups, which will be responsible for defining and monitoring so-called "voluntary" physics research and development within the national programs of the four Parties. 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 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 MHD; and Energetic Particles, Auxiliary Heating, and Current Drive). This development should result in an improved focus of the national experimental and theoretical programs on the physics needs of ITER.

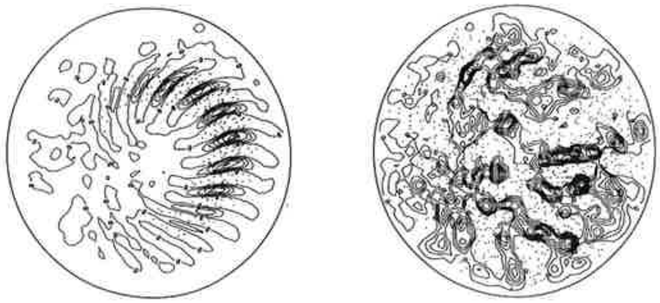
As part of the funded-ITER physics design effort, Laboratory scientists performed a number of tasks in areas such as MHD theory, high-confinement mode database development, and divertor physics.

In July, 1994, by action of the ITER Council, Dr. Robert Aymar became the new Director of ITER, replacing Dr. Paul-Henri Rebut.

Machine Parameters for the International Thermonuclear Experimental Reactor

Parameter	Value
Major Radius (R)	8.1 m
Minor Radius (a)	3.0 m
Elongation	1.55
Toroidal Field (B)	5.7 T
Plasma Current (I_p)	24 MA
Power and Particle Control	Single-Null, Poloidal Divertor
Fusion Power	1.5 GW

Theoretical Studies



Contour plots of density fluctuations from computer simulations of tokamak plasma turbulence. On the left is a time before the onset of turbulence, on the right is the turbulent state. The contour lines show different levels of the density perturbation. These results were generated by a massively parallel supercomputer using a three-dimensional toroidal gyrokinetic simulation code with eight million particles. Recent developments in numerical algorithms and massively parallel computing have allowed large enough simulations to show qualitative agreement between simulation and experimental tokamak plasma fluctuation measurements.

Theoretical research at the Princeton University Plasma Physics Laboratory (PPPL) provides leadership and support for the development of the physics knowledge required for economic fusion reactors. During the past year, progress continued in all areas of activity including analysis of energetic-particle dynamics relevant to alpha-particle physics issues in deuterium-tritium plasmas, the development and application of new capabilities to better understand plasma transport and confinement trends, and the suggestion of promising avenues to tokamak plasma performance enhancement. A significant effort by the staff was in support of the design of advanced tokamaks such as the Tokamak Physics Experiment (TPX) and the International Thermonuclear Experimental Reactor (ITER). Also, there have been extensive, ongoing collaborative efforts with other fusion groups, nationally and internationally.

Energetic-Particle Dynamics

Important progress was made in the understanding of energetic-particle dynamics relevant to alpha-particle physics. Earlier seminal theoretical contributions from PPPL established that energetic ions can interact with prominent MHD (magnetohydrodynamic) waves to stimulate experimentally observed heat and particle losses. This has motivated the development of capabilities to realistically assess the role of alpha particles in driving such instabilities as, for example, fishbone modes and toroidal Alfvén modes. The NOVA-K code developed at PPPL to study plasma stability with kinetic effects was successfully applied to the interpretation of recent deuterium-tritium experimental results from the Tokamak Fusion Test Reactor (TFTR), as well as to design studies for ITER. In addition, advances in the exploration of the feasibility of channeling the energy of fusion alpha particles to increase the reactivity of the fuel has stimulated optimistic projections for tokamak reactor performance.

Numerical Tokamak Project

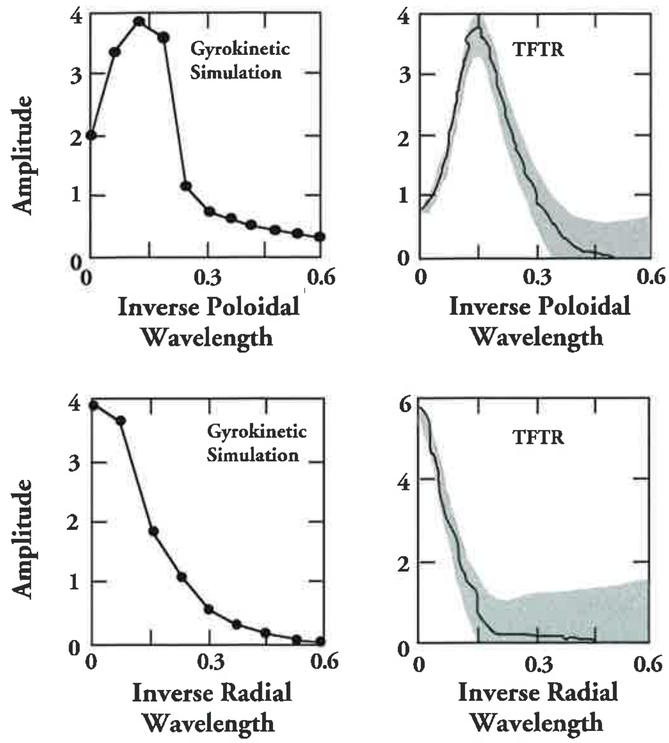
The gyrokinetic particle simulation and the gyrofluid code development activities at PPPL represent the leading innovative components of the national consortium for the Numerical Tokamak Project, which has been identified by the U.S. Department of Energy as one of the nine Grand Challenge Applications for the High Performance Computing and Communication Initiative. This project has as its major goal the development of capabilities to properly interpret and meaningfully extrapolate experimental observations of plasma transport and confinement trends.

A good example of significant progress being made is the effective utilization of high-performance computing capability by the three-dimensional toroidal gyrokinetic particle codes which are now running on the C-M5 massively parallel computer at the Los Alamos National Laboratory and the C-90 supercomputer at the National Energy Research Supercomputer Center. For the first time ever, simulation of fluctuation spectra closely resemble those measured in TFTR experiments.

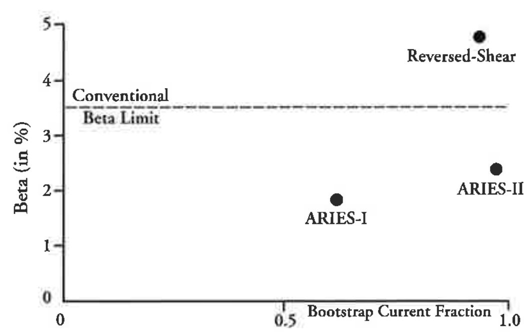
Advanced-Regime Tokamaks

It is well recognized that an attractive commercial tokamak reactor should operate at steady-state and require a minimum of external current drive. Progress in the design of such a device has been achieved in MHD studies at PPPL. Two key parameters representative of the requisite quality of a plasma are (i) the plasma beta, a measure of the energy density of particles confined by the magnetic field and related to the number of fusion reactions that can occur, and (ii) the bootstrap current, the fraction of the plasma current generated internally (with the rest driven by external means). The highest achievable beta is limited by the onset of plasma instabilities, and the bootstrap current is dependent on the details of the internal plasma profiles. Often the requirements for optimizing these two conditions cannot be simultaneously achieved.

Investigations of advanced-regime tokamaks resulted in a novel design, referred to as the reversed-shear configuration. This design has been adopted as a centerpiece of the TPX, the next major tokamak in the U.S. national program. If achieved experimentally, TPX will operate in a steady-state at values of beta which are about twice the value of the ARIES-I reactor designs, and with more than 90% internally generated currents.



Computer simulations of turbulent fluctuation spectra (left) closely resemble experimental core TFTR plasma discharges (right) measured by the Beam Emission Spectroscopy diagnostic. These large-scale simulation results are an important milestone for the Numerical Tokamak Project.



Beta, a measure of the power of a reactor, and bootstrap current fraction, which determines the ability to operate at steady-state, are shown for various operating scenarios of the Tokamak Physics Experiment (TPX). The points ARIES-I and ARIES-II for the TPX scenario refer to plasma configurations identified by the ARIES Reactor Design Project. The Reversed-Shear point for the TPX scenario allows operation at simultaneously high values of beta and bootstrap current fraction.

Engineering and Technology Development

A computer scientist (foreground) collaborates in real-time with another researcher (top right) at the University of Wisconsin.

The Engineering and Technology Development Department (E&TD) was formed in 1994 by restructuring the previous engineering divisions and organizing around functional responsibilities rather than engineering disciplines. The twofold mission of the E&TD is to provide world-class engineering and support services for the Laboratory's scientific programs and infrastructure and to develop fusion-related technologies for transfer to the commercial and industrial sectors.

TPX Engineering

Survey calculations for the Tokamak Physics Experiment (TPX) in-vessel material radioactivity inventory and activation dose rates were completed. Electromagnetic work centered on the analysis of the TPX vacuum vessel and passive stabilizers. Finite element models of the complete vacuum vessel and the inner and outer passive stabilizers were generated. From these models, axisymmetric equivalent models of the vessel and stabilizers were created. A combined model of cryostat, vacuum vessel, and passive stabilizers was developed. Additionally, an in-depth study of the U.S. Department of Energy (DOE) seismic requirements at the Princeton University Plasma Physics Laboratory (PPPL) site was completed. The resulting report will be used to justify the seismic design criteria and peak seismic accelerations to be used for TPX structures, systems, and components.

TFTR Engineering

Engineering maintenance and operations activities were streamlined to maximize the available run time for TFTR experiments. All twelve neutral-beam ion sources were successfully decontaminated, removed, repaired, and reinstalled, demonstrating that extensive maintenance can be performed safely with tritium-contaminated equipment. Several "line breaks" have been performed routinely on the tokamak, diagnostic systems, tritium-gas-handling systems, and neutral-beam systems without incident. Engineering analysis and design activities were begun to increase the TFTR toroidal magnetic field from 5.2 to 5.6 tesla, about 8% above the original design value.

TFTR Shutdown and Removal

Engineering and Technology Development provides management and oversight for the TFTR Shutdown and Removal Project. The primary objectives of this Project are to safely shut down and dismantle the TFTR and ready the facility for construction of the TPX by mid 1999. In July, 1994, a formal Conceptual Project Review was successfully held. Reviewers included both DOE and PPPL representatives. The reviewers concurred with the Project management approach, as well as the resolution of the major DOE, Federal, and State regulatory compliance issues.

Computer Systems

In early 1993, a three-year initiative was begun to expand the PPPL Network (PPLNET) infrastructure. By the close of FY94, two major aspects of the initiative were completed. All PPPL work areas, offices, and public areas were wired for full conductivity to the Local PPLNET and the World Wide Internet, and the network backbone was upgraded to a high-bandwidth fiber optic cable system. All Laboratory personnel now have access to modern e-mail, information server facilities, and multimedia information browsing applications such as Mosaic. Scientists can now collaborate on projects with colleagues and associates across the continent or around the world as if they were in the next office.

Environmental Restoration and Waste Management

The Environmental Restoration and Waste Management (ER/WM) organization serves to protect the health and safety of Laboratory personnel, property, and the environment from hazards due to regulated wastes. A major milestone in fiscal year 1994 was the preparation and final submittal of the Remedial Investigation Work Plan to the New Jersey Department of Environmental Protection.

The ER/WM oversees a proactive waste management program. All wastes are collected, stored, transported, and disposed of in accordance with DOE, Federal, and State regulations. A key component of this program is waste minimization. The ER/WM publishes waste minimization goals. These goals have been exceeded for the past two fiscal years. Additionally, no accidents involving PPPL waste disposal, on- or off-site, have occurred. An "excellent" rating was awarded from the DOE Hazardous Materials Transportation Appraisal.

Reworking of the neutral-beam ion sources was performed safely within a temporary work area set up in the TFTR Test Cell.

A computer technician troubleshoots PPPL's Network infrastructure.

Collaborations

The Princeton University Plasma Physics Laboratory actively collaborates on experiments and research activities with more than sixty 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 on TFTR and PBX-M. Laboratory personnel visiting other institutions participate in research on such devices as DIII-D (General Atomics, United States), 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.

The Laboratory is presently engaged in collaborative activities with the following organizations:

Laboratories

A.F. Ioffe Physical-Technical Institute, Leningrad, Russian Federation
Argonne National Laboratory, Argonne, IL
Asociacion Euratom-CIEMAT, Madrid, Spain
Association Euratom-CEA, Cadarache, France
Associazione Euratom-ENEA, Frascati, Italy
Culham Laboratory, Abingdon, Oxfordshire, United Kingdom
École Royal Militaire, Brussels, Belgium
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
Instituto Nacional de Pesquisas Espaciais, Brazil
ITER Joint Work Site, Garching, Germany
ITER Joint Work Site, Naka, Japan
ITER Joint Work Site, San Diego, CA
Japan Atomic Energy Research Institute, Tokyo, Japan
JET Joint Undertaking, Abingdon, Oxfordshire,United Kingdom
Lawrence Berkeley Laboratory, Berkeley, CA
Lawrence Livermore National Laboratory, Livermore, CA
Los Alamos National Laboratory, Los Alamos, NM
Max Planck Institut für Plasmphysik, Garching, Germany
Naka Fusion Research Establishment, Ibaraki, Japan
National Institute of Fusion Studies, Nagoya, Japan
Oak Ridge National Laboratory, Oak Ridge, TN
Sandia National Laboratories, Albuquerque, NM
Sandia National Laboratories, Livermore, CA
Savanna River Plant, Aiken, SC
Troitsk Institute of Innovative and Thermonuclear Research, Troitsk, Russian Federation

Industries

Babcock and Wilcox, Lynchburg, VA
Burns and Roe Company, Oradell, NJ
Canadian Fusion Fuels Technology Project, Canada
Everson Electric Company, Bethlehem, PA
Fusion Physics and Technology, Inc., Torrance, CA
General Atomics, San Diego, CA
General Physics Corporation, Columbia, MD
Lodestar, Boulder, CO
McDonnell Douglas Missile Systems, St. Louis, MO
Millitech Corporation, South Deerfield, MA
Northrop Grumman Aerospace and Electronics Corporation, Bethpage, NY
Radiation Science, Inc., Belmont, MA
Raytheon Engineers and Constructors, Inc., Ebasco Division, New York, NY
Rocketdyne Division of Rockwell International Corporation, Canoga Park, CA
Westinghouse Electric Corporation, Sunnyvale, CA

Universities

Colorado School of Mines, Golden, CO
Columbia University, New York, NY
Cornell University, Ithaca, NY
Georgia Institute of Technology, Atlanta, GA
Hebrew University, Israel
Jackson State University, Jackson, MS
Johns Hopkins University, Baltimore, MD
Massachusetts Institute of Technology, Cambridge, MA
Nagoya University, Japan
New York University, New York, NY
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 Tromso, Norway
University of Wisconsin, Madison, WI

Technology Transfer

A sapphire-to-metal bonding technique to produce a firm seal for the end caps of high-intensity lamps is being developed through a PPPL CRADA with a small business in New Hampshire.

Bar coding allows the tracking of chemicals "from cradle to grave" via a software package being developed through a CRADA between PPPL and a small, woman-owned business.

The Technology Transfer Office at the Princeton University Plasma Physics Laboratory (PPPL) actively promotes the 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 were developed through PPPL's Technology Transfer Office.

Chemical and Waste Management Report Generating System

This CRADA, with Vertére, Inc. in Rhode Island, is for the development and commercialization of a Chemical and Waste Management Report Generating System for personal computers. Computer software is being developed that will track chemicals from "cradle to grave" using bar coding and that will provide users the means to generate all of the necessary Environmental Protection Agency state and federal forms.

Investigation of 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.

Plasma Chemical Synthesis

This CRADA is to explore the potential for synthesizing chemicals of proprietary interest with commercially viable purity and yields. A proof-of-principle study will be conducted using a small-scale reactor built to produce plasmas composed of the feed stock chemicals.

Advanced Computer Modeling Environment Project

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

Sapphire-to-Metal Bonding

This CRADA is with Saphikon, Inc., a small business in New Hampshire that develops high-performance products based on industrial sapphire. The collaboration is to develop a sapphire-to-metal bonding technique that will produce a firm seal for the end caps on high-intensity lamps to be manufactured by Saphikon. Applications for the high-intensity lamps, which can operate as high as 35,000 watts, include rapid thermal drying, lithography, and robotic recognition of circuit boards by TV cameras.

Advanced Computer Modeling

This CRADA, also with Dynamic Research Corporation, is directed at the development of high-level computational environments that allow various software programs, written in different computer languages, to be easily integrated into a single computer model.

Work for Others

In Work for Others agreements, industry pays for work performed at PPPL. Presently, discussions with Princeton Electronic Systems are in progress for a Work for Others Project to develop and characterize detectors for applications in monitoring systems for nuclear nonproliferation.

Personnel Exchanges

In a Personnel Exchange, researchers from industry assume a work assignment at the Laboratory or PPPL staff work in the industrial setting. Presently, two Employee Exchanges Programs are in progress: Two PPPL engineers are working on the design of advanced industrial controls at the David Sarnoff Research Center and another engineer is working with researchers at AT&T Bell Laboratories to develop a computer code for mapping electron trajectories in a magnetic field for applications in integrated circuit technologies.

Technology Maturation Projects

Technology Maturation Projects are designed to bring technology from its early state of development closer to commercial viability. In fiscal year 1994, PPPL initiated a Technology Maturation Program with Asea Brown Boveri to improve the performance of ac and dc electric arc furnaces by improving arc position control, stability, and heat distribution within furnaces.

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.

PPPL staff who have filed invention disclosures through the Patent Awareness Program.

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 1994, twenty-two invention disclosures were filed.

Graduate Education

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

The Princeton University Plasma Physics Laboratory supports graduate education through the Program in Plasma Physics in the Department of Astrophysical Sciences of Princeton University. Students are admitted directly to the Program and are granted degrees through the Department of Astrophysical Sciences.

With more than 165 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 1994 (FY94), there were 47 graduate students in residence in the Program in Plasma Physics, holding between them one Department of Energy Computational Fellowship, three Department of Energy Magnetic Fusion Science Fellowships, one Hertz Fellowship, three Princeton/Hertz Fellowships, three National Science Foundation Fellowships, one Office of Naval Research Fellowship, and one Natural Sciences and Engineering Research Council (Canadian) Fellowship.

Six students graduated in fiscal year 1994, receiving postdoctoral positions in plasma physics at the University of California at San Diego, University of California at Irvine, University of California at Los Angeles, the Max-Planck-Institut für Plasmaphysik in Garching, Germany, Cornell University, and Argonne National Laboratory.

Students Admitted to the Plasma Physics Program in Fiscal Year 1994

Student	Undergraduate Institution	Major Field
Bryan Fong	Yale University	Physics
Robert Heeter	Stanford University	Physics
Scott Hsu	University of California at Los Angeles	Electrical Engineering
Max Karasik	The Cooper Union	Electrical Engineering
Lufeng Leng	Peking University	Radio Electronics
Karsten McCollam	University of Minnesota	Physics
Hong Qin	Peking University	Space Physics
Vladislav Savchenko	Moscow Institute of Physics and Technology	Plasma Physics
Philip Snyder	Yale University	Applied Physics
Dmitri Uzdensky	Moscow Institute of Physics and Technology	Physics

Alumni of the Program received a number of prestigious awards and appointments in FY94. The 1994 Simon Ramo Award for Outstanding Doctoral Thesis Research in Plasma Physics was awarded to a 1992 graduate, and the 1993 Kaul Foundation Award for Excellence in Science, Education, and Physics went to a 1966 graduate. Two graduates of the Program received tenure appointments in 1994, one at the University of California at San Diego and the other at the University of Iowa.

Recipients of Doctoral Degrees in Fiscal Year 1994

Mehmet Artun

Thesis:	Low-frequency Microinstabilities in Rotating Tokamak Plasmas
Advisor:	William M. Tang
Employment:	University of California at Los Angeles

David P. Coster

Thesis:	Tokamak Divertor Modeling with Fluid and Kinetic Codes
Advisor:	Charles F.F. Karney
Employment:	Max-Planck-Institut für Plasmaphysik

Karl M. Krushelnick

Thesis:	Coherent Soft X-ray Generation Using a Powerful Subpicosecond Laser
Advisor:	Szymon Suckewer
Employment:	Cornell University

Robert A. Santoro

Thesis:	Gyrokinetic Particle Simulation of a Multi-ion Species Plasma
Advisor:	Wei-li Lee
Employment:	University of California at Irvine

Giorgos Vetoulis

Thesis:	Global Structures of Alfvén-ballooning Modes in Magnetospheric Plasmas
Advisor:	Liu Chen
Employment:	University of California at San Diego

Christopher D. Zuiker

Thesis:	Laser-induced Fluorescence Measurements in an Electron-cyclotron Resonance Plasma Etch Reactor
Advisor:	Joseph L. Cecchi
Employment:	Argonne National Laboratory

New experimental facilities have been introduced for "Laboratory in Plasma Physics," a course designed to teach students the principles and techniques for diagnosing plasmas used in fusion, space propulsion, astrophysical sciences, semiconductor processing, and illumination. Here, a PPPL graduate student observes a large, hollow cathode discharge. Its density is measured with a Mach-Zender interferometer.

Science Education

The Princeton University Plasma Physics Laboratory's (PPPL) Science Education Program continued to focus on three key areas in fiscal year 1994: systemic reform, curriculum development, and teacher enhancement and student opportunities.

Trenton Partnership

In the area of systemic reform, PPPL has had, since 1990, a long-term partnership with the Trenton Public Schools aimed at improvement in math and science teaching and learning. The partnership activities grew considerably in 1994. Funding for the program was provided by the Office of Science Education Programs of the U.S. Department of Energy.

PPPL has assisted the Trenton district in revising its science curriculum and in establishing goals for its implementation. The curriculum framework was reworked in 1993, and during the summer of 1994, the elementary school curriculum committee met at PPPL and developed an extensive hands-on activities manual for grades kindergarten through 5. Flexible scheduling was introduced by the district to allow teachers time to teach activity-based science.

To ensure the successful implementation of the new curriculum, 35 workshops for Trenton teachers were held during the school year in the afternoons and on Saturdays. More than 4,200 teacher-hours of staff development were provided in this manner; more than 65 Trenton teachers participated in 1994 summer institutes, as did 50 teachers from other districts. These institutes focused on using inquiry-based methods for teaching science and mathematics. In 1994, there was an integrated math and science institute for grades kindergarten through 2, one for grades 3 through 5, a middle school science institute for grades 5 through 8, and a secondary math institute for grades 6 through 12.

The content of all of the Summer Teachers' Leadership Institutes supported the topical coverage of the new Trenton science curriculum and focused on inquiry, cooperative learning, and promoting critical thinking and problem-solving skills.

Through the Trenton Partnership, PPPL staff volunteers visit Trenton classrooms talking and working with students on a variety of topics in science and mathematics. These sessions are characterized by hands-on activities and small group discussions.

"What's in Our Water," a workshop done in conjunction with the National Geographic Society, Oak Ridge Institute for Science and Education, and Ames National Laboratory, and sponsored by the United States Department of Energy, was held for teachers of grades 3 through 7. Twenty teachers attended.

In cooperation with the Princeton chapter of Sigma Xi, scientists in residence have been placed in all of Trenton's 23 schools. Science advisors visit their schools for at least two or three hours every few weeks. They help support the implementation of the new science curriculum, attend faculty meetings, work with teachers in gathering materials and supplies, and provide model science lessons for teachers and students, as requested.

For the third year, PPPL sponsored the Summer Internships in Trenton Program. The program was administered in cooperation with the Princeton University Student Volunteers Council. During July and August of 1994, fifteen Princeton University students participated in five community-based programs in Trenton, serving as tutors and mentors to approximately 350 youngsters who reside in the inner city.

Other Programs

PPPL also presented the Fractals, Chaos, and Dynamics II Symposium in July, 1994. The week-long programs brought together a group of internationally acclaimed mathematical researchers in the field of fractals, chaos, and dynamics, and leading mathematics educators. The symposium was attended by 110 mid-level and secondary teachers, as well as college and university professors. The symposium enhanced teachers' content knowledge and their ability to teach the underlying concepts related to these emerging fields of mathematics.

From January 9 to March 20, 1994, PPPL sponsored Science on Saturday, a ten-week series of talks for high-school students, teachers, parents, and community members. The Science Education Program provided a bus from Trenton to the Laboratory, enabling students from the city to participate in the program. Between 300 and 550 students and others attended the lectures each week. Topics ranged from "The Discovery of the Binary Pulsar" to "How Animals Develop Their Shape and Form."

PPPL also provided summer research experiences for 63 undergraduates, high-school students, and high-school teachers in 1994. They worked on a variety of research projects with Laboratory scientists and engineers.

Science Education summer programs provide opportunities for students and teachers to work with PPPL researchers on scientific projects.

From top to bottom with individuals identified left to right: Joseph Taylor and Russell Hulse at Princeton University the day they were awarded the Nobel Prize in Physics; Hulse and the King of Sweden during the Nobel presentation ceremonies; Jeanne Kuhlman, Hulse, and President Bill Clinton; and First Lady Hillary Rodham Clinton shaking hands with Hulse at the White House.

Principal Research Physicist Russell Hulse and Princeton University Professor Joseph Taylor received the 1993 Nobel Prize in Physics for their 1974 discovery of the first binary pulsar. It was the first time in the history of the Laboratory that the Nobel Prize was awarded to a Princeton University Plasma Physics Laboratory (PPPL) physicist.

At the time of the discovery, Hulse was a University of Massachusetts graduate student who had gone pulsar hunting at the urging of his thesis advisor, Taylor, then a professor at the University of Massachusetts. While using a 300-meter-diameter radio telescope at an observatory in Arecibo, Puerto Rico, Hulse discovered a binary pulsar, which is a twin star system that serves as a rare natural laboratory in which to test the predictions of Einstein's general theory of relativity. Continued study of the binary pulsar by Taylor and his colleagues, over the 20 years since its discovery, has provided strong confirmation of Einstein's theoretical predictions, including the emission of gravitational waves by moving objects.

Hulse, who earned a Ph.D. from the University of Massachusetts in 1975, changed from the field of astrophysics to plasma physics and came to PPPL in 1977. Since entering plasma physics, he has become a leading expert in computational modeling of impurity transport in tokamaks. He is presently establishing an advanced computer modeling group at the Laboratory to develop new approaches to scientific computing that encourage innovative work by enabling the creation of powerful yet easily modifiable computer codes. The group is also exploring the educational potential of computer modeling, which can serve as a unique tool for teaching science and the process of scientific investigation.

In addition to his duties at PPPL, Hulse has taken on additional speaking and social engagements since winning the Nobel. He has been the featured speaker at numerous public and academic lectures at home and abroad.

The Nobel marked the first of three distinguished honors bestowed on Hulse in 1993. He was also named a Fellow of the American Physical Society and chosen as one of the first three PPPL Distinguished Research Fellows.

Award Recipients

James L. Anderson
DOE Distinguished Associate Award
U.S. Department of Energy

Dori J. Barnes
Certificate of Accomplishment
Princeton University Women's Organization

Stefano Bernabei
Fellow
American Physical Society

Ronald C. Davidson
1993 Award for Excellence in Science, Education, and Physics
Kaul Foundation

Russell A. Hulse
1993 Nobel Prize in Physics
The Royal Swedish Academy of Sciences

Fellow
American Physical Society

PPPL Distinguished Research Fellow
Princeton University Plasma Physics Laboratory

1994 Gano Dunn Award
Cooper Union

Charles E. Kessel, Jr.
1994 Excellence in Fusion Engineering
Fusion Power Associates

Russell M. Kulsrud
1993 James Clerk Maxwell Prize in Plasma Physics
American Physical Society

Ernesto Mazzucato
Fellow
American Physical Society

Dale M. Meade
DOE Distinguished Associate Award
U.S. Department of Energy

Susan E. Murphy
Certificate of Accomplishment
Princeton University Women's Organization

Allan H. Reiman
Fellow
American Physical Society

Timothy J. Riotto
(former co-op student)
Drexel's Outstanding Co-Operative Education Senior for 1994
Drexel University

James M. Scott, III
Certificate of Appreciation
U.S. Department of Energy

James C. Sinnis
DOE Distinguished Associate Award
U.S. Department of Energy

James D. Strachan
PPPL Distinguished Research Fellow
Princeton University Plasma Physics Laboratory

Roscoe B. White
PPPL Distinguished Research Fellow
Princeton University Plasma Physics Laboratory

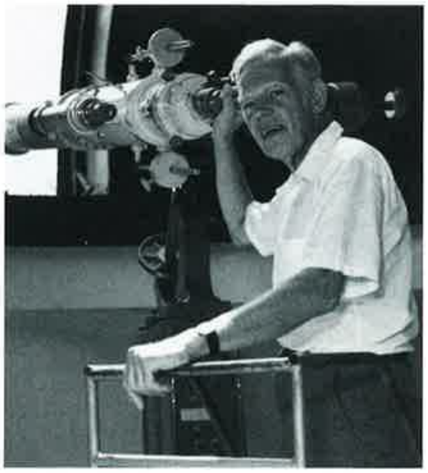
Michael D. Williams
Fusion Technology Award
Institute of Electrical and Electronics Engineers

King-Lap Wong
Fellow
American Physical Society

Lynne H. Yager
Certificate of Accomplishment
Princeton University Women's Organization

Stewart J. Zweben
Fellow
American Physical Society

Russell M. Kulsrud was a recipient of the James Clerk Maxwell Prize in Plasma Physics.



PPPL Physicists James Strachan (left), Russell Hulse (middle), and Roscoe White were the first recipients of the PPPL Distinguished Research Fellowships.

The Year in Pictures

Responding to TFTR's record-breaking fusion power results in December, 1993, are, from left, Milton Johnson, DOE Princeton Area Office Manager, Stephen Eckstrand and John Willis of DOE's Office of Fusion Energy, James Anderson, who was "on loan" at PPPL from the Los Alamos National Laboratory, and TFTR Head Richard Hawryluk.

Looking at computer monitors in the TFTR Control Room, scientists react as data from TFTR's first deuterium-tritium experiments begins to appear on screen. From left are Glen Wurden (Los Alamos National Laboratory), Stephen Paul (PPPL), Marilee Thompson (PPPL), Masanouri Murakami (Oak Ridge National Laboratory), Steven Sabbagh, Charles Bush, Alan Janos, Robert Budny, Charles Skinner, and Edmund Synakowski (all of PPPL).

In June, PPPL signed contracts totaling $34.3 million with two teams of American companies that will be involved in designing components of the Tokamak Physics Experiment. From left are PPPL Director Ronald Davidson, David Overskei of General Atomics, Stephen Eckstrand of DOE's Office of Fusion Energy, John Davis of McDonnell Douglas Corporation, Robert Iotti of the Ebasco Division of Raytheon Engineers and Constructors, Inc., Milton Johnson, Manager of the DOE's Princeton Area Office, and PPPL Deputy Director Dale Meade.

PPPL Deputy Director Dale Meade (right) leads the tour of the TFTR during Secretary of Energy Hazel O'Leary's visit to PPPL. Left to right are Martha Krebs, Director of the Department of Energy's Office of Energy Research, Linda Johnson, Associated Press News reporter, and Secretary O'Leary. ▼

▲ *Secretary of Energy Hazel O'Leary talks with PPPL staff during her visit to the Laboratory in March, 1994.*

Daughters, granddaughters, friends, and relatives of PPPL employees visited the Laboratory in April, 1994, for "Take Our Daughters to Work Day." Inside the TFTR vacuum vessel mock-up are, from left to right, Susan Malsbury, Stephanie Wise, Sandra Bara, Celia Christianson, Melissa Awad, and Lisa Iverson. ▶

During "Take Our Daughters to Work Day," some participants were able to "try on" and "use" safety equipment. From left are Elizabeth Bell, Casey Johnson, PPPL'er Jill Kwiatowski, and Amber Raymond. ▼

◀ *During the summer, the Laboratory hosted a "Free Lunch" for staff. Employees lined up at the grill and picnicked in the courtyard.*

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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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Photo of the Laboratory/Office Building at the Princeton University Plasma Physics Laboratory.

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