




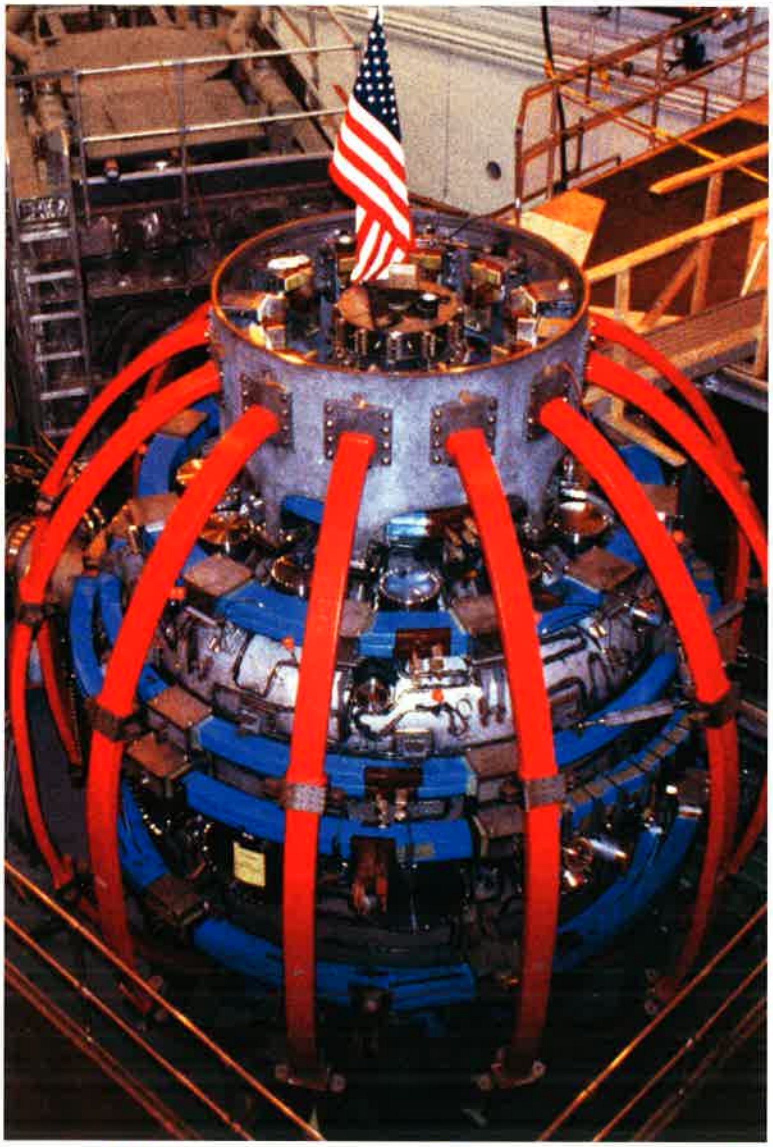






1999 Annual Highlights

PPPL
PRINCETON PLASMA
PHYSICS LABORATORY

About PPPL

Established in 1951, the Princeton Plasma Physics Laboratory (PPPL) is dedicated to developing the scientific and technological knowledge base for magnetic fusion energy as a safe, economical, and environmentally attractive energy source for the world's long-term energy requirements. It has been the site of the Tokamak Fusion Test Reactor which completed in April 1997 a historic series of experiments using deuterium-tritium fuel. A new innovative facility, the National Spherical Torus Experiment, has come into operation this year ahead of schedule and on budget.

PPPL is managed by Princeton University under contract with the U.S. Department of Energy. The fiscal year 1999 budget was approximately $57 million. The number of full-time regular employees at the end of the fiscal year was 393, not including approximately 87 subcontractors, graduate students, and visiting research staff. The Laboratory is sited on 72 acres of Princeton University's James Forrestal Campus, about four miles from the main campus.

Through its efforts to build and operate magnetic fusion devices, PPPL has gained extensive capabilities in a host of disciplines including advanced computational simulations, vacuum technology, mechanics, materials science, electronics, computer technology, and high-voltage power systems. In addition, PPPL scientists and engineers are applying knowledge gained in fusion research to other theoretical and experimental areas including the development of a non-contact diagnostic instrument for use by U.S. synthetic fiber manufacturers and propagation of intense beams of ions. The Laboratory's Office of Technology Transfer assists industry, other universities, and state and local government in transferring these technologies to the commercial sector.

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

On the Cover

In February 1999 the National Spherical Torus Experiment (NSTX) produced its first plasma, marking the completion of assembly and the beginning of operations. Shown on the cover is the completed NSTX device, surrounded by project activities. Counterclockwise from the upper left-hand corner: installation of a toroidal field coil; inspection of the center column (two photos); installation of the center column; the NSTX team assembled following the completion of construction; the vacuum vessel; staff cheering first plasma; installation of passive stabilizer plates within the vacuum vessel; vacuum chamber is lifted and then lowered in place on the NSTX pedestal (two photos); installation of flanges on the vacuum vessel ports; cutting a ribbon to celebrate the beginning of NSTX experimental operations are, from the left, Laboratory Director Rob Goldston, N. Anne Davies, Associate Director for Fusion Energy Sciences at the DOE Office of Science, Representative Rush Holt (NJ-12th), Secretary of Energy Bill Richardson, Representative Rodney Frelinghuysen (NJ-11th), Princeton University President Harold Shapiro, and Princeton Township Mayor Phyllis Marchand.

This publication highlights activities at the Princeton Plasma Physics Laboratory for fiscal year 1999 — 1 October 1998 through 30 September 1999.

Mission Statement

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

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

Vision Statement

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

Advantages of Fusion Energy

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

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From the Director

Fiscal Year 1999 was an exciting time both for the Princeton Plasma Physics Laboratory (PPPL) and for the wider fusion energy sciences community. At PPPL we brought the National Spherical Torus Experiment (NSTX) on line within budget and well ahead of schedule. This was celebrated in a visit by U. S. Secretary of Energy Bill Richardson, who was accompanied by New Jersey Representatives Rodney Frelinghuysen and Rush Holt. (See cover photos and page 91.) Our employee newsletter, the PPPL HOTLINE, aptly described the event as "Irrepressible Secretary Lauds Lab."

PPPL's research program extends well beyond NSTX, and we scored major successes this year in the smaller on-site experimental projects, both in fusion energy science and in applications research.

We are particularly pleased with plans to focus Current Drive Experiment-Upgrade research activities on support of the development of liquid-metal-wall technologies for magnetic fusion, and with our successful demonstration of the use of laser scattering techniques for on-line monitoring of artificial fiber production for the textile industry. We also had excellent results in our off-site experimental research at the DIII-D tokamak in San Diego, CA, at the C-MOD tokamak in Cambridge, MA, and at major fusion facilities overseas.

Robert J. Goldston

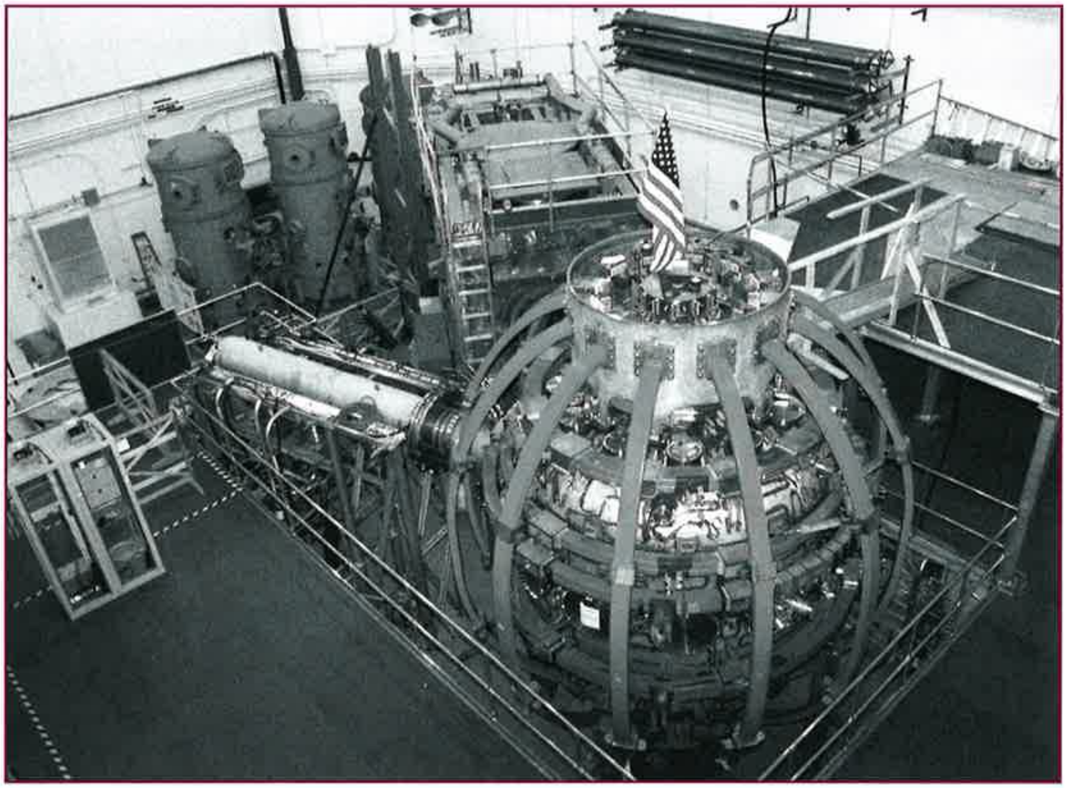
Theory and advanced computation made great strides, for example, in the understanding of the dynamics of zonal flows, taking advantage of massively parallel processor computational capabilities available to us through the National Energy Research Supercomputer Center. The design of the National Compact Stellarator Experiment, in collaboration with a wide range of institutions, most prominently the Oak Ridge National Laboratory, made substantial progress toward a construction decision. Advances were also made, through the Virtual Laboratory for Technology, on the preconceptual design of the Fusion Ignition Research Experiment, a possible next step option for international consideration, if the International Thermonuclear Experimental Reactor does not go forward.

In the wider fusion energy sciences community, this year moved the restructured program a major step forward, with the development by the Fusion Energy Sciences Advisory Committee (FESAC) of an explicit plan for fusion energy sciences, including goals and objectives on a 5, 10, and 15 year timetable. The development of this plan capped a year of events, including:

- the development of a Magnetic Fusion Energy and Inertial Fusion Energy Program Leaders' Discussion Draft Roadmap,
- the creation by FESAC of a major "Opportunities Document" outlining the fusion program and opportunities for progress,
- a comprehensive and highly supportive review by the Secretary of Energy Advisory Board, and
- a major fusion energy sciences community summer study to discuss opportunities and directions.

The fusion energy sciences community is now well-positioned, with a clear set of priorities and accountable objectives, for advancing confidently into the future. PPPL is pleased to be an integral part of that future.

National Spherical Torus Experiment



The National Spherical Torus Experiment.

The National Spherical Torus Experiment (NSTX) is a new Department of Energy (DOE) fusion energy science facility designed to prove the physics principles of spherical torus (ST) plasmas. Fiscal year 1999 was an exceptionally productive and exciting year for NSTX. On February 15, 1999, after two and half years of design and construction, first plasma was achieved 10 weeks ahead of schedule. NSTX construction was completed within budget, with an outstanding safety record.

Research operations started and the plasma current came up rapidly to the FY99 goal of 0.50 MA, exceeding the previous ST record of 0.32 MA in the Small Tight Aspect Ratio Tokamak in England.

The cross section of the NSTX device is shown in Figure 1. In an ST plasma, the size of the minor radius approaches that of the major radius, and the cross section approaches a half circle. As a result the ST plasma appears spherical, while the conventional tokamak plasma has the well-known "donut" shape. This difference in shape is expected to provide several advantages for an ST, such as the ability to contain a significantly higher plasma pressure for a given magnetic field strength

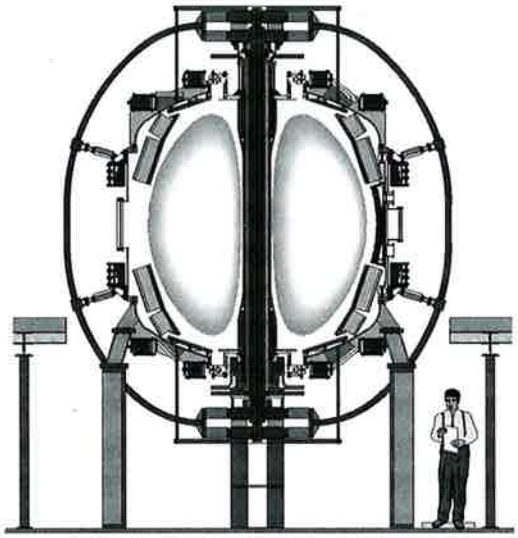


Figure 1. Cross-sectional schematic view of the NSTX device.

(i.e., a higher plasma beta, which is the ratio of the plasma pressure to the magnetic field pressure). Since the amount of fusion power produced is proportional to the square of the plasma pressure, the ST plasma configuration may lead to smaller and more economical magnetic fusion reactors.

The NSTX Program Advisory Committee (Table I) is composed of senior researchers in the fusion community. Members review and advise the Princeton Plasma Physics Laboratory (PPPL) Director on priorities and plans for the NSTX Research Program. A strong national research team consisting of 14 institutions was formed in FY99 through peer reviews of research proposals and a community-based panel review process. Members of the NSTX National Research Team (Table II) work very well together and contributed to the successful "readying" of the machine for experiments and the productive research activities in FY99.

NSTX Mission

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

- nonintuctive start-up, current sustainment, and profile control;
- global confinement and local transport physics;
- pressure limits and self-driven currents;

Table I. NSTX Program Advisory Committee	
Dr. Gerald A. Navratil, Chair Columbia University	Dr. Raffi Nazikian Princeton Plasma Physics Laboratory
Professor Raymond J. Fonck University of Wisconsin-Madison	Dr. Robert Pinsker General Atomics
Dr. Kenneth Gentle University of Texas-Austin	Dr. C. Spencer Pitcher Massachusetts Institute of Technology
Dr. David N. Hill Lawrence Livermore National Laboratory	Dr. Alan Sykes Culham Laboratory
Dr. Alan Hoffman University of Washington-Seattle	Dr. Yuichi Takase University of Tokyo
Dr. Edward A. Lazarus Oak Ridge National Laboratory	Dr. Masayuki Ono *(ex officio)* Princeton Plasma Physics Laboratory
Dr. Farrokh Najmabadi University of California-San Diego	Dr. Martin Peng *(ex officio)* Oak Ridge National Laboratory

Table II. NSTX National Research Team

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

- scrape-off-layer and divertor physics; and
- stability and resilience to plasma disruptions.

The NSTX research team will investigate ST plasma regimes that promise small fusion cores for near-term applications, such as the Volume Neutron Source and for developing fusion energy technology for electric power production in the long term. The plasma parameters extend beyond the present state-of-the-art in magnetic fusion energy and are characterized by:

- simultaneous high toroidal beta (25-45%), self-driven current fraction (40-80%), and confinement in steady state;
- noninductive start-up of full current, i.e., not relying on induction from the ohmic solenoid;
- efficient noninductive drive for the needed increment in plasma current; and
- dispersed particle and power exhausts on high heat flux components facing the plasma.

Successful proof of these desired properties will make possible cost-effective ST devices capable of increases in the plasma current and pressure by an order of magnitude, with only modest increases in plasma size. These devices could include a pulsed Performance Extension (or Proof of Performance) experiment at ~10 MA in plasma current and a steady-state Energy Technology Development experiment at a similar current.

Successful Completion of NSTX Construction

To insure construction project completion within budget, it was decided in 1998 to begin first plasma operations in February 1999, ahead of the April 30, 1999 DOE Milestone. Early plasma operations would provide very important data for the engineering and research team while reducing construction cost. To accomplish early first plasma, a success-oriented schedule was developed. All the needed components arrived just in time and device assembly went very smoothly.

The vacuum vessel and the center stack were transported into the NSTX Test Cell in early October 1998. Device assembly started with the placement of the vacuum vessel at its final location in mid-October. The center stack was installed in early November. The vacuum vessel was pumped down for the first time in mid-

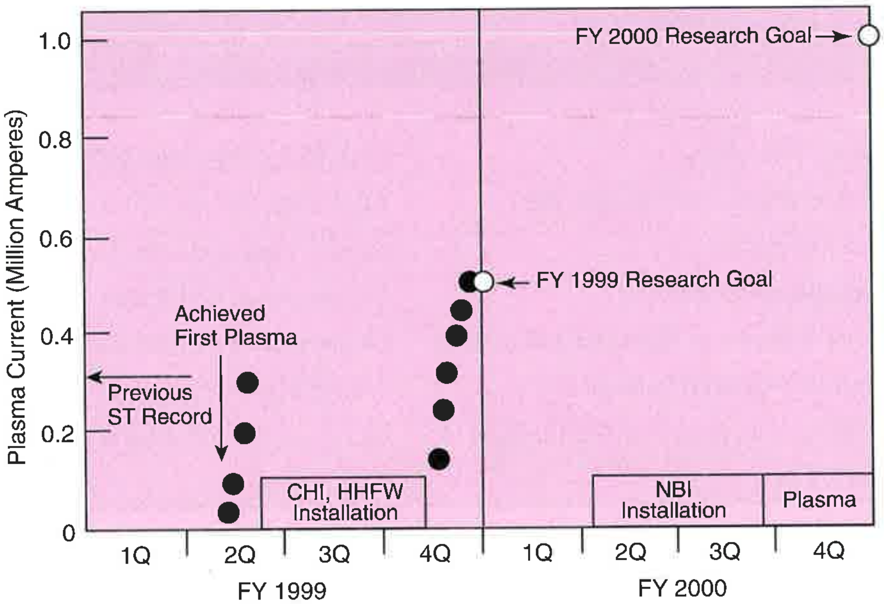


Figure 2. NSTX device assembly completed.

November and easily passed the vacuum leak check. The device assembly was largely completed in mid-December with installation of the outer toroidal field coils. Due to the excellent safety record of NSTX construction, the NSTX team received the 1998 New Jersey Governor's Occupational Health and Safety Award. During January 1999, utilities were hooked up to the device and various preoperation test procedures were performed. After the successful PPPL safety review and DOE Operations Readiness Assessment in early February, permission for the first plasma was officially given on February 11. For first plasma operations, it was decided to limit the toroidal field to 2 kG, the ohmic heating coil current to 18 kA single swing (design value of 24 kA double swing), and the poloidal field coil current to 10 kA (design value of 20 kA).

First Plasma Achieved Ahead of Schedule

On February 12, 1999, the Los Alamos National Laboratory fast camera observed the first "flash" of ohmic plasma (about 20 kA of plasma current). It was rather remarkable that a fusion device as complex as NSTX obtained an ohmic plasma on the first attempt. The NSTX physics design team was able to predict quite precisely which waveforms were needed on various poloidal coil magnets to produce desired null-field during ohmic heating initiation. The reliability of the NSTX power system was another important factor in the successful start-up. The power supplies were improved during their years of operation on the Tokamak Fusion Test Reactor, and despite their complexity, now exhibit very reliable operation.

On February 15, the plasma current quickly exceeded the DOE Level I Milestone of 50 kA, ten weeks ahead of schedule. Within the following two days of plasma operations, the plasma current reached the 0.30 MA level, which is close to the predicted value for the ohmic heating flux used (see Figure 2).

It should be noted that the newly formed NSTX National Research Team played a crucial role from the start. The Los Alamos team members brought their fast visible camera to capture the plasma evolution. By guiding the poloidal field waveform programming, this camera was a useful tool in bringing the plasma current to 0.30 MA in just two days. Also, the EFIT equilibrium code reconstruction of the first plasma was successfully carried out by Columbia University team members using magnetic data.

The success of initial NSTX operations confirmed the basic device operational readiness of power supplies and other utilities. While the device magnets were not energized to full capability, first plasma gave the engineering team confidence that the device was indeed designed and constructed correctly. The EPICS and MDS-PLUS software platforms performed extremely well.

On February 26, 1999, Energy Secretary Richardson visited the Laboratory and dedicated the NSTX facility, noting that the device was built within cost and ahead of schedule. After initial operations, the NSTX construction team went back to work. The center stack was pulled out, facilitating the installation of important components inside the vacuum vessel. Included were the passive and outer divertor plates with more than 2,500 graphite tiles, twelve element high harmonic fast wave antennas (as shown in Figure 3); Coaxial Helicity Injection ceramic insulators, plasma-facing components, and sensors on the center stack.

Restart of Plasma Operations

NSTX plasma operations restarted on September 1, 1999. The toroidal field was increased to 3 kG, which is the nominal field for 1-MA operation. The poloidal field coils were tested to full 20 kA. The ohmic heating double swing at 18 kA was also tested for the first time. Again, the ohmically heated plasma started on the first attempt. It only took a few plasma discharges to reach 0.32 MA, exceeding the previous ST plasma current record. The FY99 milestone of 0.50 MA ohmic current was achieved on schedule.

The NSTX electron cyclotron preionization system utilizes a refurbished 18-GHz klystron unit capable of delivering 30 kW of power for 0.1 sec. The system was brought to NSTX by the Oak Ridge National Laboratory team. It performed reliably from the start, creating a vertically uniform plasma sheet at the electron cyclotron resonant layer, which is approximately R = 42 cm for the nominal 3-kG toroidal field. The electron cyclotron preionization system makes ohmically heated plasma initiation less sensitive to error fields, enhancing operational flexibility. The electron cyclotron preionization system will also be used to create initial plasmas needed for Coaxial Helicity Injection experiments.

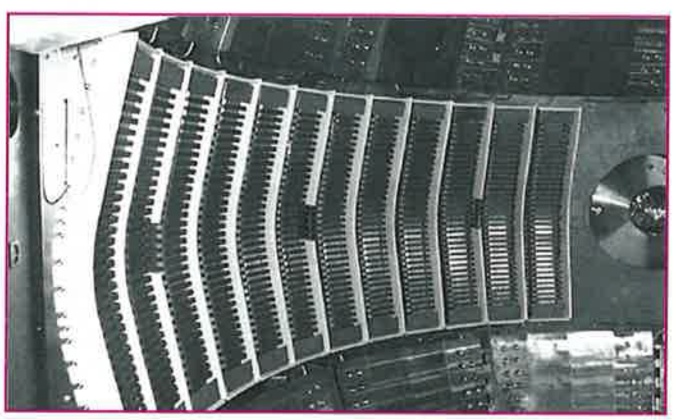


Figure 3. Twelve–element High Harmonic Fast Wave antenna array installed in NSTX.

Experimental Activities

During FY99, procedures for performing experiments in NSTX were established and the first experiments were planned for the Phase I experimental run period. The methods for preparing, reviewing, approving, and executing experimental proposals were presented and discussed at the NSTX Research Forum in January 1999. Draft forms for experimental proposals were posted on the NSTX web pages for the Research Team. The NSTX Operations Group developed a complementary process for commissioning and development tasks needed to bring the machine to full operation, ready for physics experiments.

The expectation was that the majority of experiments would be developed and conducted by members of three experimental task groups established for Phase I. Major research activities of Phase I include ohmic plasma optimization, High Harmonic Fast Wave heating, and Coaxial Helicity Injection. During the summer of 1999, specific experimental proposals needed to complete Phase I research goals were defined in meetings of the experimental task groups. Responsibility for drafting the proposals was assigned, and first drafts were discussed. As a result, the interests of several researchers could be accommodated in a single proposal in some cases.

The first formal reviews of experimental proposals were conducted in August 1999 at NSTX physics meetings, accessible to offsite team members by teleconference and through the Internet for visual materials. During these presentations, "review chits" were submitted, considered by a chit review board, and returned to the proponents of the experiment for ac-

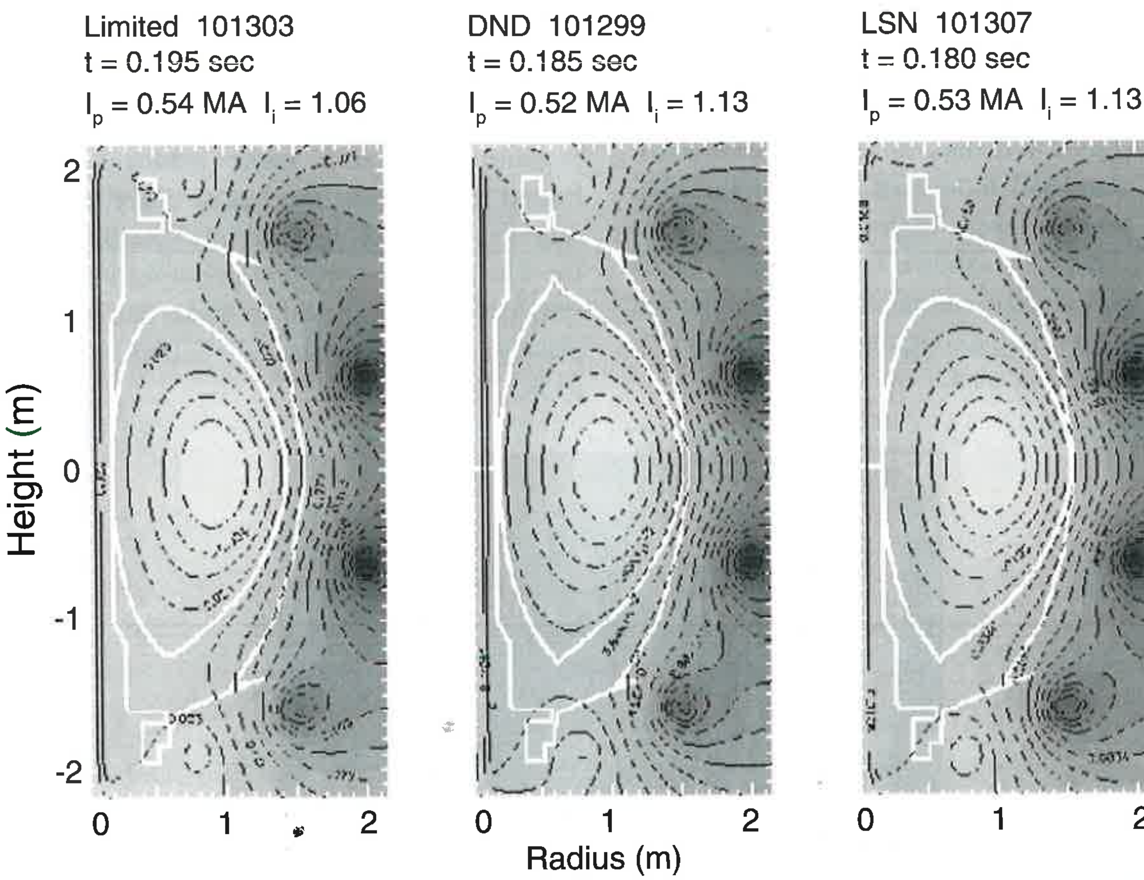


Figure 4. EFIT reconstruction of the NSTX plasma configurations: inner wall limited, double-null divertor, and single-null divertor.

tion, if appropriate. When concerns or recommendations had been addressed, the relevant task leader approved the revised proposal. By the end of FY99, seven proposals were under development and two were being revised after review.

Initial Characterization of NSTX Ohmic Plasmas

Key to the achievement of high current plasma operations was the implementation of the real-time plasma control system in collaboration with General Atomics. The Skybolt I computer system provided feedback control of the plasma radial and vertical positions, as well as the plasma current. Through closed loop operation, the plasma control system made it possible to quickly reach 0.8 MA. The system also facilitated the production of plasmas that were limited by the center stack, as well as those that were double or single-null diverted (as shown in Figure 4) and which had elongations (κ) from 1.5 to 2.3 and triangularities (δ) in excess of 0.4.

The flux consumption turned out to be relatively small, in the range of 40% of the ohmic heating flux lost to resistive heat dissipation. The rate of consumption may have been affected by magnetohydrodynamic (MHD) instabilities observed during the early phase of the discharge. Density and safety-factor (q) limits were investigated by utilizing large gas feeds (to increase density) and toroidal field ramp-downs (to decrease q). The EFIT equilibrium code estimated plasmas with volumes in excess of 12 m^3, stored energies of 30 kJ, and energy confinement times of order 20 msec at densities of about 3×10^{19} m^3. These values are consistent with temperatures between 0.5 and 1.0 keV, as indicated from the

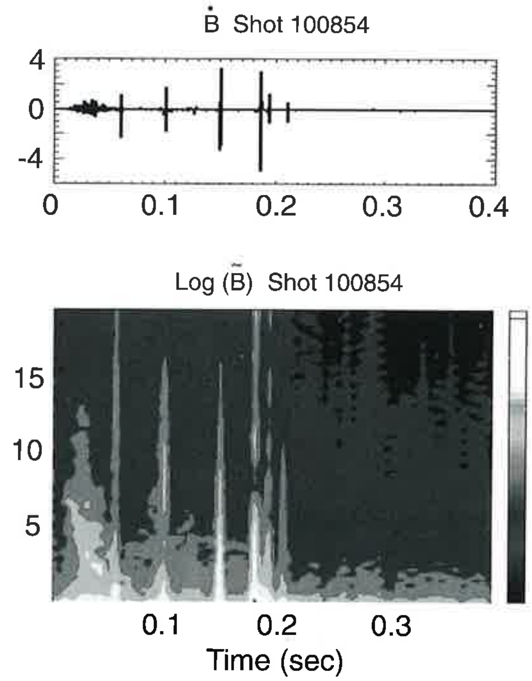
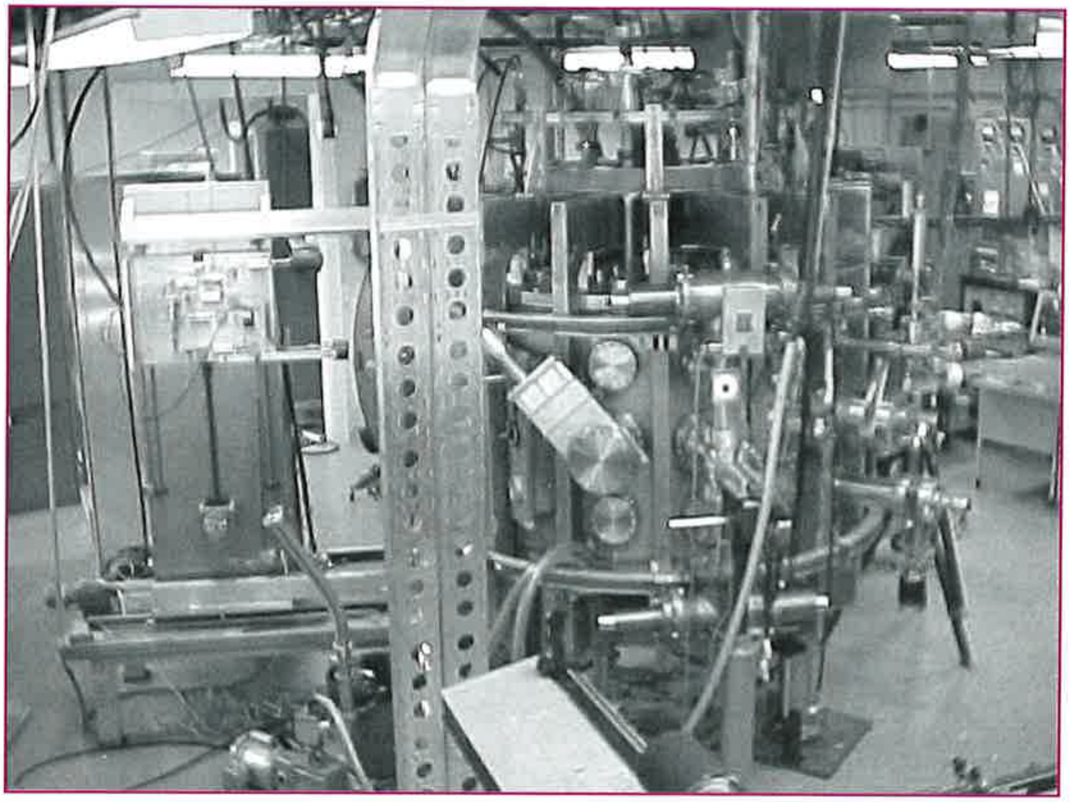


Figure 5. MHD activities during ohmic discharge evolution.

soft X-ray diagnostic. The density limit appeared to be most consistent with the Murakami-Hugill limit.

MHD instabilities played a prominent role in the plasma discharge evolution. Shown in Figure 5 is a frequency-time spectrogram of MHD activity during a typical plasma discharge. The continuous MHD activity is seen early on. It eventually slows down and locks, and may affect the flux consumption. The locking eventually leads to a kinking of the plasma (first large spike in the upper panel trace). Later on, global reconnection events (later spikes) lead to a decrease in the plasma current and stored energy. Successful reproductions of the plasma evolution in typical NSTX discharges has been accomplished in TSC simulations, and this should allow assessment of the stability of these plasmas to understand the MHD signals.

Current Drive Experiment-Upgrade



The Current Drive Experiment-Upgrade.

Technological progress and advances in fusion science have always gone hand in hand. One of the major technological problems facing the eventual commercial development of fusion energy is the design of a reactor wall which can survive the high heat and neutron fluxes generated by an ignited plasma. A novel and exciting recent development which promises to solve this longstanding engineering problem, while offering great physics benefits, is the development of the liquid metal wall concept.

Designs of inertial fusion reactors have relied for some time on the concept of a flowing liquid wall to guarantee survivability under conditions of repetitive micropellet ignition and burn. However, flowing liquid metal walls have only recently been proposed for magnetic fusion. In a tokamak, a flowing metal wall of liquid lithium may provide not only heat removal, but plasma stabilization to permit unprecedented high values of the plasma beta.

The very low recycling wall provided by liquid lithium promises high plasma performance under reactor conditions. Production of high-performance plasmas with lithium coated walls was first tested on the Tokamak Fusion Test Reactor, and resulted in the highest fusion power and gain obtained on that device. All these factors combine to make the concept of a tokamak reactor with flowing liquid lithium walls very attractive for fusion energy production.

The Current Drive Experiment-Upgrade (CDX-U) has recently begun a research program devoted to the investigation of plasma interactions with liquid lithium limiters and divertors. The program involves collaborations with numerous universities and national laboratories, including the University of California at San Diego, Oak Ridge National Laboratory, Sandia National Laboratories, Lawrence Livermore National Laboratory, Argonne National Laboratory, General Atomics, and the University of California at Los Angeles. Other institutions are participating through the Energy Advanced Liquid Plasma-facing Surface (ALPS) and Advanced Power Extraction (APEX) programs of the U.S. Department of Energy (DOE).

The goal of these experiments will be to produce a geometry in which the primary interaction of the plasma with a material wall is with a liquid lithium surface. Experiments will determine the effect of very low-recycling liquid lithium walls on the edge plasma, as well as on the core plasma parameters. The effect of plasma currents, including halo currents flowing in the edge plasma during MHD events, on the stability of the free liquid lithium surface will be investigated. This program is intended to form a strong experimental basis for the introduction of liquid lithium walls into larger confinement devices.

Facility Description

A schematic of CDX-U, indicating the magnetic field coils and vacuum vessel cross section, is shown in Figure 1. An extensive program of upgrades and modifications, which made the facility suitable for liquid lithium wall experiments, was completed in FY99. Power supplies originally installed at the Princeton Plasma Physics Laboratory (PPPL) for the Princeton Beta Experiment-Modification (PBX-M) were cabled to the CDX-U poloidal and toroidal field coils. The remaining CDX-U capacitor bank supplies, which power the ohmic solenoid and a new poloidal field coil designed to improve plasma initiation, were also upgraded. As a result, the maximum toroidal field has increased to 2.2 kG (from 1 kG), with a flattop of 100 ms.

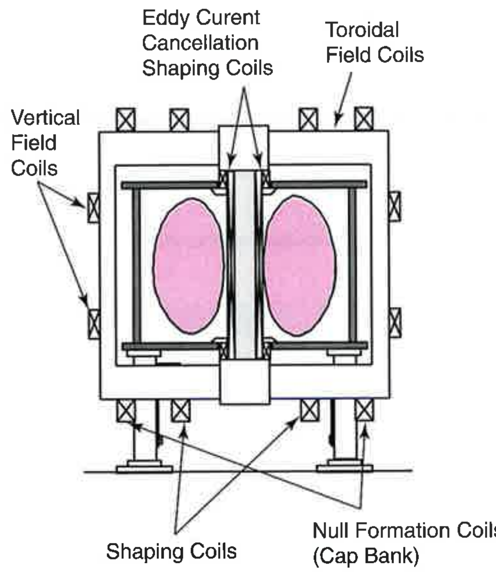


Figure 1. Cross-sectional view of CDX-U, highlighting the poloidal field coil set.

The new power supplies for the vertical and shaping fields will eventually permit discharges with plasma current up to 150 kA, while the discharge duration will be extended to greater than 25 ms. All power supplies (with the exception of the two capacitor banks) are presently preprogrammed and controlled by digital-to-analog waveform generators. Feedback control of radial and vertical position will be introduced during FY00. The plasma geometry remained substantially unchanged with major radius R = 34 cm, minor ra-

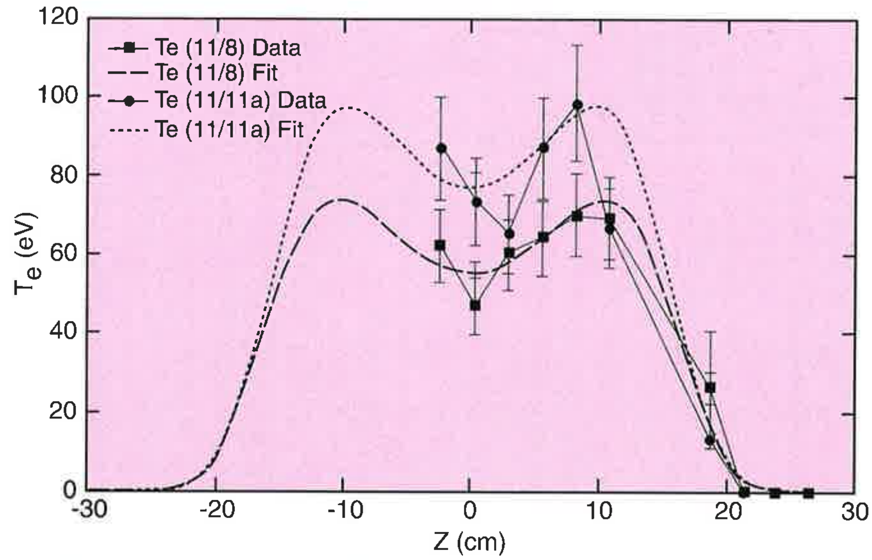


Figure 2. Electron temperature profiles from the new Thomson scattering diagnostic.

dius a = 22 cm, and an aspect ratio A = R/a ≥ 1.4.

A new transmitter for radio-frequency (rf) heating experiments in the High Harmonic Fast Waves (HHFW) regime has been completed. The transmitter will double the available rf power (from 100 kW to over 200 kW) to extend the liquid wall studies to higher power densities.

Plasma Diagnostic Development

A new Thomson scattering system became operational in FY99. The system utilizes a vertical laser beam and horizontal viewing of 12 radial points in the plasma discharge. The entire system (laser and viewing optics) is installed on a movable optical table, which can be repositioned on successive discharges to permit two-dimensional (2-D) images of the plasma. This diagnostic is now providing profiles of electron temperature (Figure 2) and density (Figure 3) at a single time point in the discharge. The Thomson scattering data will provide profile information for planned experiments in spherical torus (ST) transport, monitoring of the

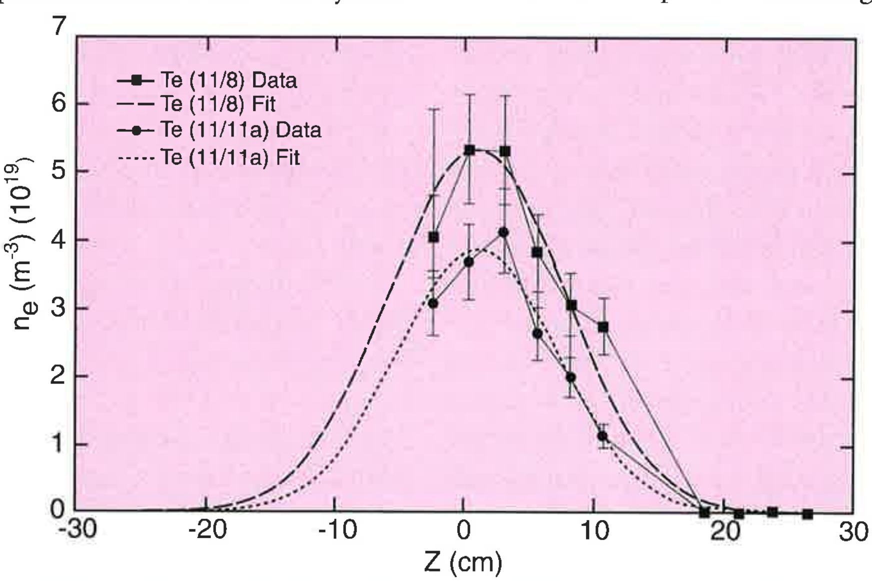


Figure 3. Electron density profiles from the Thomson scattering diagnostic.

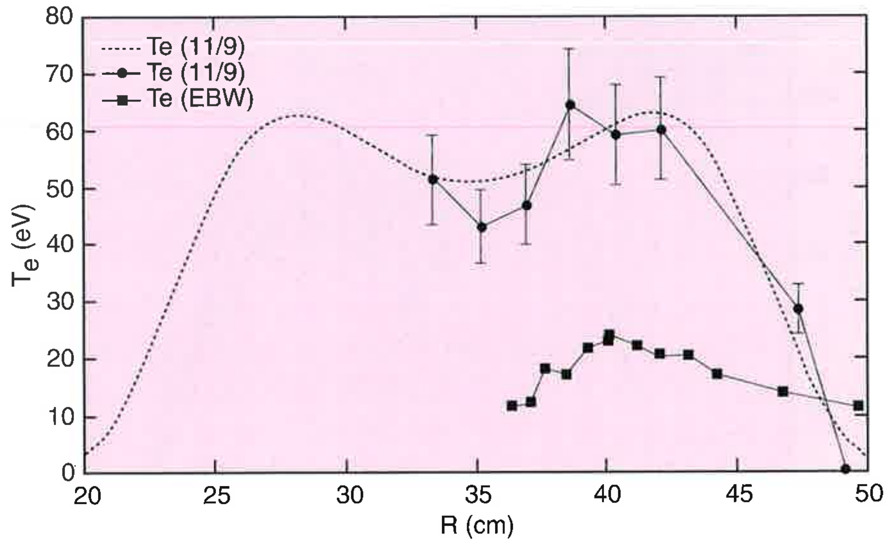


Figure 4. Comparison of Thomson scattering data and EBW emission. The EBW temperatures are lower due to polarization and mode conversion effects that are still being evaluated.

core plasma during liquid metal wall experiments, and calibration for advanced electron temperature diagnostics, such as the electron Bernstein wave (EBW) emission diagnostic.

The ST represents a novel plasma regime for large confinement experiments such as the National Spherical Torus Experiment (NSTX), and in some cases novel diagnostics are needed for the particular characteristics of the ST plasma. As part of the CDX-U program, an effort is underway to develop a replacement for the electron cyclotron emission (ECE) diagnostic on which conventional tokamak programs have long relied for detailed, time-resolved measurements of the electron temperature profile. The high density of a ST plasma relative to the magnetic field implies that $(\omega_{pe}/\omega_{ce})^2 >> 1$, where ω_{pe} is the electron plasma frequency and ω_{ce} is the electron cyclotron frequency. Under these conditions, electromagnetic radiation from the first four or five electron cyclotron harmonics cannot propagate from the emitting layer to the plasma edge, which prohibits conventional ECE diagnostics. The EBW will propagate to the plasma edge, however, where it can be either detected directly or mode-converted to an electromagnetic wave and collected with a microwave antenna.

A first test of the EBW diagnostic has been performed in CDX-U, and the results have been compared with the data from the new Thomson scattering diagnostic. Initial results (Figure 4) have been obtained with microwave antennas to detect the mode-converted EBW. While both sets of measurements show a similar trend with the plasma major radius (R), there is a large discrepancy in the electron temperatures deduced from them. A collaborative effort is presently underway with researchers at the Massachusetts Institute of Technology (MIT) to model the mode conversion efficiency, one of the factors that may account for this difference. Future experiments involving direct detection of the Bernstein wave are planned for FY00.

The plasma spectroscopy group at Johns Hopkins University has been a major participant in the CDX-U program for several years. During FY99, the Johns Hopkins group constructed, installed, and operated several new diagnostics on CDX-U. These include a new tangential bolometer array, a grazing incidence extreme ultraviolet spectrometer, and a multilayer mirror (MLM) array for ultrasoft X-rays. The MLM array is prototypical of an instrument designed for NSTX. The mirrors in the array presently image the 150 Å OVI line, and results which indicate a striking oxygen impurity accumulation in the CDX-U core plasma are shown in Figure 5. This core impurity accumulation may be responsible for the slightly hollow electron temperature profile shown in Figure 2. In addition to the OVI line, a set of mirrors has been prepared to image the 130 Å lithium line. The MLM array will therefore provide information on lithium influx and the profile of lithium accumulation during the upcoming liquid metal wall experiments.

Other diagnostics that became operational during FY99 include a fast, 10,000 frame-per-second visible light camera and two collaborator-developed diagnostics. These are a Fourier transform spectrometer developed at the Australian National University and a laser-induced fluorescence diagnostic developed and installed by Florida Agricultural and Mechanical University. The Florida system uses an argon ion laser to pump trace amounts of argon injected into the plasma discharge. The light emitted as the excited argon ions relax is detected by an array of photomultiplier tubes to provide information on edge plasma turbulence.

Future Plans

Experiments with liquid lithium will begin with a removable rail limiter, to be designed and constructed by the PISCES group at the University of California, San Diego. Installation of the rail limiter and additional associated diagnostics is scheduled for the spring of 2000. Following about three months of experiments with the rail limiter, a toroidal liquid lithium

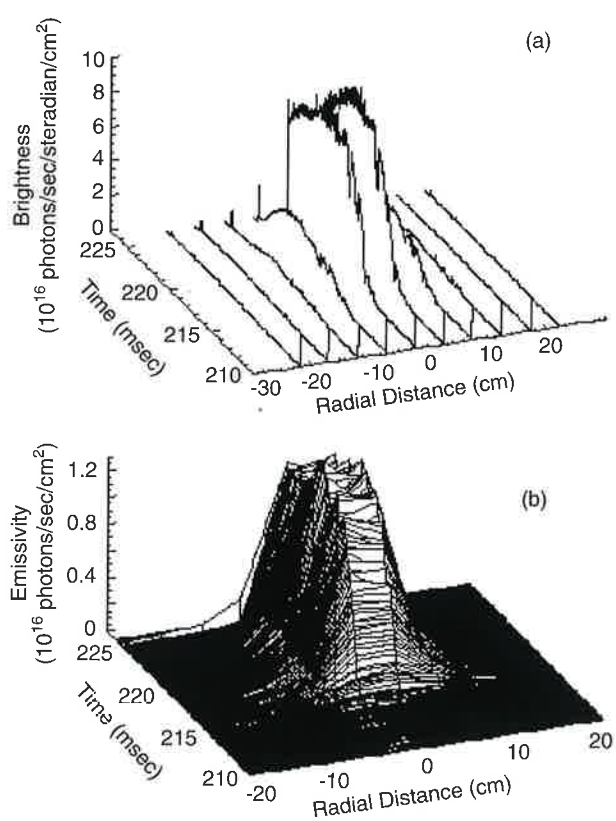


Figure 5. Data from the Johns Hopkins Multilayer Mirror Array showing line-integrated (a) and Abel inverted (b) profiles of OVI emission.

"tray," which is designed to function as a toroidal belt limiter, will be installed in CDX-U. Experiments with the toroidal tray will utilize the diagnostic set developed during the rail limiter experiments. During FY01, the toroidal limiter tray will serve as a single-null divertor target, when additional poloidal field coils are added to CDX-U to permit positioning of an X-point above the lithium tray.

During the lithium experiments, the EBW emission investigations will continue. Low power EBW heating investigations using 14 GHz klystrons on loan from the University of Wisconsin PEGASUS program are also planned. In addition, there will be upgrades to increase both the level of auxiliary HHFW heating and the pulse length of CDX-U. This will permit the liquid wall experiments to be extended into more relevant parameter regimes.

Collaborations and Graduate Studies

The liquid lithium wall effort has introduced a major new component into CDX-U collaborations. The first liquid lithium system to be installed in CDX-U will be a rail limiter designed and constructed by collaborators from the University of California, San Diego. They will also participate closely in the experiments with this limiter. Numerous other institutions associated with the USDOE ALPS and APEX programs to develop liquid metal walls and limiters will participate in these experiments also.

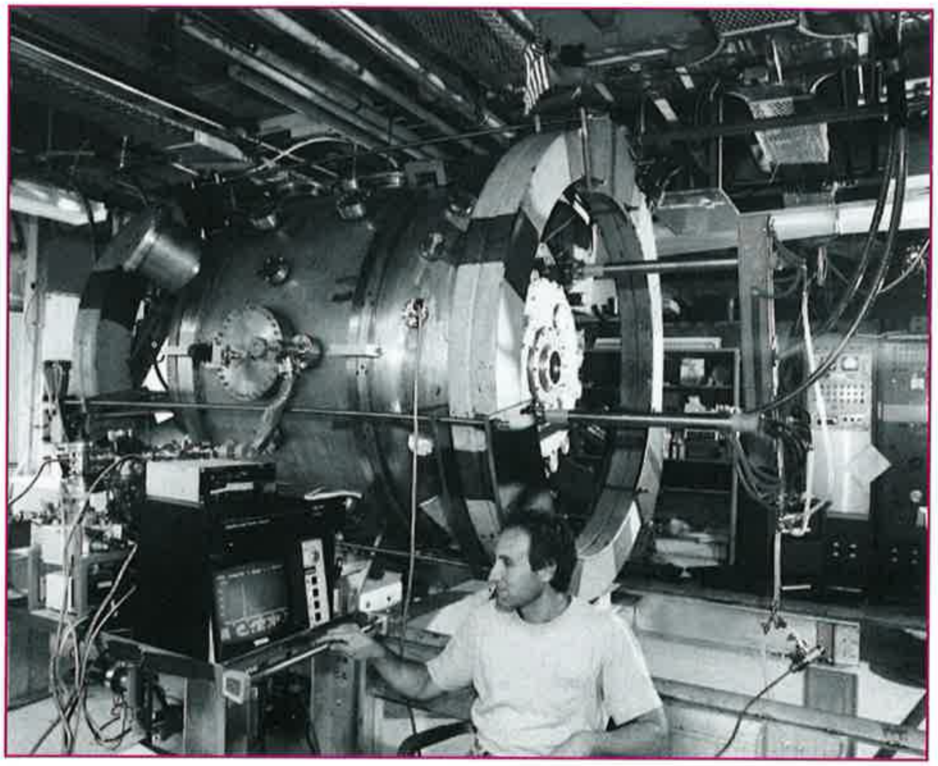
The CDX-U group and the plasma spectroscopy group at Johns Hopkins University, Baltimore, plan to continue their long-term collaboration in the area of diagnostic development for the ST. The CDX-U group also maintains ongoing collaborations with the University of Wisconsin, Madison, the University of Tokyo, Japan, the A.F. Ioffe Physical-Technical Institute, St. Petersburg, Russian Federation, and the Hebrew University, Israel. In addition, CDX-U scientists have worked with ST researchers from the Small Tight Aspect Ratio Experiment at Culham Laboratory in England. A collaboration with Fisk University and Florida Agricultural and Mechanical University resulted in the installation and preliminary testing of a laser-induced fluorescence diagnostic for the study of edge plasma turbulence, and this work will be continued in FY00.

A primary role of CDX-U at PPPL has always been to serve as a training ground for graduate students in experimental plasma physics. Princeton University graduate student Tobin Munsat is expected to defend his doctoral thesis on transport in an auxiliary-heated ST in the spring of 2000. Vladimir Soukhanovski, a graduate student from Johns Hopkins University, is expected to complete his thesis research on CDX-U in the same time frame. Brent Jones, another Princeton University student, is currently collecting data for his thesis research on EBW emission on CDX-U. Graduate students from Florida Agricultural and Mechanical University used data collected on CDX-U as part of their Master of Science thesis research.

The CDX-U played a significant role in the PPPL Plasma Science and Fusion Energy Institute, a summer training program for high school science teachers. Since CDX-U now has a particularly simple control interface, it was possible for the teachers to design their own experiments and operate the machine as part of their summer research experience.

Undergraduate and high school students have also worked with CDX-U as part of summer science honors programs. It is hoped that this strong commitment to education will continue in FY00 and beyond.

Magnetic Reconnection Experiment



The Magnetic Reconnection Experiment.

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

Despite its omnipresence, reconnection is not a well-understood phenomenon. In laboratory fusion plasmas, such as tokamaks, reconnection manifests itself as "sawtooth" oscillations in electron temperature and ultimately degrades plasma confinement. In nature, reconnection plays an important role in the dynamics of solar flares and in the origins of the aurora borealis. In recent years, the solar satellite Yohkoh has produced remarkable pictures of the Sun, shown in Figure 1, and has provided the best evidence yet that reconnection is involved in solar flare energy release. However, the rate of energy release is a mystery, unaccountable by current understanding of reconnection physics. The observed "fast reconnection" has made magnetic reconnection a very active area of research.

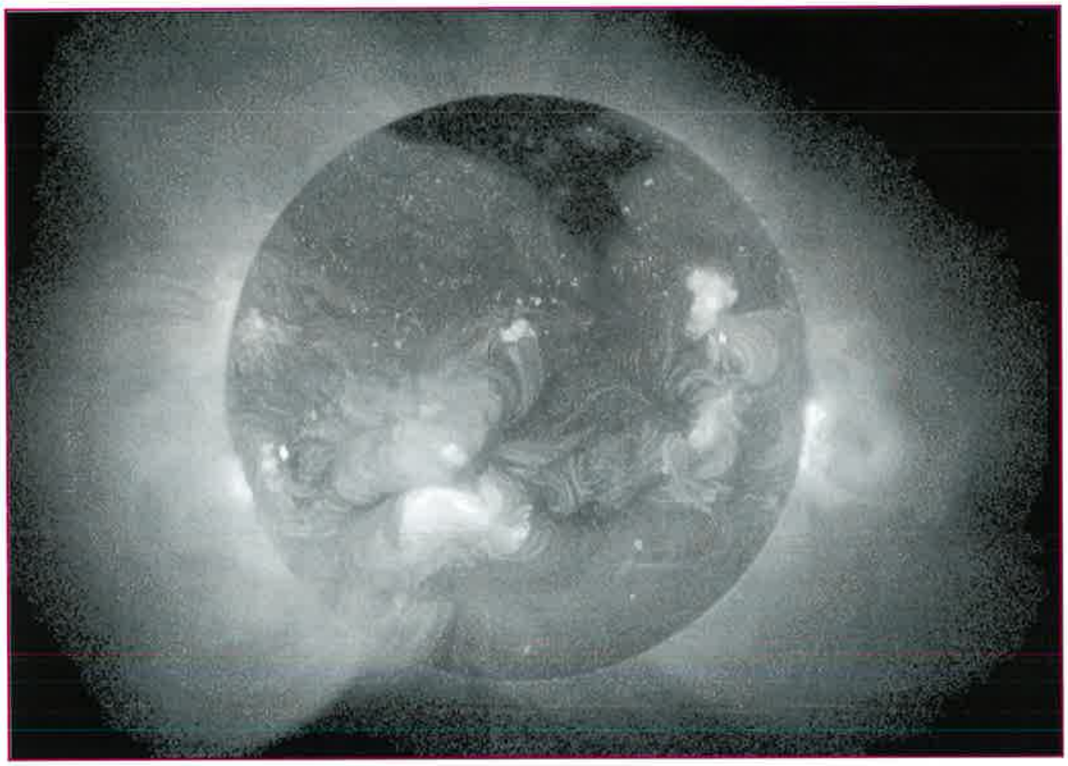


Figure 1. Soft X-ray picture of the Sun taken by the Yohkoh satellite. Visible are bright spots, called "active regions" which are believed to be associated with strong magnetic activity including magnetic reconnection.

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

The small size and rich plasma physics of MRX make it an ideal facility on which to study basic science and to train graduate students. Because of the strong impact of this experiment on many fields of research, MRX is jointly funded by the U.S. Department of Energy, the National Science Foundation, and the National Aeronautics and Space Administration.

Research Objectives

The primary objective of experiments on the Magnetic Reconnection Experiment is the comprehensive analysis of magnetic reconnection both locally and globally in solar and magnetospheric relevant plasmas. The analysis focuses on the coupling between microscale features of the reconnection layer and global properties such as the driving force, the magnetohydrodynamic (MHD) flows, and the third component of the magnetic field.

In particular, MRX has the following research goals:

- Experimentally evaluate two-dimensional theoretical models;
- Determine the circumstances under which three-dimensional effects will dominate;
- Study global MHD issues, including evolution of magnetic helicity;
- Identify the mechanisms by which magnetic energy is converted to plasma flow and thermal energies;

- Investigate the role of non-MHD physics in the reconnection layer.

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

Experimental Setup

Two plasma toroids with identical toroidal currents are formed using inductive electric fields generated from two sets of coil windings. The two plasma toroids are then merged together via (1) their mutually attractive force and (2) an applied external magnetic field. MRX was designed to achieve a variety of merging geometries and magnetic field topologies. Two types of reconnection have been studied: null-helicity and co-helicity. In the former there is no toroidal magnetic field in the reconnection layer, and in the latter there is a sizable toroidal field. Qualitative differences in the reconnection layer arise depending on the presence of the toroidal field. A picture of an MRX plasma discharge appears in Figure 2.

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

Results

Experimental Test of the Sweet-Parker Model. The well-known Sweet-Parker model of magnetic reconnection predicts reconnection rates faster than that of resistive diffusion, but much slower than those observed in solar flares. The model is a resistive MHD model and assumes a two-dimensional, incompressible,

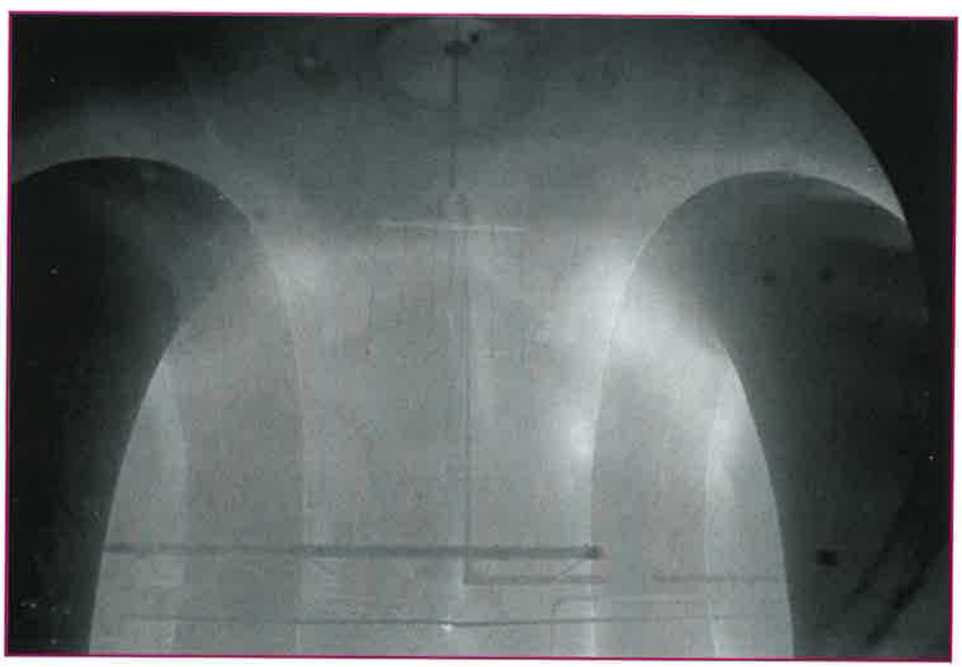


Figure 2. A plasma discharge in the Magnetic Reconnection Experiment.

and steady-state plasma. Despite these constraints, however, the model captures many of the essential local features of the magnetic reconnection layer. For forty years, the merits and shortcomings of this and other more elaborate models have been debated. The first laboratory experiments on the Sweet-Parker model were performed on MRX.

Null-helicity experimental data indicated a reconnection speed consistent with a generalized Sweet-Parker model, which includes the effects of plasma compressibility, finite pressure in the downstream region of the field lines, and nonclassical plasma resistivity. Compressibility allows more incoming plasma to accumulate in the current sheet, leading to a slight enhancement in reconnection speed over the classical Sweet-Parker speed. Conversely, finite downstream pressure hinders the outgoing plasma, leading to a reduction in plasma outflow speed and hence reconnection speed. The measured plasma resistivity was found to be enhanced over the classical Coulomb-collision value by up to a factor of ten; this enhancement is thought to play a crucial role in determining the reconnection rate. Further experiments investigated the validity of the generalized model for co-helicity reconnection. It was found that the reconnection rate in the co-helicity case agreed with the generalized Sweet-Parker model within experimental error. Figure 3 shows the experimentally measured reconnection rate plotted as a function of the generalized Sweet-Parker value for both null-helicity and co-helicity reconnection. These combined results suggest that the Sweet-Parker model with nonclassical resistivity may explain the fast reconnection required to be consistent with solar flare observations.

Testing the Sweet-Parker model in a laboratory experiment is an important first

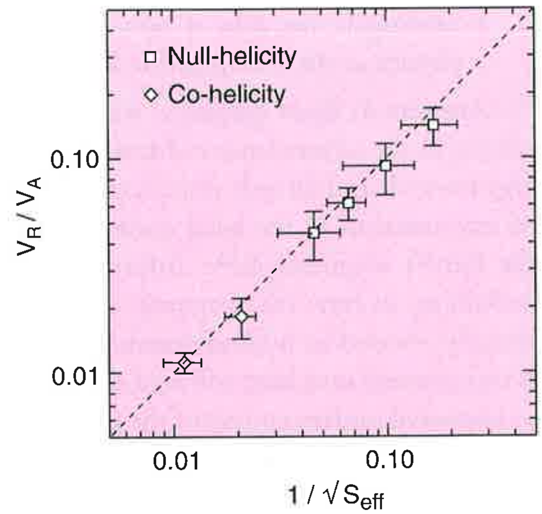


Figure 3. Experimentally measured reconnection rate (in flow speed, V_R, divided by Alfvén speed, V_A) in MRX.

step in sorting out the essential physics behind "fast reconnection." However, much research must be performed before any definitive answers can be obtained. Most important is the identification of (non-MHD) mechanisms for the enhanced, nonclassical resistivity.

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

In collaboration with Dr. G. Fiksel of the University of Wisconsin, an optical probe called IDSP (Ion Dynamic Spectroscopy Probe) was inserted to measure local ion temperature and flows during reconnection events. In null-helicity reconnection, a clear surge in ion temperature by a factor of up to three during reconnection phase was observed (see Figure 4) while the ion temperature was basically flat when no reconnection is induced. Spacially resolved measurements showed that ions are heated only in the diffusion region, further indicating direct ion heating due to the reconnection process. In co-helicity reconnection, a weaker ion heating was measured to be consistent with a slower reconnection rate compared to the null-helicity case.

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

MRX results showed that about 65% of magnetic energy is directly converted to ion thermal energy, of which only 17% can be accounted for by classical processes, including viscous heating. As a result, roughly 50% of dissipated magnetic energy is converted to ion thermal energy through nonclassical processes. Experimentally, it was observed that the ion energy increase correlates well with resistivity enhancement, suggesting that the same

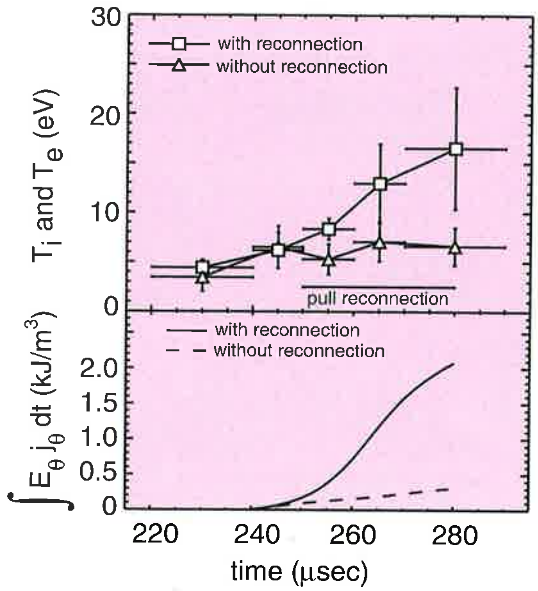


Figure 4. Time evolution of ion temperature (top) and magnetic energy dissipated per unit volume (bottom), both in the center of reconnection layer, indicating the causality between reconnection and ion heating.

fast reconnection mechanism(s) also directly heats ions.

Study of Current Sheet Profile

In 1962, E.G. Harris found an elegant collisionless solution of the one-dimensional equilibrium profile when plasma is confined by oppositely directed magnetic field, a situation which is very similar to magnetic reconnection. Since then, many theoretical and numerical studies of magnetic reconnection use the Harris solution of magnetic field profile, $B(x) \sim B_0 \tanh(x/\delta)$. However, this profile has not been observed in real plasmas.

In MRX, the precise profiles of magnetic field across the current sheet has been measured by a very high-resolution magnetic probe array (5-mm spatial resolution). It turns out that the measured magnetic profiles fit very well the Harris solution, as shown in Figure 5. This agreement is remarkable since the

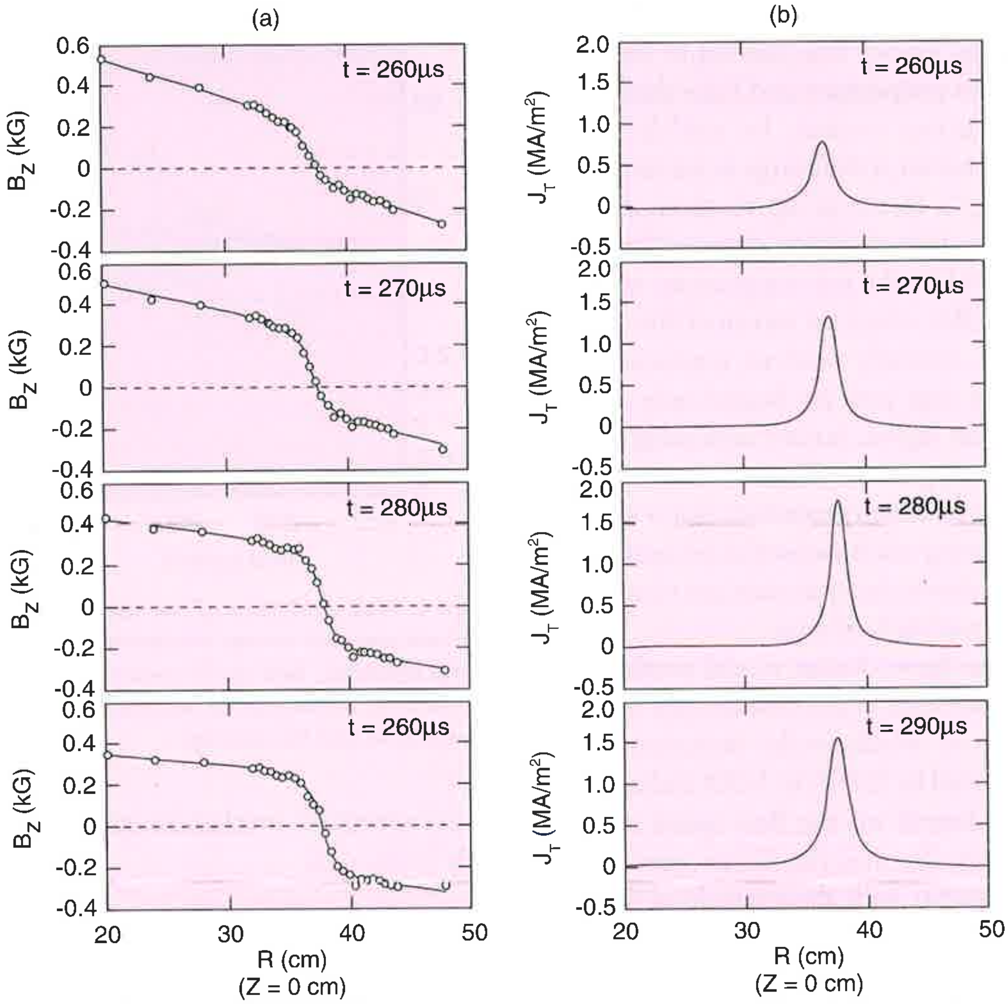


Figure 5. (a) Radial profile of reconnecting magnetic field (B_Z) measured by a high-resolution magnetic probe array. (b) Current sheet inferred from B_Z measurements. The thickness of the current sheet is approximately c/ω_{pi} and also ρ_i.

Harris theory does not take into account reconnection and associated electric fields and dissipation. The sheet thickness δ is found to be approximately 0.4 times the ion skin depth, which agrees with a generalized Harris theory incorporating non-isothermal electron and ion temperatures and finite electric field. Interestingly, both in the magnetotail and the magnetopause of the Earth's magnetosphere, it has also been observed that the thickness is on the order of the ion skin depth.

Future Work

Future work will address the source of the enhanced resistivity, including the role played by waves, instabilities, and turbulence. The reconnection process in global MHD aspect and three-dimensional perturbations to the quasi two-dimensional current sheet geometry will be studied concurrently.

The results from these efforts should bring us closer to understanding the fundamental process of magnetic reconnection.

Fusion Theory and Advanced Computing

During fiscal year 1999, the Princeton Plasma Physics Laboratory (PPPL) Theory Department continued its lead role in helping the U.S. Department of Energy's (DOE) Fusion Energy Sciences Program attain the scientific understanding needed to establish magnetic confinement of plasma as an attractive, technically feasible fusion reactor option. This involves innovative development of improved calculation capabilities and the application of state-of-the-art theoretical and computational tools to the interpretation of experimental results. Predicting the properties of an energy-producing fusion plasma is a great scientific challenge which depends on the integration of many complex physics phenomena that cannot be deduced from empirical scaling and extrapolation alone. Increasingly powerful computational resources have stimulated progress, and the PPPL Theory Department continues to be at the forefront in demonstrating how such capabilities advance scientific knowledge and impact innovation.

The research areas addressed by the Theory Department impact plasma science issues of importance to all of the major magnetic confinement experiments and to the design and operation of proposed future devices. Key topics include:

- classical as well as turbulence-driven transport in the presence of sheared magnetic topology and plasma flow;
- dynamical interplay between small-scale dissipation mechanisms and the evolution of large-scale MHD systems;
- wave-particle interactions featuring energetic particle dynamics and their influence on alpha-particle physics in present-day experiments and future ignited plasmas; and
- plasma boundary physics with emphasis on a realistic depiction of the transport of neutrals which is needed to realistically assess the properties of advanced divertor configurations.

The PPPL Theory Department fulfills its mission in a cost-effective manner:

- by generating the physics knowledge required for realistic extrapolation of present experimental results;
- by suggesting new approaches to stimulate experimental campaigns to improve performance;
- by developing improved theoretical analysis capabilities that are fundamentally sound;
- by contributing to the innovative design of new experimental devices; and
- by providing a stimulating research environment which effectively enables the Laboratory to attract, train, and assimilate the young talent es-

sential for the excellence of the plasma sciences.

Achieving the Theory Department goals requires continued advances in analytical capabilities, together with the active applications of the best existent theoretical tools for interpretation and design. Key contributions to the areas highlighted below are reminders of the lead role theory can play in the fusion program. They underscore the fact that many of the advances in the field have resulted from an improved understanding of the basic mechanisms involved in toroidal confinement, not just from the development of empirical rules for scaling. The continuing improvements in operating regimes in magnetically confined plasmas and in diagnostic techniques should enable even more realistic comparisons of experimental results with theoretical models. As more reliable physics-based models emerge, it is expected that the pace of breakthroughs will be accelerated by more efficient harvesting of key results from experimental facilities and from identification of attractive new approaches and the associated designs for new facilities.

Examples of significant progress in the fusion program enabled by scientific results from the PPPL Theory Department are discussed below.

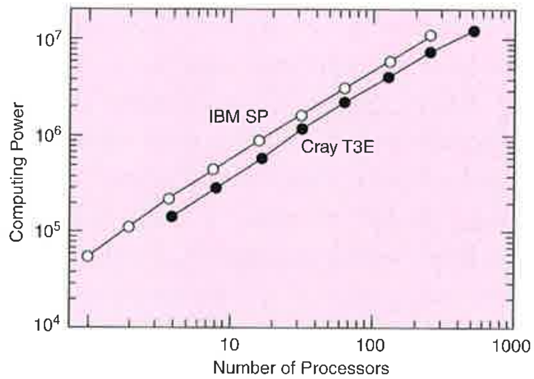
Three-Dimensional Nonlinear MHD

The physics capabilities of the three-dimensional extended-MHD code, M3D, have been significantly improved and generalized in collaboration with New York University and the Massachusetts Institute of Technology to enable more realistic analysis of advanced tokamaks and alternate concept devices. Accomplishments include:

- Utilization of M3D's two-fluid capability to calculate the growth and rotation of magnetic islands in tokamaks — an important step in the development of an appropriate nonlinear computational model for studying the neoclassical tearing mode.
- Derivation and successful implementation of finite Larmor radius corrections to the energetic-ion pressure response, enabling the application of a model with gyrokinetic ions and fluid electrons to show reduction of the growth rate of the fishbone mode due to Landau damping by background thermal ions; and the application of a model with fully kinetic (nongyrokinetic) ions in productive studies of configurations without a strong toroidal field, such as Field Reversed Configurations.
- Addition of an all-real-space three-dimensional representation to the existing two-dimensional real-space and one-dimensional Fourier-space, unstructured mesh version of the M3D code. This allows study of stellarator configurations with non-axisymmetric boundaries, and enables investigations of key questions, such as under what conditions good flux surfaces exist in stellarators, and what the nonlinear consequences of instabilities might be in new configurations, such as the National Compact Stellarator Experiment (NCSX).

Turbulent Transport Simulations and Analysis

Gyrokinetic Simulations. Transport scalings, with respect to collisionality and device size, have been obtained from massively parallel gyrokinetic particle simulations of electrostatic toroidal ion-tempera-



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

Three-dimensional Gyrokinetic Turbulence Code is scalable on massively parallel computers.

ture-gradient turbulence in the presence of zonal flows. Simulation results show that ion thermal transport from electrostatic ion-temperature-gradient turbulence depends on ion-ion collisions, due to the neoclassical damping of self-generated zonal flows that regulate the turbulence. Fluctuations and heat-transport-level exhibit bursting behavior with a period corresponding to the collisional damping time of poloidal flows. Results from large-scale full-torus simulations with device-size scans indicate that ion-temperature-gradient transport can deviate from the gyro-Bohm scaling, even with small-scale fluctuation and isotropic spectra. With regard to more comprehensive treatment of electron dynamics, significant progress has been achieved with the innovative introduction of a split-weight scheme. This new method has been successfully demonstrated for treating nonadiabatic electron dynamics in simple geometry.

Gyrofluid Simulations. The nonlinear gyrofluid (GF) code has been extended to include fully electromagnetic fluctuations, and initial studies have been carried out. These are especially important in regions of large pressure gradients, such as in the National Spherical Torus Experiment (NSTX), in advanced tokamak regimes, or in other advanced fusion concept operating scenarios. Building upon its well-established capability for dealing with effects of turbulence-generated small-scale fluctuating E×B zonal flows, the gyrofluid code has now been extended to include the linear effects of external E×B shear flow, such as those driven by neutral beams. It is presently being exercised in studies of this stabilizing effect in optimized shear discharges in the Joint European Torus, in NSTX, and other experiments.

Kinetic Electromagnetic Analysis

A generalized gyrokinetic formalism called the gyro-gauge kinetic theory has been derived to nonperturbatively deal with kinetic effects on global MHD modes including the ability to account for high-frequency modes such as Ion Bernstein Wave and Compressional Alfvén wave. The new electromagnetic code, KIN-2D, has now been successfully benchmarked against the PEST and NOVA-K codes with numerical results calculated for the n=1 kink mode and the n=2 Toroidal Alfvén Eigenmode (TAE) mode.

Basic Turbulence

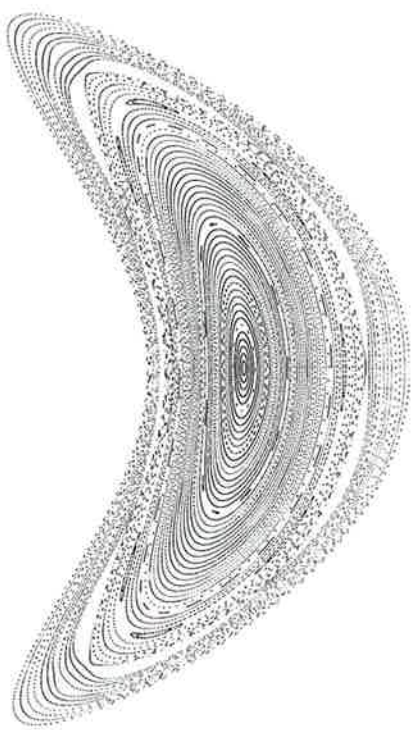
Theoretical analysis was directed toward understanding the assertion that long-time, nonintegrable tails on experimentally measured correlation functions may vitiate the "standard transport paradigm" (of local, diffusive transport). The topic is related to the relevance of self-organized criticality in microturbulent transport, and involves fundamental issues of nonequilibrium plasma statistical dynamics. A nonlinear stochastic model was constructed that reproduces the salient features of the observed tails, yet lacks crucial features of self-organized criticality. Both theoretical and numerical analysis lead to the conclusion that such tails are generic and are not necessarily associated with the breakdown of local transport.

Stellarator Physics

Excellent progress on key physics issues arising in the design of a compact stellarator experiment has continued to be made in the past year with numerous papers published. Results include:

MHD Stability. Improved diagnostics have been added to the Terpsichore 3D MHD stability code, and have been used to elucidate the physics of kink mode stabilization. It has been found that stabi lization via three-dimensional shaping works by producing a strong local shear. In kink stability calculations at a beta of 4%, the destabilizing contributions due to the current and the pressure are roughly equal.

Equilibrium Flux Surfaces. Improvements have been made to the PIES code algorithm to increase its speed. An improved blending algorithm for handling PIES initialization with a VMEC solution has been incorporated, and has speeded up W7X calculations by about a factor of 6. Also in collaboration with the Institute for Plasma Physics in Greiswald, Germany, the free-boundary version of PIES has been improved. Specifically, the normal component of the magnetic field is now adjusted at the "control surface" interfacing the external Green's function solution (provided by the NESTOR code) with the interior PIES solution. The field line following in the code has also been speeded up by transforming from a Fourier representation to a spline representation of the magnetic field. For speeding up the Ampere's Law solution in the code, it has been recognized that key matrix inverses can be stored after the first iteration, and do not need to be recalculated.

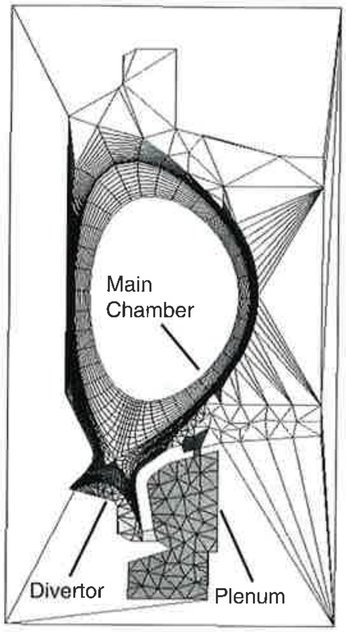


Poincare plot showing the flux surfaces for an NCSX configuration. The plot was produced by computation with the PIES code.

Plasma Control. A control matrix method has been developed which applies singular value decomposition methods to determine the adjustments to coil currents required to control key physics properties. The method has been applied to study the control over transport and stability properties available in a candidate coil set, and will be applied in the assessment of future coil designs.

Axisymmetric Modeling of Noninductive Current Build-up in Spherical Torus

An investigation of the feasibility of increasing the toroidal current in a spherical torus via noninductive current drive was performed using the TSC code. It was concluded that building up the plasma current by way of bootstrap overdrive should be possible, but the timescales for this are very long due to the desire to avoid transient back-currents. TSC modeling of existing NSTX plasma current evolution has been very successful, giving excellent



Contour plot of molecular deuterium pressure in a DEGAS 2 simulation of the Alcator C-Mod divertor baffling ("flapper") experiments, showing the flow of gas from the divertor region through the plenum and into the main chamber.

agreement with the experimental data. The current evolution in the coaxial helicity injection experiments has also been modeled by including the coaxial helicity injection voltage source, and allowing for current flowing on the open filed lines.

Plasma Boundary Physics

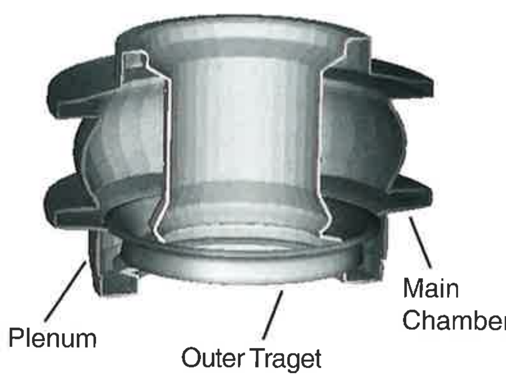
The coupling of the DEGAS 2 neutral and Lawrence Livermore National Laboratory's UEDGE fluid plasma transport codes was demonstrated. H. Takenaga (Japan Atomic Energy Research Institute) has modeled JT-60U (tokamak in Japan) and DIII-D (tokamak at General Atomics in California), running the coupled codes in a noniterative mode. Neutral-neutral elastic scattering has been added to DEGAS 2 by R. Kanzleiter (Rensselaer Polytechnic Institute) as part of his thesis work. Initial efforts indicate that the elastic scattering processes will be critical to understanding Alcator C-Mod's (tokamak at the Massachusetts Institute of Technology) divertor baffling ("flapper") experiments. There are now at least five external sites using DEGAS 2.

Resistive Wall Modes

A circuit equation formulation of resistive wall mode feedback stabilization schemes, which had been developed for a straight plasma column, has now been extended to a toroidal configuration. It is being benchmarked on DIII-D in anticipation of its use for NSTX. The PEST code has been modified and tested to approach within 0.9999 of the flux at the separatrix.

RF Physics

New results from systematic studies of plasma rotation induced by Ion Cyclotron Range of Frequency (ICRF) heating in tokamaks have shown that even though ICRF introduces no angular momentum into a tokamak, the torque density source consists of separate regions of positive and negative torque. This process has been



Cut-away view of a three-dimensional visualization of the hardware geometry used in DEGAS 2 simulations of the Alcator C-Mod divertor baffling "flapper" experiments. The ring-like structure near the bottom is the outer divertor target. A realistic treatment of the vacuum plenum region is included to permit modeling of the flow of gas from the divertor through the plenum to the main chamber.

studied with a Hamiltonian-guiding center code, ORBIT, with ion-ion pitch-angle scattering and drag, and Monte-Carlo initial particle distributions fitting expected ICRF profiles. A diffusion equation for the angular momentum transport then gives a plasma rotation profile. When the resonance location is on the low-field side, the calculated rotation has the magnitude, profile, and co-current sense of Alcator C-Mod observations. Tore Supra (tokamak in France) heats primarily on the high field side, and simulations in this case give negative central plasma rotation, in agreement with the Tore Supra observations. Scaling to reactor size devices follows a diamagnetic velocity relation.

Advanced Computing

As noted earlier, the advanced scientific computing activity at PPPL is an integral part of the research program in the Theory Department. In this area, PPPL has continued to provide the national leadership and technical progress essential for the effective development and deployment of advanced computing capabilities to deal with problems of extraordinary complexity encountered in the plasma sciences. This involves the application of modern computational techniques and high-performance computers to address outstanding issues facing fusion energy research. PPPL has responded to the charge from the USDOE Office of Fusion Energy Sciences (OFES) to take the lead role in working with the rest of the fusion community to develop an appropriate vision and implement the associated plan for the Plasmas Science Advanced Scientific Computing Initiative (PSACI).

Technical progress, which has entailed close collaborations between the Theory Department and the Computational Physics Group at PPPL, includes the introduction of new physics capabilities and the conversion and optimization of several major PPPL codes to effectively utilize massively parallel computers. Associated activities involved the introduction of new algorithms and computational techniques and the application of modern visualization tools.

Participation in the new advanced computing programs proposed by the DOE Office of Science is of great benefit to the Fusion Energy Sciences Program with respect both to accelerated research and the general perception of its scientific stature.

The PSACI represents the OFES thrust in this key area. It aims to discover and employ crosscutting computer science and applied mathematical methods to help drive research progress and also to begin to establish a national terascale distributed scientific simulation infrastructure for the plasma sciences. Because of the broad scope of the PSACI and the eventual need for possible interagency and interdisciplinary coordination, it will be managed as a project at all levels.

In the interest of the overall U.S. Fusion Energy Sciences Program, PPPL was chosen by OFES to serve as the lead institution in managing PSACI research activities. The pilot programs to be launched during FY00 are expected to enable new capabilities in realistic transport and turbulence simulations and in nonlinear macroscale simulations.

In the coming year, the advanced scientific computing program at PPPL will participate in the research and provide leadership for the PSACI. In response to the charge from OFES, PPPL will also continue to build the infrastructure capabilities needed to establish a Distributed Center of Excellence in Computational Plasma Science.

Off-Site Research

Princeton Plasma Physics Laboratory (PPPL) scientists conduct research on leading domestic and international off-site facilities to address key scientific issues emphasizing PPPL's core competencies in theory, diagnostics, experiment design and analysis, and operations. PPPL's domestic collaborations on DIII-D at General Atomics (GA) and Alcator C-Mod at the Massachusetts Institute of Technology (MIT) focus on optimization and understanding of the tokamak. International collaborations focus on large-scale burning-plasma issues and long-pulse steady-state issues.

The primary tokamak physics issues are the understanding and the knowledge-based control of the spatial profiles of the plasma current density, pressure, and transport, as well as improvement of macroscopic stability by feedback control of wall modes and neoclassical tearing modes. In innovative concepts, researchers apply PPPL's toroidal physics expertise and tools to promising toroidal magnetic confinement concepts and apply diagnostic and analysis techniques to increase understanding, with the objective of exploiting that understanding to improve performance and to optimize the concepts.

Doublet-III-D Collaboration

PPPL is a major collaborator in the tokamak program at the DIII-D National Fusion Facility at GA. The collaboration was extremely productive during 1999. PPPL physicists made substantial contributions to DIII-D results reported in journals and in papers presented at major conferences, and also played leading roles in planning and execution of experiments. PPPL engineering and technical staff completed important projects needed for calendar year 1999 (CY99) and CY00 experiments and provided valuable support for the CY99 DIII-D major shutdown activities. PPPL also continued to provide needed operations engineering and applications software support.

Stability

In collaboration with researchers from Columbia University, the Oak Ridge National Laboratory (ORNL), and GA, PPPL researchers conducted the first tests of active feedback stabilization of resistive wall modes (RWM) and reported favorable results. Stabilization of RWM is a very important element in the development of high-performance advanced tokamak plasmas, and DIII-D is the only large tokamak with a major effort in that area. The main objective of the first experiments was to stabilize the RWM by creating a "perfectly" conducting shell with active compensation of the n=1 flux leaking through the resistive vacuum vessel. Results indicate that the n=1 flux leakage from the vacuum vessel can be compensated by the feedback system. The amplitude of the magnetohydrodynamic (MHD) mode was reduced, and its onset was delayed. In addition to this so-called "smart shell" technique, a survey of several other control methods was carried out, including a preprogrammed rotating magnetic field and the "fake rotating shell" and "mode control" feedback schemes. In FY00, these experiments will be extended to higher-performance plasmas and will emphasize optimization of control algorithms.

The FY99 experiments were enabled by the delivery and commissioning of three switching power amplifiers, which were procured by PPPL to provide current to the feedback control coils. In the initial experiments, one power amplifier supplied both feedback control and error field correction to each of the three pairs of existing active coils (C-coils) at modest current. After delivery, installation, and commissioning of the remaining two power supplies, which was accomplished seven months ahead of schedule, the experiments were extended to higher-performance plasmas.

Figure 1 illustrates the feedback stabilization scheme. Magnetic fields produced by nonaxisymmetric MHD modes are detected by six "saddle loops," which were installed by PPPL in FY98. Each saddle loop sensor covers a 60° toroidal segment on the DIII-D midplane and is paired with the diametrically opposed loop. This arrangement provides three signals for determining the amplitude and toroidal phase of the modes. After processing the sensor data using one of a variety of feedback algorithms, control commands are generated for the three power supplies, each of which energizes one pair of the six active coils. To improve characterization of the helical structure of resistive wall modes during CY00 experiments, PPPL has installed twenty-four new saddle loop sensors in two toroidal arrays of twelve coils each, as shown in Figure 1.

Among other experimental results obtained in FY99, the first attempts at feedback stabilization of low-density locked modes were not successful, but analysis suggests that application of feedback earlier in the plasma discharge, and use of improved feedback algorithms, may allow control of locked modes. Soft X-ray measurements of plasmas with resistive

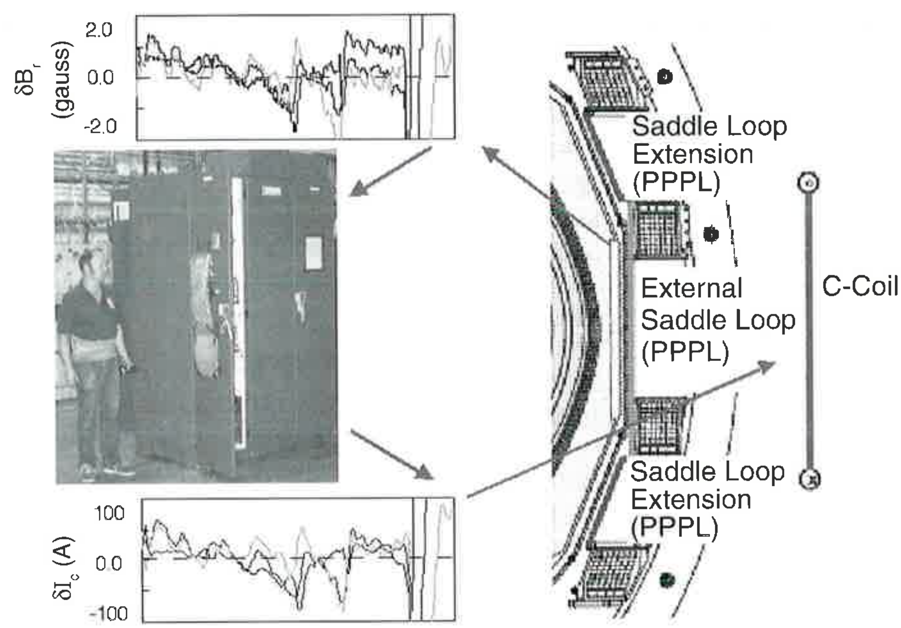


Figure 1. Schematic illustration of the feedback stabilization equipment used on DIII-D, including input and output waveforms for the three switching power amplifiers.

wall modes, using toroidally separated cameras, are in good agreement with saddle loop magnetic measurements and confirm the n=1, kink-like mode structure. The first measurements on DIII-D of halo currents during nondisruptive MHD events were also reported.

Confinement and Transport

The second area of major emphasis of the PPPL/DIII-D collaboration was in the formation and sustainment of internal transport barriers. In FY99, PPPL collaborated in a number of experiments on DIII-D aimed at understanding internal transport barrier dynamics and demonstrating some degree of barrier control. Studies with counter neutral-beam injection complemented previous work performed with co-injection, as well as that performed on the Tokamak Fusion Test Reactor (TFTR) with co and counter neutral-beam injection. The role of the interplay between pressure and rotation drive in governing barrier dynamics was examined using data from these studies. It was shown that barrier dynamics are critically dependent on the alignment of pressure and rotation profiles.

Wave-Plasma Interactions

Studies of electron cyclotron heating (ECH) and electron cyclotron current drive (ECCD) are central to DIII-D's mission to develop the tools necessary for advanced tokamak operation. These tools will also be useful for alternate concept research and for standard tokamaks. Specifically, the ECH/ECCD program will use high-power gyrotrons for localized control and modification of pressure and current profiles, and for suppression of neoclassical tearing modes. In addition, heating in the ion cyclotron range of frequencies (ICRF) has played a prominent role in past experiments on DIII-D and will be used in conjunction with ECH/ ECCD and neutral-beam heating in studies of high-performance, advanced tokamak plasmas.

Experiments on DIII-D in FY99 were hampered by the availability of only a single 1-MW, 110-GHz gyrotron. Furthermore, very little time was devoted to ICRF operation because of system upgrades and other experimental priorities. No ICRF experiments are planned for FY00, so that technical personnel can concentrate on commissioning new gyrotrons. Nevertheless, PPPL physicists obtained significant new results by carefully analyzing data from earlier experiments.

Evidence was reported of an internal kink instability possibly driven by barely trapped suprathermal electrons produced by off-axis ECCD. It occurs in plasmas with an evolving safety factor profile q(r) when q_{min} approaches 1. This instability is most active when ECCD is applied on the high-field-side of the flux surface. It has poloidal and toroidal mode numbers m/n=1/1 with a bursting behavior. In positive magnetic shear plasmas, this mode becomes the fishbone instability. The observation can be qualitatively explained by the drift reversal of the barely trapped suprathermal electrons.

A study of Alfvén instabilities during ICRF sawtooth stabilization experiments suggests that these energetic particle modes, whose frequency decreases as q(0) decreases, may cause transport of fast ions and lead to monster sawteeth. If q(0) can be controlled by ECCD, it may be possible to extend sawtooth-free operation. These phenomena will be studied further when ICRF operation resumes in FY01.

Four gyrotrons should be ready for use in the FY00 experimental campaign. This will allow significant extensions of previous studies, and PPPL will play key physics and technical support roles in those experiments. One of the major PPPL accomplishments during FY99 was the development, delivery, and installation of a remotely steerable ECH/ECCD launcher, capable of controlling toroidal and poloidal injection angles of two 110-GHz gyrotron beams. This will allow precise and convenient localized heating and current drive, and will substantially improve experimental flexibility with respect to the antennas previously in use, which required a clean vent of the vacuum vessel in order to change between heating and current drive configurations. Now, for the first time, the current drive or heating configuration can be changed remotely between plasma discharges.

Figure 2 shows the new launcher during laboratory tests prior to installation on DIII-D. The upper fixed copper mirrors direct the input beams onto the lower molybdenum and graphite steering mirrors. After installation, as shown in Figure 3, a fixed shield protects the upper mirrors, and a shutter can be positioned to protect the steering mirrors when the launcher is not in use.

Theory and Modeling

The PPPL/DIII-D collaboration in theory and modeling has objectives across a range of plasma theory, modeling, and code development areas. These activities are integrated with the experimental pro-

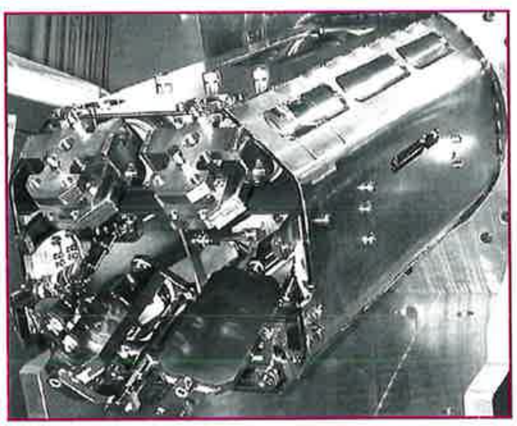


Figure 2. The steerable launcher during laboratory tests.

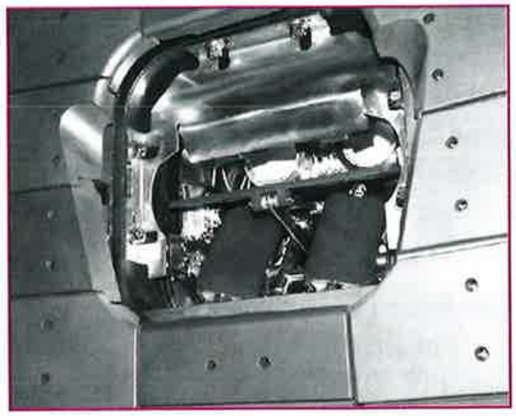


Figure 3. The steerable launcher after installation and testing, viewed from inside the DIII-D vacuum vessel.

grams in stability (resistive wall modes, extension of the duration of high-performance modes by stabilization of edge modes, and stabilization of neoclassical tearing modes) and transport (emphasizing understanding and control of transport). The VACUUM code is currently being modified to simulate the feedback stabilization of the resistive wall mode in DIII-D. VACUUM relates the perturbations on the various surfaces, i.e., the plasma, both sides of the resistive shell, and the active control C-coils. As a first approximation, a PEST or GATO surface eigenmode of an ideal kink is assumed. By energizing the C-coils in the code according to the various proposed feedback schemes, code results can be compared with experimental results, and the modeling will also provide helpful guidance for future experimental runs.

Substantial progress has also been made in the understanding of zonal flows. For this year, a key issue was developing diagnostics to try to measure the zonal flows that are so important in gyrokinetic turbulence simulations. Discussions are ongoing between PPPL theorists and GA and PPPL experimentalists to find the best combination of code and equipment development.

A new theoretical model has been developed to account for toroidal rotation in plasmas heated by ICRF alone, as has been observed in Alcator C-Mod. The model is based on a detailed study of fast ion orbits and demonstrates the possibility of sustainment of core plasma rotation by ICRF, even though there is no net torque on the plasma.

Diagnostic Development

In collaboration with GA and the Lawrence Livermore National Laboratory, PPPL completed installation of the Tangential Central Thomson Scattering System, which provided measurements of core plasma electron temperature and density during the FY99 experimental program. In cooperation with GA and ORNL, PPPL designed and installed modifications needed to accommodate both ASDEX and Penning gauges for the new upper divertor area. These diagnostics are important for fast neutral gas pressure measurements and for measurements of partial pressures of different neutral gas species in the divertor plenum.

Alcator C-Mod Collaboration

PPPL physicists and engineers made major contributions to MIT's Alcator C-Mod tokamak scientific program during FY99. PPPL physics and engineers designed, fabricated, and helped install a new four-strap ICRF antenna which doubles C-Mod's auxiliary heating power and allows the launch of directed waves for current-drive experiments. PPPL's radio-frequency engineering group has provided hands-on assistance with the tuning of the ICRF transmitters, as well as incorporating PPPL's operating experience into the transmitter rebuild, following the loss of several high-power output tubes. The addition of lower-hybrid current drive will allow C-Mod to explore plasma parameters in the advanced tokamak regime, and a joint MIT/PPPL proposal was submitted to the U.S. Department of Energy (DOE).

New plasma diagnostics were brought on line. The grating polychromator #2 electron cyclotron emission (GPC2 ECE) diagnostic improvement allows greater spatial resolution of electron temperature profiles across the plasma core. The addition of edge Thomson scattering extends electron temperature measurements to the plasma edge. Other plasma diagnostics installed or initiated include the motional Stark effect measurement of the plasma current distribution, two-dimensional imaging of turbulence at the plasma edge, and upgrades to the microwave reflectometer to allow density and fluctuation measurements to be extended farther up the edge pedestal.

TRANSP code modeling of plasma transport in C-Mod discharges has allowed their inclusion into the International Thermonuclear Experimental Reactor (ITER) database and comparison with a number of transport models. TORIC and METS code modeling of the ICRF physics processes allows for benchmarking of these codes to electron power deposition data and gives confidence in their use in a predictive mode.

ICRF Antenna

A new four-strap ICRF antenna (Figure 4), designed and fabricated at PPPL, was installed into C-Mod in December, 1998. It was designed to couple up to 4 MW of ICRF power to the C-Mod plasma, doubling the auxiliary heating power from 4 MW to 8 MW. Its more advanced design is intended to allow operation at approximately twice the power density of previous antennas, and it allows the launch of directed waves for current-drive experiments. The external resonant

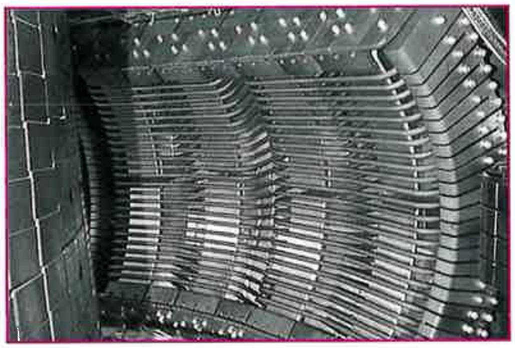


Figure 4. The new four-strap ICRF antenna mounted inside Alcator C-Mod.

loops were installed and tuned to operate at both 78 and 60 MHz through the simple addition of transmission line segments. Repeated transmitter failures in March, 1999 led to the delay of start-up until September. The antenna was then vacuum conditioned up to 40 kV, followed by the application of increasing amounts of radio-frequency power into the plasma.

In the D(H) hydrogen minority heating regime at 78 MHz, the new antenna achieved ~2.5 MW power into the plasma, with (0, 180, 180, 0) current strap phasing, and ~3 MW, with (0, 180, 0, 180) phasing. Preliminary studies show heating comparable to the older antennas at D- and E-Port, but with higher levels of impurity generation (titanium, carbon, and molybdenum from the front tiles). The total power into the plasma using all three antennas together pushed up to 5 MW for brief periods.

The rapid increase in impurity generation above ~1.3 MW and the decreasing power-handling capability during the run prompted a critical inspection of the antenna following the end of the FY99 experimental campaign. Substantial arc damage was found on the antenna structure and the front tiles. The antenna was disassembled, the arc damage was cleaned, and modifications to the antenna structure and tile assembly were performed. Further modifications, to both the fault protection circuits and the conditioning procedures, were also implemented.

ICRF Operational Support

PPPL physicists have been fully integrated into the operation of the C-Mod ICRF system for a number of years, while the PPPL radio-frequency engineering group has provided close assistance with hardware installation and maintenance. The calamitous transmitter failures of the Spring of 1999, which resulted in the loss of several high-power transmitter output tubes, led to a stand-down for the whole ICRF system and the formation of a task force to assess the failures. This group incorporated both PPPL engineers and physicists, along with their MIT counterparts. The transmitter fault modes were analyzed, and a substantial rebuild was initiated, including circuit modifications based on PPPL transmitter experience. This hands-on involvement, initially aimed at transmitter protection, now includes transmitter tuning and optimizing to achieve maximum power into the plasma.

Lower-hybrid Current Drive

C-Mod's new auxiliary heating capacity of 8-MW ICRF source power may be leveraged very effectively to push C-Mod into the advanced tokamak physics parameter space, if an additional method for off-axis current profile modification is provided. A joint MIT/PPPL proposal adding off-axis current drive based on the absorption of 4.6-GHz lower-hybrid waves was written and submitted to DOE. PPPL will supply the lower-hybrid launchers (see Figure 5), based on the successful design used on the Princeton Beta Experiment-Modification, and a TFTR neutral-beam high-voltage transformer and rectifier. MIT will supply the klystrons, high-voltage switchgear, and controls. The project timetable is funding limited, but

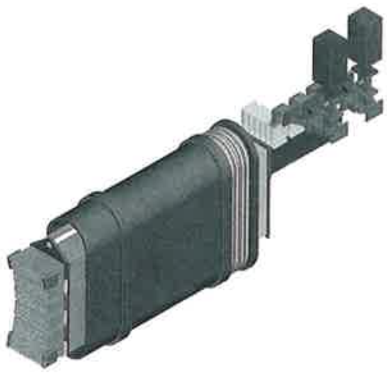


Figure 5. Planned lower-hybrid current-drive launcher.

operation with the first launcher is planned to start late in FY02.

Electron Cyclotron Emission Diagnostic Improvements

Improvements continued to be made to the electron cyclotron emission (ECE) diagnostic which measures electron temperature. The performance of the GPC2 diagnostic was upgraded to provide 18-channel spatial resolution, with 40-microsecond time resolution. Up to 27 radial channels are available, if the older GPC1 is included. These measurements were used to study electron power deposition during ICRF heating and the shape of the edge pedestals in high-confinement modes (H-modes). These results were presented at the 1999 American Institute of Physics' *Applications of Radio-frequency Power to Plasmas* Conference held in Annapolis, Maryland. These measurements have also shown direct evidence of off-axis mode-conversion heating of electrons in the D(H) regime (see Figure 6), consistent with predictions of several ICRF deposition codes.

Edge Thomson Scattering Diagnostic

Additional fibers were added to the core C-Mod Thomson scattering diagnostic (see Figure 7) and imaged onto the spectrometer originally installed for divertor X-point Thomson measurements, providing increased edge electron temperature measurement capability. A review of the original divertor X-point Thomson scattering collection optics revealed a design flaw, causing extremely low light transmission and a cancellation of this diagnostic. The newly enhanced edge capa-

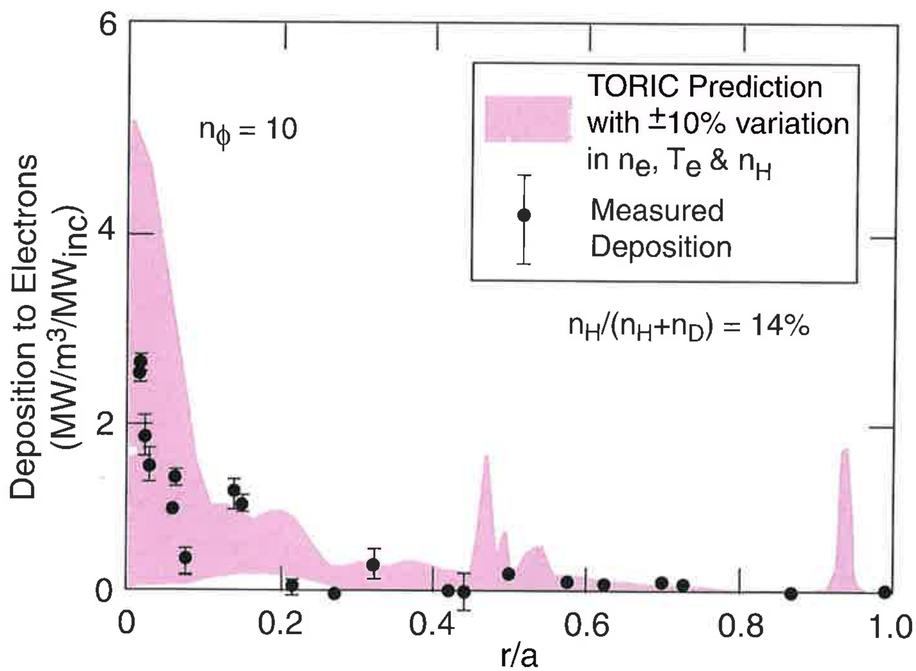


Figure 6. ECE measurement of electron power deposition and comparison with ICRF codes.

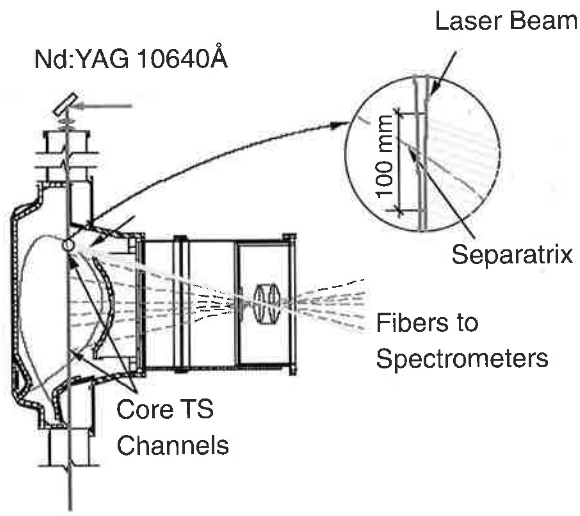


Figure 7. Edge Thomson scattering diagnostic.

bility now routinely provides electron edge temperature and density profiles for pedestal studies.

Motional Stark Effect Diagnostic

A measurement of the poloidal magnetic field via the motional Stark effect on fast neutral atoms injected by a diagnostic neutral beam allows the spatial distribution of the plasma current which generated the field to be determined. PPPL designed, fabricated, and installed the optical system (see Figure 8) which will view and analyze the light emitted by the diagnostic beam being installed by the University of Texas. This optical system will also provide signals for the Texas Beam Emission Spectroscopy diagnostic.

The internal optics were installed inside the C-Mod vacuum vessel. The external optics and data acquisition electronics were prepared, but await completion of the diagnostic beam.

Two-Dimensional Imaging of Edge Plasma Turbulence

Tangential viewing of a gas puff injected into the plasma edge may reveal a two-dimensional image of plasma turbulence there. Light emitted from the gas atoms by plasma collisional excitation can be photographed with a fast video camera to reveal turbulence structure and scale lengths (see Figure 9). This information may then be correlated with plasma core transport to determine the relevant role of edge turbulence on transport.

Initial measurements of edge light using existing optical equipment were made, clearly revealing fluctuation signals. A

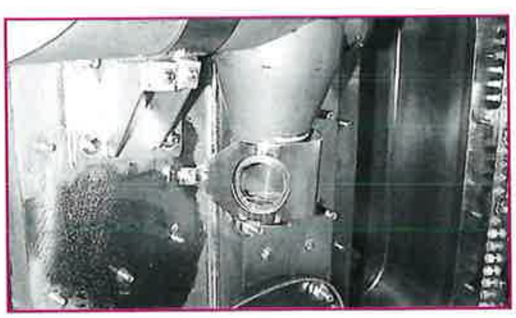


Figure 8. Motional Stark effect vacuum optics mounted inside Alcator C-Mod.

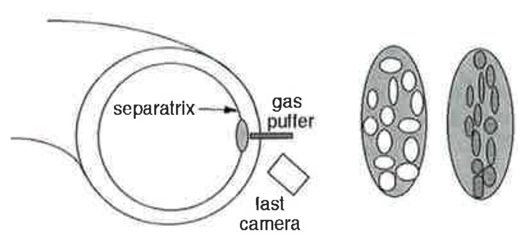


Figure 9. Sketch of proposed two-dimensional edge turbulence imaging diagnostic.

dedicated optical system is now in preparation to allow full two-dimensional imaging.

Reflectometer Upgrade

During FY99, an upgrade to the C-Mod microwave reflectometer was initiated with the addition of microwave receiver components to allow plasma density and fluctuation measurements to be performed farther up the plasma edge pedestal (see Figure 10). This upgrade will also provide fluctuation correlation length measurement capability. Further upgrades to extend this capability to the plasma core are being considered.

Transport Modeling

Several C-Mod plasmas have been used to test a number of transport models (IFS-PPPL, Multi-mode, RLW, RLWB), all of which predict temperatures lower than the measured values. The IFS-PPPL model, based on ion-temperature gradient-driven turbulence, predicts critical ion-temperature gradient scale lengths about 50% longer than those measured. C-Mod plasmas have collisionalities which are higher than the range of validity of the model, so new calculations of the expected critical ion-temperature-gradient scale lengths were made. The GS2 gyrokinetic stability code was used in collaboration with W. Dorland, University of Maryland; critical ion-temperature-gradient scale lengths for linear stability were found to be somewhat longer than that of the IFS-PPPL model, the theoretical expectation is still not consistent with the measurements. Nonlinear simulations of the turbulence will be made next to see if the "nonlinear upshift" of the location of "effective criticality" can reconcile theory and experiment. Such an upshift has been established theoretically in other plasmas, but the unusually high collisionality of C-Mod is expected to reduce this effect.

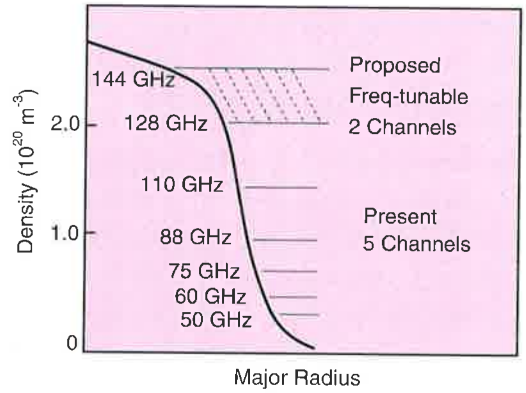


Figure 10. Plasma edge region showing reflectometer measurement capability.

ICRF Modeling

The experimental capability of C-Mod to enter the advanced tokamak regime through the application of high-power ICRF heating and current drive, as well as the planned lower-hybrid current drive, requires accurate modeling for experiment planning and to assess the subsequent physics results. Though PPPL's TRANSP code is capable of analyzing minority ion heating experiments, the ICRF package must be extended to treat the ion Bernstein wave (IBW), excited via mode conversion from the fast wave, especially at higher minority concentrations. The TORIC full-wave ICRF code, which includes a quasi-localized treatment of the IBW, will be installed in TRANSP during FY00. Benchmarking comparisons of TORIC against the METS integral one-dimensional kinetic code was performed, and good agreement was found. Electron heating predictions of both codes have been compared with a variety of C-Mod mode-conversion experiments. Both codes show a strong sensitivity to the electron density in mode-conversion heating of D(H) plasmas. Reasonable agreement is found in D(^{3}He) for on-axis heating of the ^{3}He, while differences in the off-axis predictions are believed to be due to poloidal resolution limits in TORIC. TORIC will be installed in the TRANSP time-dependent transport analysis package, and initial testing will be conducted in FY00.

International Collaborations

During FY99, the PPPL International Collaborations Program continued to provide opportunities for Laboratory researchers to take part in experiments at the most advanced fusion facilities abroad to enhance scientific understanding.

PPPL's International Collaborations Program fits nicely with the recommendations for the U.S. Fusion Energy Sciences Program defined at the U.S. fusion community's 1999 Fusion Summer Study Workshop and subsequently by the Fusion Energy Sciences Advisory Committee. The focus of PPPL's international collaborations has been on physics studies on the world's largest tokamaks, the Joint European Torus (JET) in England and the Japanese Tokamak (JT-60U) and the world's largest stellarator, the Large Helical Device (LHD), in Japan.

JET is the only device capable of carrying out burning-plasma physics experiments using deuterium-tritium (D-T) fuel. PPPL's experience from TFTR contributed to the JET DTE1 experimental program last year and, this year, has provided support in creating improved confinement regimes in preparation for a future D-T operation. PPPL's strength in transport modeling and in modeling of MHD behavior, particularly involving energetic particles such as alpha particles, has proven significant for understanding plasma behavior.

The plasmas in JT-60U have provided the highest fusion performance, in terms of projection from deuterium-deuterium (D-D) neutron emission to that of D-T. Again the concentration has been on improving the plasma confinement. The modeling of the plasma behavior has been the major part of the PPPL contribution.

The LHD in Japan, began operation in March, 1998, and has achieved good plasma parameters as its heating power has increased. PPPL has so far participated mostly by providing plasma diagnostics, but Laboratory researchers look forward to taking part in physics studies as this important program matures.

The PPPL International Collaborations Program has been enhanced by studies on smaller devices where specific issues were being investigated. International collaboration on spherical tori (STs) will begin to flourish in FY00, when the Mega Amp Spherical Torus (MAST) device at Culham, England, and GLOBUS-M in St. Petersburg, Russia, begin to operate.

Experiments and analysis elucidating features in four significant areas of fusion science research were carried out during FY99. These are detailed below. An important diagnostic development is also highlighted. In addition, a collaborative study program on aspects of the use of tritium in TFTR, under an Annex to the DOE/JAERI (Japan Atomic Energy Research Institute) Collaborative Agreement, moved forward. This program is carried out in collaboration with the Los Alamos National Laboratory.

Plasma Turbulence and Transport

PPPL's strength in involving theorists closely with experimentalists in interpretation of their results led to the application of new modeling codes to determine whether the impact of microturbulence should be reduced in plasmas for configurations with improved confinement. Studies were carried out in both JET and JT-60U. The ability to evaluate the transport properties of the plasma using the PPPL-developed TRANSP analysis code and the fast computing capability at PPPL benefited this effort greatly. For JET, plasmas in the "optimized-shear" mode of operation were analyzed. The understanding of these plasmas is now being greatly improved by the use of the motional Stark effect diagnostic. Built jointly by PPPL and JET, this apparatus provides a measurement of the local magnetic field inside the plasma. The q-profiles were found to be flat or mildly reversed with q(0)>1 in both the target and high-power phases of optimized-shear discharges. TRANSP-analysis was also applied in support of the JET study of the edge localized mode (ELMy) H-mode configuration, considered to be the most probable operational mode for a steady-state fusion reactor. On JT-60U, an attempt to discriminate between the transport models used to predict the performance of a next-step device was in progress at the end of FY99. Included in this study is an evaluation of the relationship between core and pedestal temperatures for ELMy H-mode plasmas. An important aspect of the effort on JT-60U has been an attempt to explain changes in density fluctuations during the creation of an improved-confinement region, observed using the correlation reflectometer instrument provided by PPPL.

Macroscopic Stability

New modeling codes were applied with some success to understand the low-frequency, potentially confinement-damaging MHD instabilities in both JET and JT-60U. These codes predict the impact of fast ions, either being created by the neutral beams or by radio-frequency waves heating the plasma, on the growth of these instabilities. Three codes were used to analyze JET ELM-free deuterium and deuterium-tritium plasmas. Plasma-sheared rotation was introduced into the calculations. The m=1 instability mode was assumed to rotate with a frequency equal to the plasma rotation frequency at the q=1 surface. The instability has a global structure and can interact with fast particles at different minor radii. It was found that rotation increases the fast particle contribution to m=1 stability, in qualitative agreement with observations of long sawtooth periods in JET high-performance plasmas.

A new type of magnetic probe, making use of micro-chip technology, was designed. Eight were installed on LHD to measure both the steady and MHD-instability-generated fields. Preliminary data was obtained.

Fast Particle Physics

During FY98, experience gained from TFTR D-T experiments was used in JET experimental operations and theoretical analysis of JET D-T data, including measurements of the behavior of alpha particles created in the fusion reactions.

Theoretical analyses performed by PPPL physicists during FY99 aided the understanding of some measurements of the loss of fast ions, associated with internal disruptions on JET. A new code, which can resolve kinetic Alfvén-type modes, was applied to identify the observed precrash chirping mode — a very low-frequency mode with strongly ballooning structure. It is stable in the absence of fast ICRF-driven H-minority ions, but becomes unstable when minority ICRF ions are introduced. It is suggested that this mode, identified as a kinetic ballooning mode (KBM), during its chirp, can produce particle transport from the center to the q=2 surface, where a 2/1 internal kink mode is excited. The transport driven by KBM must still be demonstrated, and another code is being used to calculate the redistribution of particles from the central region outward when the mode amplitude is sufficiently large.

In these regimes, very high-frequency fluctuations have been observed in plasmas heated by radio-frequency waves or by neutral beams. These fluctuations have been related to a type of instability mode identified initially as being driven by alpha particles. On JT-60U, however, fast neutral particles created by a negative-ion-source neutral beam are injected into the plasma. (PPPL has been contributing to the steady improvement of the performance of this source, both in maximum energy and in reliability, by developing a thorough understanding of the physics of this novel type of beam.) Here instabilities of a similar type have been predicted theoretically and observed. Collaborative experiments on JT-60U were performed where chirping and burst modes of the Toroidal Alfvén Eigenmode type, excited by negative-ion neutral-beam injection, were investigated. Two theoretical codes, NOVA-K and HINST, have been used for analysis of chirping modes. Three possible physical mechanisms for the frequency chirping in the Alfvén frequency range have been identified. They are: (1) the slowly evolving q profile which leads to a radial shift of the mode, and its subsequent change in frequency, and has been already studied in JT-60U and TFTR; (2) the change in the fast-particle pressure profile as a result of increased plasma density and, hence, broadening of the beam-deposition profile; and (3) the change in particle distribution function in phase space in a very short time (3-5 msec). The range of the frequency chirp estimated from the HINST analysis is consistent with that experimentally measured.

Another kind of Alfvén Eigenmode instability, ellipticity-induced Alfvén eigenmodes (EAEs), was observed during ICRF heating, and was stabilized with negative-ion neutral-beam injection. High frequency modes in the range 525-550 kHz, with toroidal mode numbers of n=3-7, were excited after the sawtooth crash, during the ICRF heating. The high-frequency modes were stabilized by negative-ion neutral-beam injection at 350 keV. Stability analysis using the NOVA-K code showed that fast ions created by negative ion neutral-beam injection enhance the damping of the EAEs and tend to stabilize them.

During FY99, PPPL provided scientists at the LHD with a new analyzer for measurements of high-energy particles lost as a result of neutral-beam heating in the LHD's complex magnetic field. This analyzer is of the type developed for TFTR, which can provide the distribution in energy of the fast particles. An analyzer for escaping fast ions of the scintillator type, also developed for TFTR, has been used on the stellarator W7-AS in Germany to determine the losses caused by scattering of the fast ions. Similar equipment for application on LHD is being designed with PPPL support. Design and analysis software has been prepared for a detector for the small Japanese tokamak, JFT-2M, where the effect of variation in the magnetic field due to the finite nature of the toroidal field coils (ripple), is to be explored. Ripple is expected to have a significant impact on the loss of fast particles, and JFT-2M will reduce these losses by adding soft-iron pieces under the coils. A significant toroidal rotation of the plasma, and its associated radial electric field, could lead to significant reduction in these losses; a theoretical study is being carried out in support of the French Tore-Supra tokamak team.

Plasma Boundary Physics

PPPL experimentalists participated in experiments at both JET and JT-60U where impurity noble gases were injected at the plasma edge to improve the plasma confinement in the core. This technique of radiative impurity discharges (RI-mode) was developed by the TEXTOR team in Germany. For both devices, studies were still in progress at the end of FY99.

The control of the influx of impurities from the solid wall surfaces surrounding the plasma into its hot core is an important issue for good core confinement. A study of the screening out of carbon impurity, injected as methane into the JET divertor, already clearly shows that this screening process plays a significant part in establishing the intrinsic impurity levels in the core.

Diagnostic Development

In the area of plasma diagnostics, there has been progress in the development of X-ray crystal spectroscopy being carried out at TEXTOR with a team of physicists from Institute for Plasma Physics, Jülich, Germany, the University of Bochum, Germany, and Auburn University. Spectra of ArXVII were obtained with a spherically bent quartz crystal and a two-dimensional position-sensitive detector. Spherically bent crystals are at the heart of a new type of X-ray imaging crystal spectrometer, which provides spatial resolution in the plasma in a direction perpendicular to the diffraction plane. This instrumental capability will greatly enhance measurements of ions in devices without neutral-beam heating. An imaging X-ray crystal spectrometer is now under construction for the National Spherical Torus Experiment (NSTX) and another will be installed at the W7-X stellarator in Greifswald, Germany.

PPPL has provided neutral-particle analyzers of the TFTR type, with the electric field parallel to the magnetic field in the analyzer, for installation at the LHD in Japan and at the MAST in England.

Tritium Studies in TFTR

The Princeton Plasma Physics Laboratory is also benefiting from a jointly funded collaboration with the Japan Atomic Energy Research Institute to study the retention of tritium in the graphite tiles which made up the plasma-facing first-wall of TFTR. Graphite is a highly favored material for the first wall of a fusion reactor, but its absorption of tritium and difficulty of subsequent removal could prevent its use. Hence studies were started to quantify tritium retention in the TFTR tiles and possible ways for removing it. Analyses of baking were started at PPPL, and other techniques are being evaluated at other institutions. An additional part of this program is being performed in collaboration with the Los Alamos National Laboratory. It involves techniques for reducing and handling tritiated waste, which will be germane to the decontamination and decommissioning program for TFTR.

It was observed that some of the graphite tiles, which formed the bumper limiter on the inside wall of TFTR, began to show flaking, which significantly increased during the year. This behavior at one bay-location, K, is displayed in Figure 11. In-situ measurements of the surface tritium on these tiles, in the location

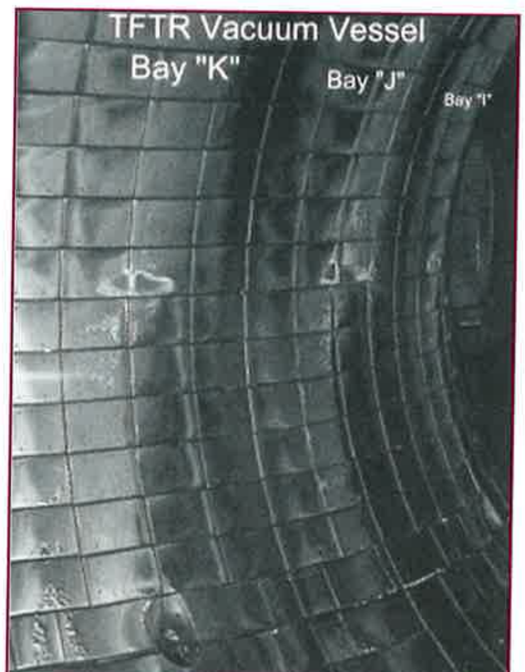


Figure 11. Tiles making up the bumper limiter on the inside wall of TFTR showing flaking developing at bay "K" in the lower left corner.

of the single bay, were made using detectors on the end of a long arm and end-effector by technicians outside a vessel port. Some tiles were carefully removed using remote tooling, and these tiles were subsequently baked in a special facility to release their tritium for measurement. Because of the quality of the data, it was decided to have a manned entry into the vessel, with bubble-suits, to obtain more readings, collect more tiles, and extend the range of measurement, further around the torus, to the top, bottom, and outside of the vessel. Mock-up training has been completed for an early-October, 1999 entry into the TFTR vessel.

A very successful aspect of this program has been the demonstrated use of highly oxidizing agents to clean up tritiated TFTR components to a degree that allows use on the National Spherical Torus Experiment. At the end of FY99, tests began on the use of polyacrylates to solidify tritiated water, and the use of imaging techniques for viewing the distribution of tritium on the tile surfaces.

Off-Site University Research Program

The Off-Site University Research Program makes available to U.S. universities some of the scientific and technical resources of PPPL (e.g., diagnostic expertise, radio-frequency technology, engineering analysis, computer codes, and loans of equipment), and also creates opportunities for the PPPL staff to participate in university fusion science programs. In fiscal year 1999, this program supported fusion science research at fifteen universities.

Some of these FY99 University Research Support Programs were:

- California Institute of Technology. Development of an ultra-soft X-ray pinhole camera diagnostic for the solar flare simulation experiment.
- Columbia University. Construction of the radio-frequency antenna for the High Beta Tokamak-Extended Pulse, and development of a toroidal flow diagnostic.
- Massachusetts Institute of Technology. Engineering design for the launcher and catcher system for the Levitated Dipole Experiment
- Swarthmore College. Diagnostic and physics support for Swarthmore Spheromak Experiment.
- University of California, Los Angeles. Engineering support for the Electric Tokamak.
- University of California, San Diego. Development of a scintillator-based diagnostic for two-dimensional imaging of edge turbulence in the PISCES device.
- University of Wisconsin, Madison. Support for the Thomson scattering diagnostic on the Helically Symmetric Experiment and two-dimensional Electron Cyclotron Emission systems.
- University of Washington, Seattle. Measurement of ion temperature in the Star Thruster Experiment-Field Reversed Configuration and contributions to the Field Reversed Configuration experimental and theoretical programs.

Space Plasma Physics

The Earth's magnetosphere and the solar atmosphere have been the principal areas of research in space plasma physics at the Princeton Plasma Physics Laboratory. The primary goal is to understand solar activity, such as the solar wind, corona mass ejection, and prominence eruption, and how these solar activities couple to the magnetosphere. Coupling between solar activity and the magnetosphere determines how energy, momentum, and mass are transported into the magnetosphere. Such coupling problems typically involve disparate scales. To adequately treat the coupling, a kinetic-fluid model has been developed which incorporates kinetic effects into the fluid model. In addition to the global MHD simulation efforts, the kinetic-fluid model has been successfully applied in the study of several fundamental magnetospheric physics problems. This report focuses on three topics: (1) energetic particle injection during substorm, (2) ion cyclotron waves along auroral field lines, and (3) solar flares and their homologous behavior.

Energetic Particle Injection during Substorm

Energetic electron and ion flux enhancement events in the magnetosphere have been observed in connection with substorms and sudden storm commencements. It has been noticed for a long time that energetic particles appear at geosynchronous orbit (6.6 R_E) subsequent to a substorm expansion phase, in a narrow "wedge" at or near local midnight. The increase in the flux of these high-energy particles can be very large (two or three orders of magnitude larger than the geomagnetic quiet time flux). This increase happens simultaneously for particles having a broad range of energies, and for this reason, these events have been called "dispersionless injections." Similar flux increases, affecting ions and electrons of much higher energies, characterize the formation of new radiation belts following sudden storm commencements.

In order to understand the particle acceleration and flux enhancement related to strongly disturbed events in the magnetosphere, analytical calculations based on a model in which the magnetospheric event consists of an electromagnetic pulse of finite radial and azimuthal extent have been performed. This pulse has a westward electric field and consistent magnetic field, which propagates Earthward with a constant radial velocity. The radial dependence of the fields is dictated by the cylindrical geometry of the problem. The pulsed magnetic field is superimposed on the background Earth field, which is taken to be dipolar. The energetic particle flux enhancement is mainly due to the betatron acceleration process: particles are swept by the Earthward propagating pulses via the **E**×**B** drift toward the Earth to locations of higher magnetic field and are energized because of magnetic moment conservation. The most energized particles stay in the pulse for a long time and experience an **E**×**B** drift motion toward the Earth for a long radial distance. The results provide complete analytical solutions for the particle motion in the combined pulse and Earth fields. These solutions are applied to the case of a substorm injection, obtaining the particle flux for comparison with geosynchronous satellite observations. From the modeling results of energetic particle flux enhancements, it is found that the bulk of injected energetic particles arrive from distances less than 9 R_E. This is much closer to the Earth than the values (larger than 15 R_E) obtained by previous models. These results are consistent with the observations from geosynchronous satellites. Energetic particle flux enhancement events, observed by geosynchronous satellites near midnight location, usually occur within 1-3 minutes after the start of substorm expansion. Consequently, it has been concluded that the initial location of the pulse, corresponding to the magnetic field dipolarization location during the substorm expansion phase, might be at a distance as close as 10 R_E from Earth in the midnight sector.

Ion Cyclotron Waves Along Auroral Field Lines

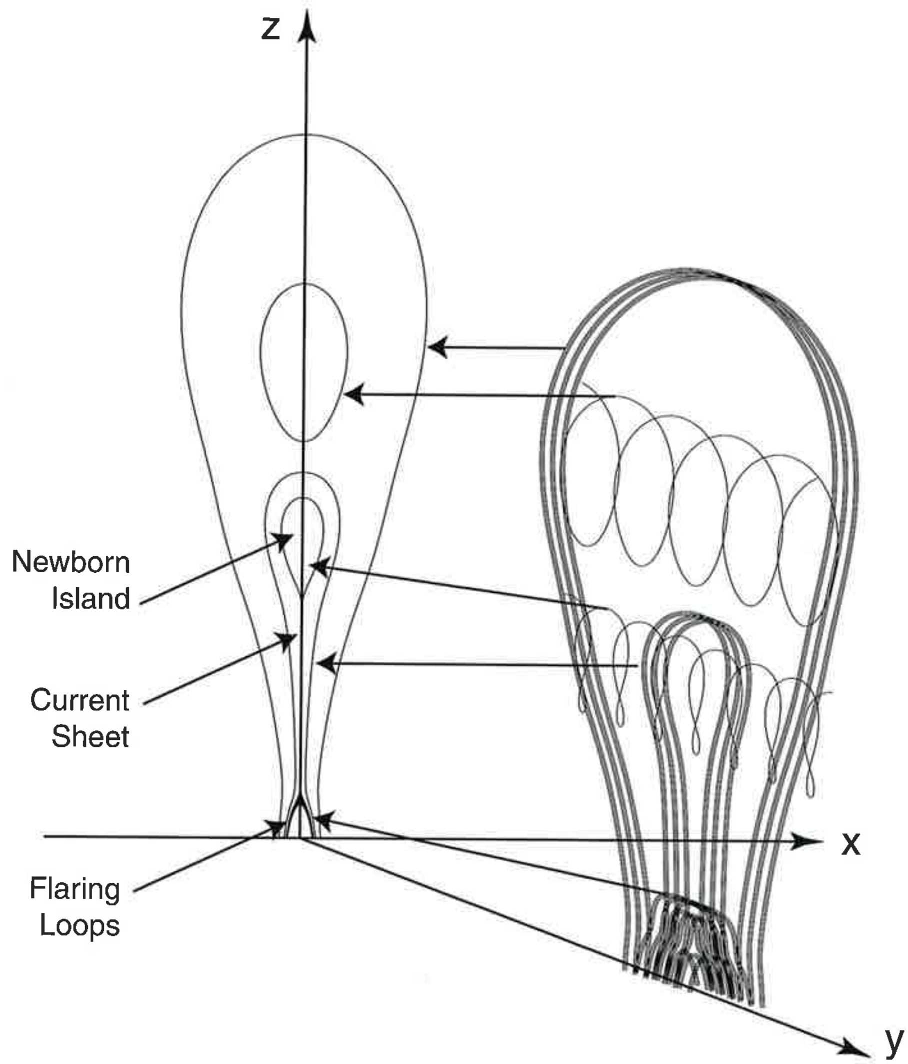
Ion cyclotron waves with frequencies ranging from about 1 Hz to 100 Hz are regularly observed along auroral field lines, from ionospheric altitudes into the magnetosphere. They are important for transferring energy from protons to heavy ions, as remote indicators of proton dynamics, and in regulating proton anisotropy. As such, the waves play an important role in mediating ionosphere-magnetosphere coupling. However, for over a decade, it has been a matter of contention how Pc 1 waves (continuous pulsations of type 1 with frequency ≈1 Hz) could be generated in the equatorial magnetosphere and be observed on the ground so reliably. Previous theoretical results based on the ray-tracing theory are inconsistent with the observations at least 50% of the time. Recent work on ion cyclotron waves has resolved this issue.

The discrepancy between ray-tracing theory and observation has been resolved by solving the full wave equations for ion cyclotron waves propagating from the equatorial magnetosphere to the ionosphere. For a specified external source of cyclotron waves, as observed in the equatorial magnetosphere (or at satellite altitudes), wave amplitudes and polarizations in regions where wave heating occurs can be predicted. Analysis demonstrates that mode conversion occurs near the He^+ and O^+ resonances, which allows the equatorial waves to penetrate to ionospheric altitudes. Previous approaches based on ray-tracing did not describe this coupling, which is due to magnetic field gradients. Near the ionosphere the waves are essentially Alfvén waves, which have substantial amplitude and shifted polarization consistent with observational studies. The results explain how waves generated in the equatorial magnetosphere can propagate to the ground and predict the polarization shift which is commonly observed. A natural step for future research would be to include kinetic effects using the kinetic-fluid model that has been developed recently.

Solar Flares and Their Homologous Behavior

Solar flares are intense, abrupt releases of energy occurring usually in the vicinity of an active region where the magnetic field is stressed. A large flare can release over 10^{32} erg of energy in an hour or so. Based on the temporal evolution of the flare emission, the progress of a flare can be divided into several phases. In the preflare phase, which lasts about 10 minutes before the flare onset, enhanced thermal emissions from the coronal plasma are detected, mostly in the soft X-ray. During the flash phase, which lasts typically about 5 minutes, the intensity and area of the emission rapidly increase. Then, in the main phase, the intensity slowly declines for about an hour and sometimes as long as a day. Large flares also exhibit an impulsive phase before the main phase, lasting 10-100 seconds, during which hard X-ray and microwave bursts are observed.

A model describing physical processes of solar flares and their homologous behavior based on resistive MHD simulations of magnetic arcade evolution, subject to continuous shear-increasing footpoint motions have been studied. In the



A solar flare model based on reconnection processes of arcade magnetic fields and island coalescence. The three-dimensional magnetic field lines and their projection onto the x-z plane are shown. Magnetic reconnection takes place in the thin current sheet below the newborn (lower) island and produces a large reconnection electric field in the y-direction to accelerate electrons along the field lines to more than 10 keV. These high-energy electrons emit hard X-rays and subsequently slow down to generate flaring loops of soft X-ray and optical emissions. The projected view of the flaring loops, the shaded area below the current sheet, is shown in the two-dimensional (x, z) plane.

model it is proposed that the individual flaring process consists of magnetic reconnection of arcade fields, generation of magnetic islands in a magnetic arcade, and coalescence of magnetic islands. When a magnetic arcade is sheared, a current sheet is formed and magnetic reconnection can take place to form a magnetic island. A continuing increase of magnetic shear can trigger a new reconnection process and create another island in the underlying arcade below the magnetic island. The newborn island rises faster than the preceding island and merges with it to form one island. Before the merging process with the upper island is completed, the newborn island exhibits two different phases of rising motion: the first phase with a slower rising speed and the second phase with a faster rising speed. This result is consistent with the Yohkoh observations of the motion of X-ray plasma ejecta. The first phase, in which reconnection of line-tied fields in the underlying arcade is important, is considered to be the preflare phase. In the second phase, the island coalescence takes place and creates an elongated current sheet below and enhances the reconnection rate of line-tied arcade fields. This phase is interpreted as the impulsive phase or a flash phase of flares. The calculated reconnection electric field is large enough to accelerate electrons to a level higher than the 10 keV necessary for X-ray emission. After merging of the islands is completed, magnetic reconnection continues in the current sheet under the integrated island for a longer period which can be considered as the main phase of flares.

An explanation for another interesting feature of flare phenomena, the recurrence of homologous flares, is provided. It is often observed that a series of solar flares takes place repetitively in the same active region with essentially the same position and with a common pattern of development. Such flaring phenomena are called homologous flares. The time interval between successive flaring events varies from several hours to a few days. Observations have also suggested that the majority of flares might be homologous in the sense that the foot points reappear very near the same place. The modeling results show that by continuing the footpoint shear-increasing motion, the flare process described above is repeated with some time interval. Thus, it is proposed that a series of these flaring processes constitutes a set of homologous flares. The time interval between successive flaring events depends on the energy input rate into the system, which is governed by the nature of the footpoint motion and the plasma dissipation rate.

Hall Thruster Experiment

Figure 1. The Hall Thruster Team and the PPPL Hall Thruster Experiment.

The Hall Thruster is a plasma-based propulsion system for space vehicles. The amount of fuel that must be carried by a satellite depends on the speed with which the thruster can eject it. Chemical rockets have very limited fuel exhaust speed. Plasmas can be ejected at much higher speeds, therefore less fuel need be carried on board.

During the past 20 years, the Russians placed in orbit about 100 Hall Thrusters. However, the vast majority of satellites worldwide have relied on chemical thrusters and, to a lesser extent, ion thrusters.

During FY99, a Hall Thruster Experiment — funded by the U.S. Department of Energy and the U.S. Air Force Office of Scientific Research — was established at the Princeton Plasma Physics Laboratory (PPPL). It is the result of an earlier collaborative theoretical research effort (funded by U.S. Air Force Office of Scientific Research) with the Center for Technological Innovation at Holon, Israel. This earlier study identified improvements that might make Hall Thrusters more attractive for commercial and military applications.

Hall Thruster Operation

A conventional ion thruster consists of two grids, an anode and a cathode, between which a voltage drop occurs. Positively charged ions accelerate away from the anode toward the cathode grid and through it. After the ions get past the cathode, electrons are added to the flow, neutralizing the output to keep it moving. A thrust is exerted on the anode-cathode system, in a direction opposite to that of the flow. Unfortunately, a positive charge builds up in the space between the grids, limiting the ion flow and, therefore, the magnitude of the thrust that can be attained.

In a Hall Thruster, electrons injected into a radial magnetic field neutralize the space charge. The magnitude of the field is approximately 200 gauss, strong enough to trap the electrons by causing them to spiral around the field lines. The magnetic field and a trapped electron cloud together serve as a virtual cathode (see Figure 2). The ions, too heavy to be affected by the field, continue their journey through the virtual cathode. The movement of the positive and negative electrical charges through the system results in a net force on the thruster in a direction opposite that of the ion flow.

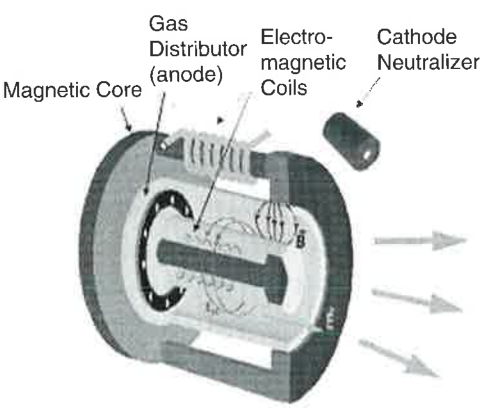


Figure 2. The Hall Thruster concept.

Applications

Generally, thrusters are used to compensate for atmospheric drag on satellites in low-earth orbit, to reposition satellites in geosynchronous orbit, or to raise a satellite from a lower orbit to geosynchronous orbit. As a basic rule of thumb, for each kilogram of satellite mass one or two watts of on-board power are available. PPPL's Hall Thruster consumes several hundred watts of power, making it suitable for a satellite with a mass in the range of a few hundred kilograms. PPPL physicists believe there may be a market for Hall Thrusters operating at 1,000 watts or more, but say predictions are difficult to make. They also speculate about the development of Hall microthrusters with power outputs in the 100-watt range, useful for very small satellites with masses of 50 to 100 kilograms. One could envision a large satellite disbursing hundreds of the smaller ones for the exploration of a planet or as a spaced-based radar array. The Hall Thruster may be too power hungry for this application, but answers to these and other questions may emerge from research now underway at PPPL.

Hall Thruster Propellant

Plasma thrusters for current space applications employ xenon propellant. Xenon is relatively easy to ionize and store onboard the spacecraft. It also has a high atomic number (54), which means a lot of mass per ionization energy expended. The ionization energy is an unavoidable inefficiency; in the range of exhaust velocities most useful for current space applications — about 15 km/sec — this energy loss for once-ionized xenon is less than 10 percent of the exhaust energy. (If the

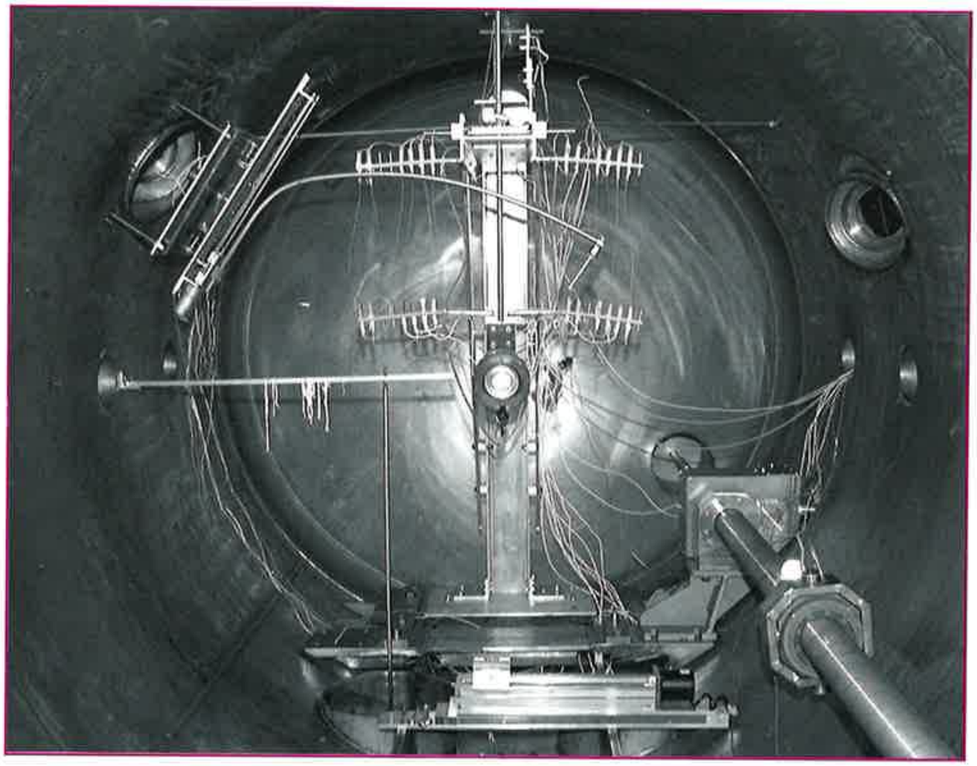


Figure 3. Interior view of PPPL Hall Thruster.

weight per atom were half, this percentage would double.)

Installation

The site of the former PPPL S-1 Spheromak Experiment was selected for the Hall Thruster Experiment. Facility work began with the relocation of the 15-ton, 28-foot by 8-foot manipulator tank, previously constructed for use on the Tokamak Fusion Test Reactor. The vessel is now being used as the vacuum chamber for the Hall Thruster Experiment. PPPL's state-of-the-art prototype Hall Thruster was then assembled inside the vacuum chamber. A complete set of diagnostics was installed and experiments got underway. Less than $200,000 was spent to assemble the P.PPL's Hall Experiment, which has capabilities comparable to installations that are considerably more expensive.

Initial Results

Initial results indicate that PPPL's Hall Thruster operating at 900 watts does so with an efficiency that is comparable to state-of-the-art thrusters. Planned upgrades include segmenting the thruster. Each segment would be held at a specific electric potential, enabling researchers to control exactly where the voltage drop occurs along the length of the thruster. PPPL's Hall Thruster was designed with a modular configuration to allow multiple thruster geometries that could be diagnosed in detail easily. This includes the ability to measure precisely in three dimensions how the thrust varies with position. This information could be used to arrive at techniques to narrow the plume and obtain more control over the outflow from the thruster, possibly improving its efficiency.

Nonneutral Plasmas and High-Intensity Accelerators

A nonneutral plasma is a many-body collection of charged particles in which there is no overall charge neutrality. Such systems are characterized by intense self-electric fields and, in high-current configurations, by intense self-magnetic fields. Nonneutral plasmas, like electrically neutral plasmas, exhibit a broad range of collective properties, such as plasma waves and instabilities. The intense self-fields in a nonneutral plasma can have a large influence on detailed plasma equilibrium, stability, and confinement properties, as well as on the nonlinear dynamics of the system.

There are many practical applications for nonneutral plasmas:

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

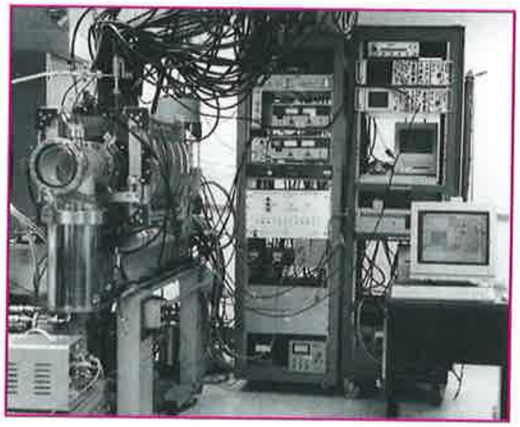


Figure 1. Electron Diffusion Gauge experiment.

Research on nonneutral plasmas and high-intensity accelerators at the Princeton Plasma Physics Laboratory (PPPL) focuses on two areas:

- Basic experimental investigations of nonneutral electron plasmas confined in a Malmberg-Penning trap, including the effects of electron-neutral interactions on plasma confinement and stability properties;
- Analytical and numerical studies of the nonlinear dynamics and collective processes in intense nonneutral ion beams propagating in periodic-focusing accelerators and transport

systems, with particular emphasis on next-generation accelerators for heavy ion fusion and spallation neutron sources.

Experimental research on nonneutral plasmas at PPPL is performed on a Malmberg-Penning trap called the Electron Diffusion Gauge Experiment (see Figure 1). The pure electron plasmas studied are confined with cylindrically symmetric fields: a uniform, static, axial magnetic field provides particle confinement radially, and applied potentials on the electrically isolated, cylindrical, end-wall electrodes provide confinement axially. The electrons trapped in the device are introduced from a directly heated spiral of tungsten wire. By varying the bias on the filament, the size and density of the plasma can be changed. The plasma column rotates because of the radial electric field generated by space-charge effects that produce an E × B rotation in the azimuthal direction. Single-species nonneutral plasmas have very robust confinement properties because the conservation of total canonical angular momentum provides a powerful constraining condition on the allowed radial positions of the particles. If no external torques act on the plasma, it cannot expand radially and touch the wall. However, electron collisions with background neutral gas atoms exert a torque on the rotating electron plasma, thus allowing the plasma to expand. This effect is being investigated as the principle of using pure electron plasmas as a pressure-sensing medium by studying electron-neutral collisional transport and collective excitations. Typical results are illustrated in Figure 2, where the dependence of the plasma's expansion rate on background gas pressure is displayed. The expansion rate of the plasma has been measured for background pressure variations by a factor of 10^5, and found to vary linearly with the pressure, as predicted theoretically, above a minimum expansion rate attributed to field asymmetries and small construction defects in the device.

Theoretical advances in high-intensity accelerators and beam transport have also been achieved in several areas. A kinetic (Vlasov-Maxwell) model for describing intense nonneutal beam propagation in periodic focusing field configurations has been developed, including the application of Hamiltonian averaging techniques, and the derivation of a nonlinear kinetic stability theorem for quiescent beam propagation over large distances. The kinetic model has also been used to determine detailed properties of the electron-ion two-stream instability when an (unwanted)

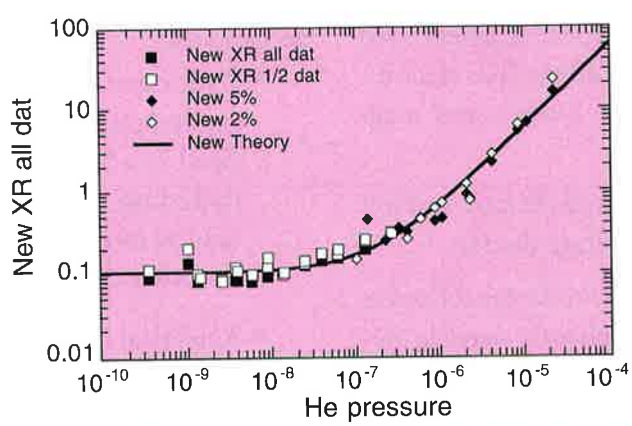


Figure 2. Experimental and theoretical expansion rates versus background gas pressure. Experimental and theoretical results agree very well.

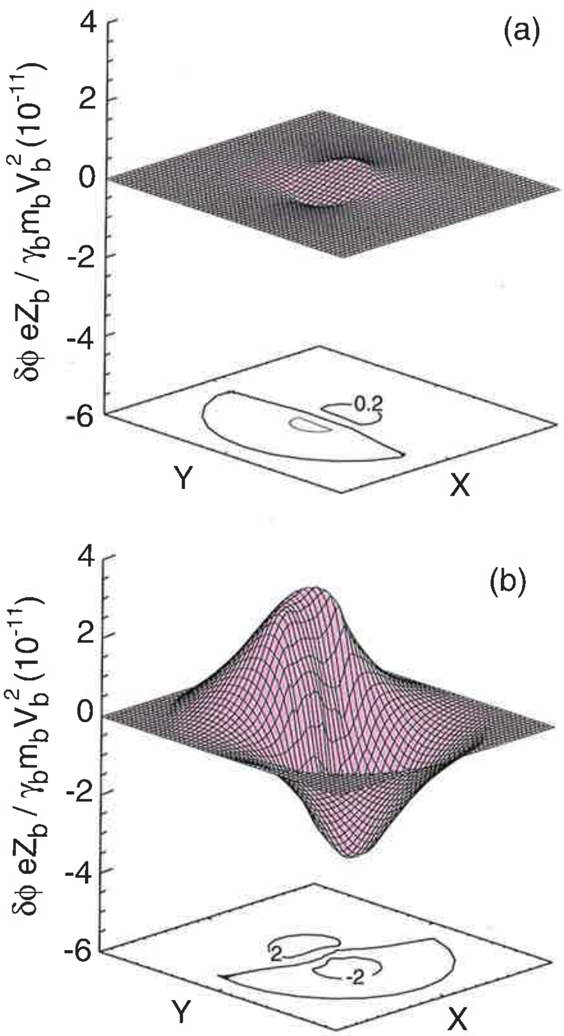


Figure 3. Electron-proton two-stream instability simulated by the BEST code. (a) The x-y projection of a small initial potential perturbation. (b) The x-y projection of the unstable potential perturbation at 200 lattice periods.

electron component is present in the acceleration region or beam transport lines. In addition, a three-dimensional multispecies nonlinear perturbative (δf) particle simulation scheme has been developed to simulate intense beam propagation in periodic focusing systems. The Beam Equilibrium Stability and Transport (BEST) code has also been applied to stable, matched-beam propagation of a thermal equilibrium beam over hundreds of lattice periods, and to detailed investigations of the nonlinear evolution of the two-stream instability at high beam intensities. Illustrated in Figure 3 are typical simulation results for the electron-proton two-stream instability in the Proton Storage Ring experiment at the Los Alamos National Laboratory. Shown in Figure 3(a) is a small initial potential perturbation, which grows into a much larger dipole potential perturbation 200 lattice periods later as shown in Figure 3(b). A macroscopic warm-fluid model has also been developed to describe collective processes in high-intensity beams, including preliminary investigations of a collective instability driven by pressure anisotropy. In addition, a test-particle model has been used to explore chaotic particle dynamics and halo formation induced by collective mode excitations in high-intensity ion beams, including estimates of the maximum radial excursion of the halo particles. Shown in Figure 4 is the Poincaré surface-of-section plot of a test particle's trajectory in phase space under the influence of self-consistent eigenmodes of warm-fluid waterbag equilibrium. Simulations indicate that islands exist in the beam interior, allowing particles initially in the beam core to escape into the halo region.

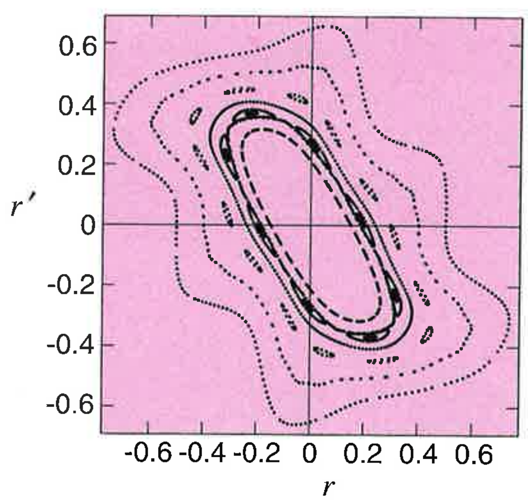
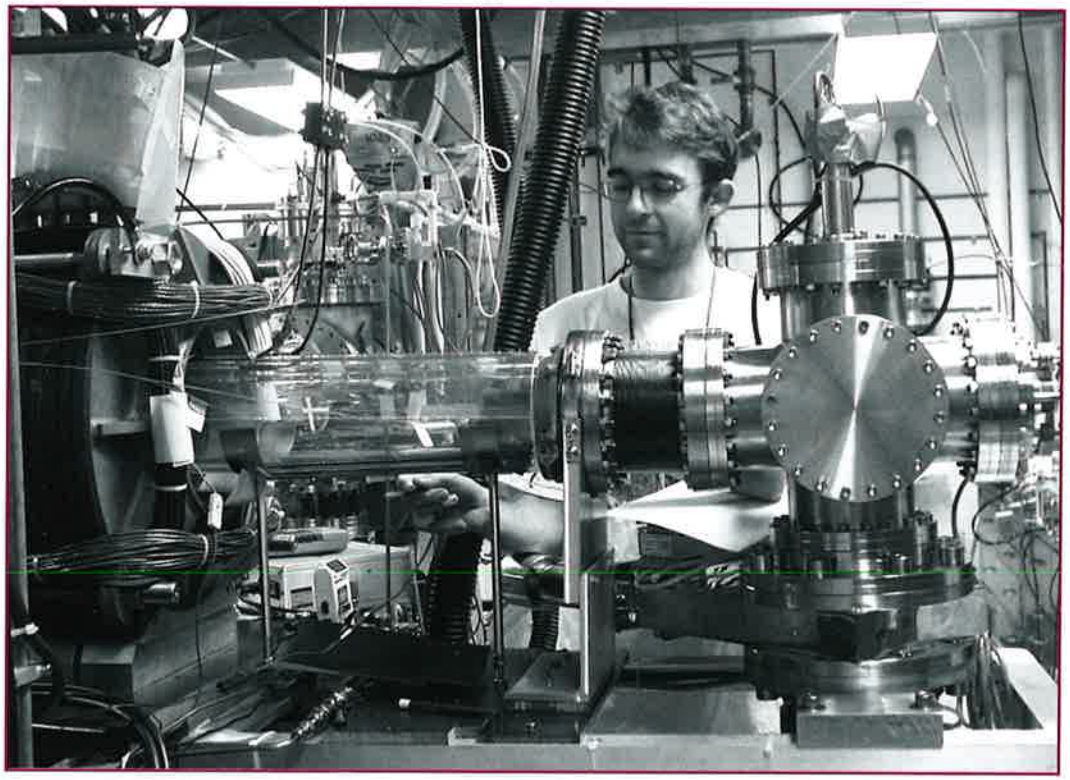


Figure 4. A Poincaré surface-of-section plot of position versus velocity for test-particle motion in a waterbag equilibrium with collective mode perturbations.

Magnetic Nozzle Experiment



Graduate student Tom Kornack stands next to the nozzle expansion region of the Magnetic Nozzle Experiment.

The purpose of the Magnetic Nozzle Experiment (MNX) is to study the flow of magnetized linear plasmas expanding through a constriction formed by increased magnetic field intensity. It is predicted that, under certain conditions, rapid plasma recombination will occur because of expansion cooling. This has applications to the fields of fusion physics, space propulsion, materials processing, and lasers.

MNX formally began its life when funding commenced in February 1999. During the next eight months, rapid progress was made in developing the facility and installing diagnostics. Much credit goes to a collaboration with Dr. F. Levinton of Fusion Physics and Technology, Inc. (FPT), who is developing the use of Laser-induced Fluorescence (LIF) for the motional Stark effect and a second diagnostic for visualization of turbulence. The motional Stark effect diagnostic will be used on the National Spherical Torus Experiment while the turbulence diagnostic will be used on the Magnetic Reconnection Experiment and the Current Drive Experiment-Upgrade.

Several important milestones were met, all ahead of schedule. These include:

- the construction, testing, and operation of the first magnetic nozzle coil and nozzle expansion region;
- the conversion of MNX to steady-state operation, through the installation of a helicon plasma source by FPT;
- the evaluation, purchase, and operation of an iCCD camera for a 1/2 meter spectrometer; and
- the installation of a LIF diagnostic by FPT.

With the helicon source, ion-duration (>4 hours) argon and xenon plasmas were formed and diagnosed. At a coupled power of 500 W, plasma density and electron temperature, measured with a scanning Langmuir probe, were 5×10^{13} cm^{-3} and 5 eV, respectively. The ion temperature, measured by LIF, was in the range 0.6-0.8 eV. Spectroscopic measurements were made in the nozzle expansion region to look for supersonic flow. None was found, as expected, due to the weak nozzle field. However, by both spectroscopic and probe techniques, recombination was detected in the expansion region. The preliminary assessment is that the recombination is due to collisions with neutral gas. An improved pumping system is being installed to control the neutral density in the expansion region.

During this year, the MNX group hosted Dr. A. Fredricksen (University of Tromso, Norway) and assisted Professor E. Scime (West Virginia University) in the submission of a proposal to the U.S. Department of Energy. Other collaborations were initiated. A graduate student, T. Kornack, and an undergraduate, S. Fahmy, joined the MNX group.

National Compact Stellarator Experiment

Figure 1. Machine concept for 1999 NCSX reference design using PBX-M toroidal field coils. Shown installed are the three-dimensional vacuum vessel, three-dimensional coil support shell, and cryostat.

A critical issue for magnetic fusion energy is the requirement for a high-beta magnetic plasma configuration that can be sustained in steady-state without disrupting. There are currently two major research thrusts aimed at this goal, the advanced tokamak and the stellarator. Researchers at the Princeton Plasma Physics Laboratory (PPPL), in collaboration with colleagues from the U.S. and abroad, have been developing the physics of the "compact stellarator" — an innovative, high-beta, low-aspect-ratio hybrid of advanced tokamaks and stellarators that builds on the scientific foundations of both concepts.

Stellarators, a family of plasma confinement concepts characterized by three-dimensional magnetic fields and plasma shapes, are the most developed magnetic concept after the tokamak. The concept has advanced greatly since its invention by PPPL's founding Director Lyman Spitzer, Jr. in the 1950s. Now, two large superconducting-coil stellarator experiments in the billion-dollar class are under way. The Large Helical Device (LHD) is operating in Japan and the Wendelstein 7-X is under construction in Germany. The existence of an active world program and the availability of a broad knowledge base from decades of research are advantageous for stellarator research in the U.S.

Plasma sustainment in the LHD and Wendelstein 7-X relies on magnetic fields generated by coils instead of plasma currents. While this approach avoids the need for externally driven plasma currents (which in a reactor would require recirculating some of the output power), self-generated plasma currents may be unavoidable at high beta and could degrade the physics properties. The currentless designs have large plasma aspect ratios (5-12) and project to relatively conservative, low power density (<1 MW/m^2 neutron wall load) power plant designs. The axisymmetric advanced tokamak takes advantage of the bootstrap current to sustain a configuration with lower aspect ratio (≤4) and higher power density (~5 MW/m^2) than the currentless stellarator, and would make use of first-wall and magnet technologies being developed by the world fusion community. However, it may require elaborate plasma controls, with their added complexity and attendant requirements for recirculating some of the output power to maintain a stable plasma configuration and avoid disruptions.

Compact stellarators use the self-generated bootstrap current in combination with three-dimensional stellarator magnetic fields from coils to sustain a configuration with advanced-tokamak-like plasma aspect ratios and beta values. They provide an alternative to the existing approaches that could prove to be the best. In a compact stellarator device, the magnetic fields are used to tailor the plasma configuration so as to stabilize it without the active plasma controls or conducting structures close to the plasma required by an advanced tokamak. A compact stellarator reactor would approach an advanced tokamak in size and power density, while retaining the stellarator's advantages for steady-state, disruption-free operation. The quest for a steady-state solution for magnetic fusion energy is sufficiently important, and the existing solution strategies sufficiently uncertain, that the complementary compact stellarator solution path must be followed in parallel with existing programs to increase the chances for success.

The National Compact Stellarator Experiment

PPPL is proposing the construction of a proof-of-principle device, the National Compact Stellarator Experiment (NCSX), at Princeton in partnership with the Oak Ridge National Laboratory. NCSX would be the central element of a new U.S. research program to develop compact stellarators during the next several years. PPPL is leading a national design team that includes several U.S. universities, with collaborators from many fusion institutions around the world.

In FY99, the national team developed a reference design for the NCSX. Though not a complete conceptual design for the NCSX, the 1999 reference design showed that a high-beta compact-stellarator plasma configuration can be realized in a practical device that meets physics requirements for plasma stability, a necessary condition for avoiding disruptions. It provides a point of reference for proceeding with further development to satisfy all physics requirements.

A key feature of the 1999 design is its use of the existing toroidal and poloidal field coils from the former Princeton Beta Experiment-Modification (PBX-M) tokamak. This approach is of interest for its potential to reduce the construction cost of NCSX, provided the physics requirements for the facility could be met within its constraints. The value of this approach will be measured by comparing it with designs to be developed in 2000 that use all-new coils optimized for NCSX.

The NCSX team is developing a compact stellarator concept based on the principle of quasiaxisymmetry (QA). A QA plasma configuration is toroidal, but unlike its axisymmetric relative, the tokamak, it is three-dimensional in shape. The QA magnetic field structure, on the other hand, is axisymmetric insofar as its effects on energetic particle drift trajectories are concerned. The QA strategy makes it possible to gain stability benefits from three-dimensional shaping while, at the same time, having particle drift trajectories that are as well confined as those in exact symmetry, and hence have low alpha-particle losses and low neoclassical transport. At finite beta, a QA plasma naturally generates a bootstrap current similar in magnitude to that of a corresponding tokamak.

In previous years, project scientists learned how to shape a QA plasma toroid so as to stabilize ballooning modes, neoclassical tearing modes, and external kink modes — helical deformations of the plasma that can be unstable in high-beta toroidal plasmas and negatively impact performance. In FY99, they found that the external fields could also be used to stabilize the vertical instability, a major cause of disruptions in tokamaks. The team developed a capability to compute optimized coil designs with practical numbers of coils for finite-beta QA plasma configurations, and they demonstrated that these designs could provide the magnetic fields needed to produce a reference plasma with its important physics properties preserved. They showed that the coils could be used to perturb the plasma shape so as to vary its stability to the external kink mode, affording the flexibility needed to resolve key physics issues experimentally. A methodology for projecting the performance of three-dimensional stellarator plasmas with energetic-particle heating was developed. It uses Monte Carlo simulation methods to model the thermalization of energetic ions such as neutral-beam ions or alpha particles, and to calculate the thermal losses due to neoclassical transport. These simulations, combined with empirical confinement scalings to account for anomalous transport, are used to project experimental operating parameter sets.

A reference QA plasma configuration stable at beta of 4% and compatible with the PBX-M toroidal field coil geometry was generated as a physics design basis. Projected parameters for this configuration are summarized in the table below. The analysis shows that a beta of 4% could

Parameters for NCSX High-Beta Operating Point.

Magnetic field, B	1.5 T
Injected power, P	6.9 MW
Volume-averaged beta ⟨β⟩	4.0%*
Volume-averaged density, ⟨n⟩	11.3×10^{19} m^{-3}
Central temperature, T_0	2.0 keV
Energy confinement time, τ_E	53 ms

*Includes 10% beam beta.

be reached with slightly more than the available 6 MW of neutral beam heating power, assuming hydrogen operation and an optimal injection geometry.

The new coil design tools were used to generate a system of three-dimensional "saddle" coils — loops that do not enclose either the plasma or the machine axis. The saddle coils are used in conjunction with the background fields provided by the PBX-M coils to provide the shaping fields needed to maintain the reference plasma with an accuracy sufficient to preserve its key physics properties. The saddle coils were found to have complex shapes and require high current densities. However, engineering solutions to these problems were found in a design using flexible, liquid-nitrogen-cooled copper conductor installed in grooves machined on the surface of a structural shell. The shell conforms to a shape defined by the plasma with a surrounding layer to accommodate required components between the plasma and coils, including a conformal vacuum vessel. In this design (see Figure 1), the jointed PBX-M toroidal field coils would be disassembled, then reassembled around the completed stellarator core subassembly consisting of the vacuum vessel, shell, and saddle coils.

The development of a reference design in FY99 provided a concrete vision of a possible machine embodiment, incorporating the physics characteristics of the QA concept. It is the product of advances in understanding the physics of compact stellarators and innovative engineering solutions, which already represent significant contributions to stellarator research. Further development is in progress to incorporate requirements for experimental flexibility, robustness of the plasma equilibrium, and access for heating and diagnostics into the NCSX design process. As these additional requirements become better understood, their implications for the design, including the suitability of using existing components, will be evaluated. Alternate machine designs using optimized coils will be developed for comparison purposes.

Korea Superconducting Tokamak Advanced Research

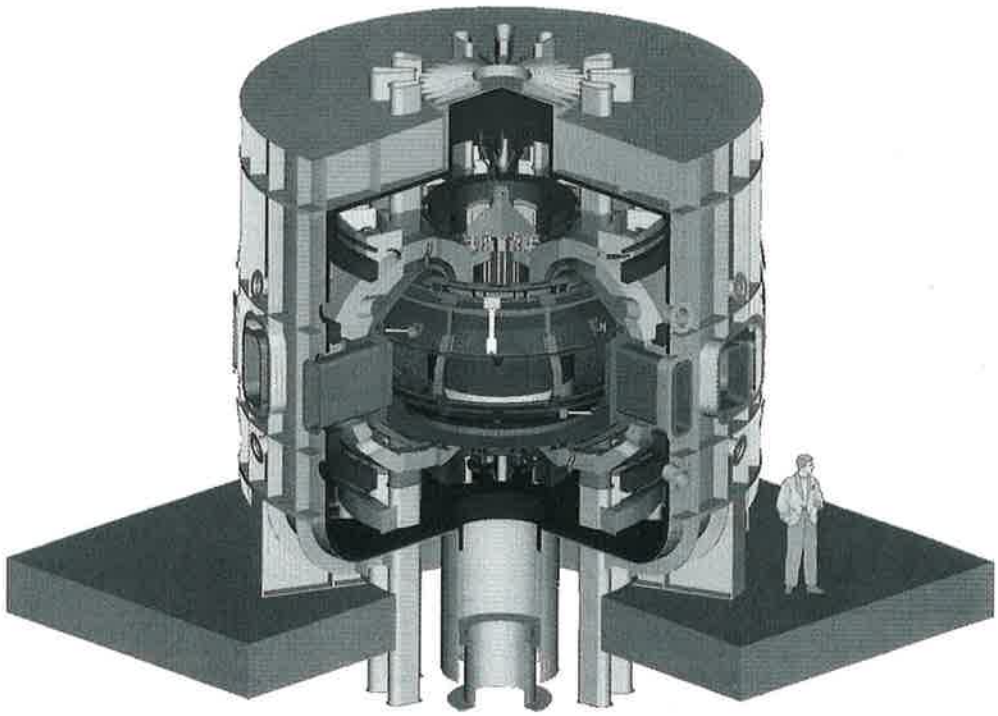


Figure 1. Artist's rendering of the Korea Superconducting Tokamak Advanced Research device.

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

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

- Extend stability and performance boundaries of tokamak operation through active control of plasma profiles and transport;
- Explore methods to achieve steady-state operation for tokamak fusion reactors using noninductive current drive;

- Integrate optimized plasma performance and continuous operation as a step toward an attractive tokamak fusion reactor.

U.S. interest and support for the KSTAR Project stems from the fact that the basic mission and specific research objectives for KSTAR are consistent with the requirements for developing the advanced tokamak as a magnetic confinement concept.

KSTAR will play an important role in worldwide fusion research. Its contributions will include:

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

KSTAR is a long-pulse (20 sec upgradable to 300 sec) tokamak featuring fully superconducting magnets, long-pulse operation, flexible pressure and current profile control, flexible plasma shape and position control, and advanced plasma pro-

KSTAR Major Parameters.

Plasma Parameter	Base	Upgrade
Toriodal Field (B_t)	3.5 T	—
Plasma Current (I_p)	2.0 MA	—
Major Radius (R_0)	1.8 m	—
Minor Radius (a)	0.5 m	—
Elongation (κ)	2.0	—
Triangularity (δ)	0.8	—
Poloidal Divertor Nulls	2	—
Pulse Length	20 sec	300 sec
Plasma Heating		
Neutral Beam	8 MW	14 MW
Ion Cyclotron	6 MW	6 MW
Lower Hybrid	1.5 MW	1.5 MW
Electron Cyclotron	0.5 MW	—
Deuterium Operation	20,000 sec/year	—
Number of Pulses	50,000	—

file and control diagnostics. This tokamak will be constructed in a new facility at the Korea Basic Science Institute and is scheduled for operation in 2004.

The machine configuration includes sixteen superconducting toroidal field coils and thirteen superconducting poloidal field coils, symmetrically located about the plasma midplane. The seven inner poloidal field coils form the central solenoid assembly. A cryostat encloses all of the superconducting coils. The cryostat and vacuum vessel form the vacuum boundary for the superconducting toroidal field and poloidal field coils. KSTAR is being designed for hydrogen and limited deuterium operation, eliminating the need for remote maintenance. The KSTAR machine parameters are presented in the table on previous page.

During FY99, significant progress was made on engineering design and building construction. As part of this activity, the U.S. team was responsible for selected elements of the tokamak design. By the end of FY99, the basement for the tokamak facility/office building was completed and work was progressing on the experimental cell level, as shown in the Figure 2. The facility construction relies in part on input from the U.S. design integration effort. A strong Korean industrial team has been organized and final design is being completed.

PPPL and Oak Ridge National Laboratory completed activities centered on design and integration issues dealing with: internal control coils and plasma-facing components, the vacuum vessel, machine support structures, the thermal shield system, and cryostat. A reference configuration for the vacuum vessel was established, including a double-walled shell. A machine support system assembly model was created, and the reference model for the neutral beams, ion cyclotron resonance heating, and pumping systems was updated.

PPPL developed an internal control coil configuration for KSTAR. These coils provide dynamic control of the magnetic

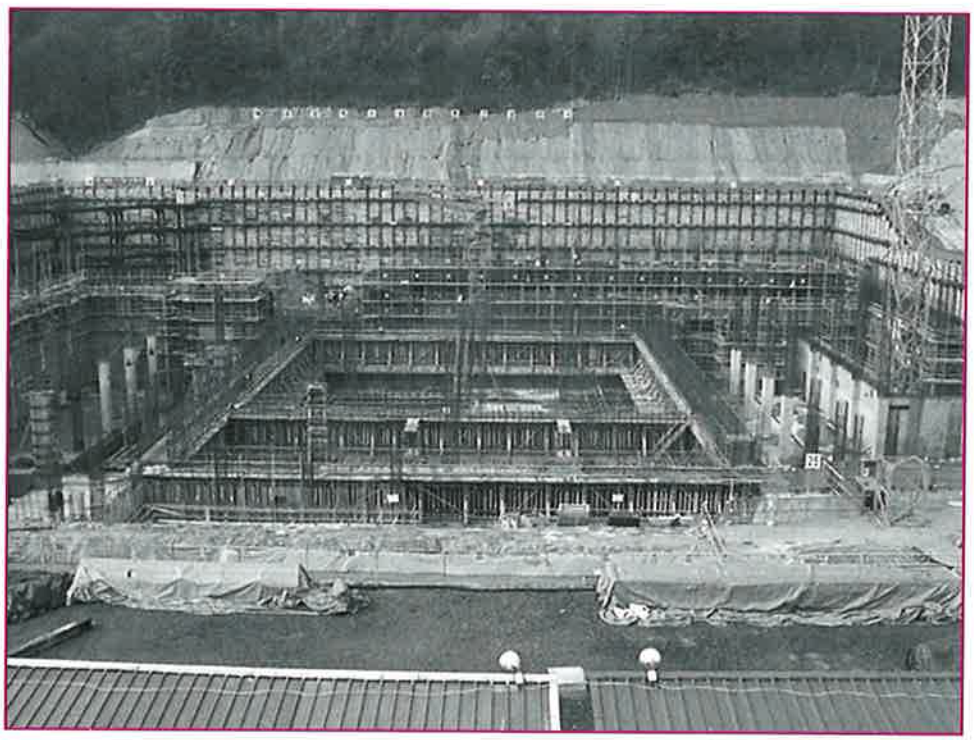


Figure 2. Work progressing on the experimental cell level of the Tokamak Facility/Office Building.

field during startup and rapid plasma position control during the discharge. Locating the control coils in the vacuum vessel, close to the plasma, minimizes disturbances to the poloidal and toroidal coils from the control coils, and significantly reduces the power requirements for the control coils. Each coil is a single turn and is constructed of stainless-steel-jacketed hollow copper conductor, with magnesium oxide insulation between the conductor and jacket.

As part of the PPPL diagnostic activity, a conceptual design of a diagnostic cassette for a median radial port was developed to contain three diagnostics. Analysis verified the feasibility of supporting the cassette, and the benefits and drawbacks of different concepts for mounting the cassette were analyzed. A concept was developed that will provide a reliable means for installing midplane diagnostics with excellent accessibility and maintainability during operation and maintenance. A conceptual design of a far-infrared interferometer and polarimeter for measurement of the plasma density and the poloidal field was also developed. This system would function in the early operational phase of KSTAR prior to the installation of the heating or diagnostic neutral beams, necessary for a more commonly used magnetic field measurement. Also, since the device will operate initially at low magnetic field (<1.5 T), a concept of a simple electron cyclotron emission diagnostic has been proposed for this phase.

During FY99, General Atomics supported the design of KSTAR's plasma-facing components. One focus of this activity was problems associated with thermal stress during bakeout. General Atomics modeled this operation and concluded that maintaining the vessel at 250 °C while baking the plasma-facing components to 350 °C resulted in very large temperature variations in the vessel with unacceptable thermal stresses. A variant to the original bakeout system was developed and analyzed with lower coolant flow and more control of the temperature of individual components, resulting in favorable thermal stresses.

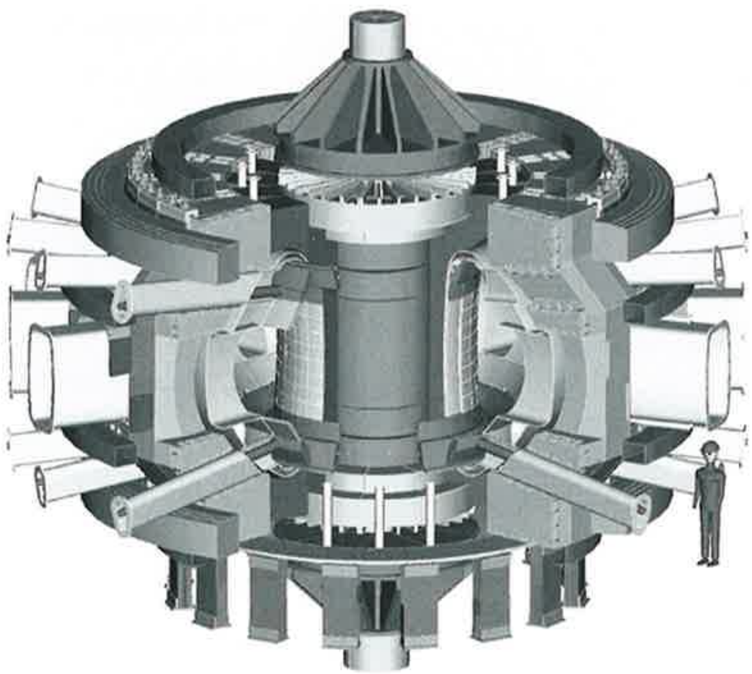
Massachusetts Institute of Technology personnel continued support of the KSTAR magnet design which they presented at the August Superconducting Magnet Design Review in Taejon. As part of this year's activities, a new conductor design was proposed and its performance analyzed for the field error correction coils.

PPPL took the lead in developing a proposal for U.S.-Korea collaborations titled: "Opportunities for U.S.-Korea Collaboration on the Physics and Technology of Advanced-Tokamak Profile Control and Sustainment on KSTAR." Four general areas of common interest were identified:

- Development of advanced-tokamak operating modes;
- Development and implementation of remote experimental collaboration techniques for the participation of U.S. scientists in the KSTAR research program;
- Development and implementation of diagnostic, data collection, and plasma control systems;
- Development and implementation of fusion plasma technologies.

Subsequently, U.S. and Korean experts in each of these areas were identified as contact persons, and the joint planning began.

Fusion Ignition Research Experiment



The Fusion Ignition Research Experiment.

The Next Step Options (NSO) study began in early FY99 following the withdrawal of the U.S. from the International Thermonuclear Experimental Reactor (ITER) program. NSO is organized as a national integrated physics and engineering design activity within the Virtual Laboratory for Technology of the U.S. Department of Energy's Office of Fusion Energy Sciences.

The initial studies have focused on a compact high-magnetic-field tokamak called the Fusion Ignition Research Experiment or FIRE. The programmatic strategy is to provide the physics basis for an attractive fusion reactor using intermediate stepping stones between existing tokamak facilities and the vision of an attractive magnetic fusion reactor, ARIES (Advanced Reactor Innovation and Evaluation Study).

Physics Objectives

The FIRE is being designed to attain, explore, understand, and optimize alpha-dominated plasmas, providing knowledge for the design of attractive magnetic fusion systems. An important consideration is to achieve this mission at the lowest practical cost. The FIRE design concept uses compact, high-field, cryogenically cooled copper magnets and takes advantage of ad-

Major Parameters of the FIRE Tokamak.	
Plasma Parameter	**Baseline**
Major Radius, R_0	2.0 m
Minor Radius, a	0.525 m
Magnetic Field on Axis, B_0	10 T
Q	~10
Plasma Current, I_p	6.5 MA
Fusion Power	200 MW
Flattop Time, sec	18.5 sec coil limit
Triangularity, δ_{95}; δ_x	0.4; 0.7
Elongation, κ_{95}; κ_ε	1.8; 2.0

vances in tokamak engineering and physics made during the past decade.

The fundamental physics objective of FIRE is to attain alpha-dominated plasmas ($Q \geq 5$, where Q is the ratio of the fusion power produced to the power used to heat the plasma) that are sustained for timescales long compared to pressure profile evolution and comparable to plasma current profile evolution. This would permit the attainment of the plasma conditions required to explore, understand, and optimize alpha-dominated plasmas including: energy confinement scaling, density limit scaling, and β-limits with alpha-dominated heating. In addition, FIRE would be used to begin the critically important task of integrating burning plasma physics with advanced tokamak operating modes.

The FIRE magnetic systems are designed to support several operating modes that would make it possible to explore high-Q regimes utilizing the high-confinement mode, advanced tokamak regimes, and quasi steady-state operation.

In addition to the "baseline" mode with magnetic field B_T =10 T, plasma current I_P = 6.44 MA, a flattop of 18.5 sec with deuterium-tritium (D-T) plasmas at a fusion power of 200 MW there are:

- the advanced physics D-T mode with B_T = 8 T; I_P = 5 MA; a flattop of 33 sec at a fusion power of 150 MW and
- the advanced physics deuterium-deuterium (D-D) mode with B_T = 4 T; I_P = 2 MA; a flattop of about 220 sec, similar to that of the Tokamak Physics Experiment.

There is the potential to increase the magnetic field to 12 T, plasma current to 7.7 MA with the flattop reduced to 12 sec in a D-T plasma. These advanced-physics modes would require the addition of active cooling to the first wall and baffle. The cost of these options will be evaluated in late fiscal year 2000. They could permit FIRE to explore advanced tokamak operating regimes at quasi steady state, in addition to its primary mission of exploring high-Q plasmas with alpha-dominated heating and testing advanced tokamak regimes at about 20-sec pulse length. These options are envisioned as upgrades that could be implemented during the operational phase.

Design Features

The major design features of the FIRE include:

- Liquid-nitrogen-cooled, wedged toroidal field (TF) coils with inner legs of beryllium copper and the balance of the coils in high-conductivity copper. Sixteen coils were chosen for low field ripple (≈0.3% at the outer mid-plane). The FIRE design has easily exceeded the original design goal of 10-sec flattop time at 10 T.
- Liquid-nitrogen-cooled, high-conductivity copper, freestanding modular central solenoid;
- Liquid-nitrogen-cooled copper poloidal field (PF) coils.
- A double-walled vacuum vessel with integral shielding, a passive stabilization system, and active control coils.
- Sufficient shielding (by using a water and steel filling in a double-walled vacuum vessel) to reduce activation to allow hands-on maintenance outside the TF coils. This arrangement also reduces the nuclear heating of the TF coils, reduces the dose at the coil insulation to ~1.4 $\times 10^{10}$ rads for 3,000 full-power pulses, and makes possible "hands-on" servicing of components external to the vessel.
- Plasma-facing components using beryllium in the first wall. The thickness of the tiles is chosen primarily by the stress induced in the vessel walls due to the temperature differential between the inner and outer walls. This temperature difference is caused by differential nuclear heating in a double-walled integral shield configuration.
- Double-null radiative divertors with tungsten plates based on the ITER design. The outer divertor plate is actively cooled.
- 30 MW of ion-cyclotron radio-frequency heating. A four port system is planned with two antennae per port.
- A tritium-rich pellet source will be used for core fueling and a deuterium-rich gas source for edge fueling.

The TF coils are a critical element in a high-field tokamak such as FIRE. A series of finite element analyses were made to qualify the design. These analyses show that the TF coil peak conductor stress is

FIRE Design Participants.

Advanced Energy Systems
Argonne National Laboratory
General Atomics Technology
Georgia Institute of Technology
Idaho National Engineering and Environmental Laboratory
Lawrence Livermore National Laboratory
Massachusetts Institute of Technology
Oak Ridge National Laboratory
Princeton Plasma Physics Laboratory
Sandia National Laboratories
Stone and Webster
The Boeing Company
University of Illinois
University of Wisconsin

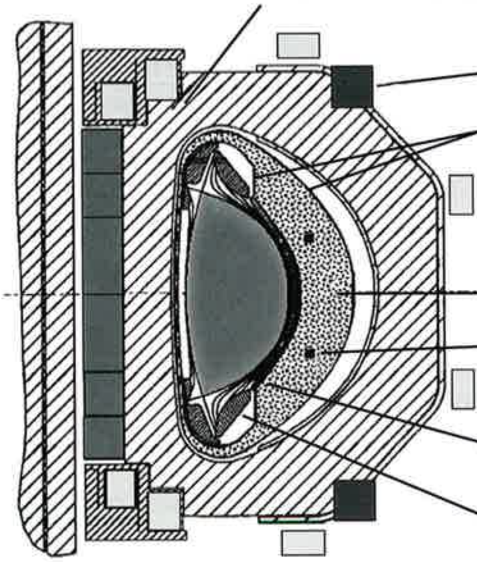


Figure 1. Cross section of the FIRE device.

well within the allowable stress for the beryllium-copper chosen. FIRE is being designed to have a lifetime of 3,000 pulses at full field and 30,000 pulses at two-thirds field. The repetition time at full power and full pulse length is less than 3 hours and is significantly faster at reduced fields and pulse lengths.

One of the design issues for tokamaks with highly shaped plasmas and "external" PF coils is the support for the overturning moment on the inner coil leg. Nonlinear simulations indicate that the wedging pressure and expected friction between coils is adequate to resist the overturning moment with little or no slippage. To provide engineering margin, a large pair of compression rings encircle the TF coils to make the allowable wedge pressure and shear stress more uniform. (See Figure 1.) The effect of the rings increases as the TF coils heat up and expand outwards, an attractive feature providing additional engineering margin when it is needed.

The maximum stress in the PF coils is within the allowable range for oxygen-free copper for all proposed operating modes, including the possible extended modes described below. The maximum temperature in these coils is ~180 K — well below the 373-K limit.

Present engineering efforts are focused on the in-vessel components (active and passive control coils, first wall, and divertor) and in developing cost estimates. A preliminary cost breakdown includes roughly one-third for the tokamak (TF and PF coils, vacuum vessel, and structure), one-third for power supplies, diagnostics, heating systems, and remote maintenance (with the power supplies being the dominant cost item in this category), and one-third for facilities and siting. Consequently, power supplies, facilities, and siting are seen as important areas that will receive close attention.

In summary, technical goals set for the NSO study were exceeded by a considerable margin during FY99. Several very attractive options for expanded physics missions were identified within the capability of the magnet systems.

Engineering and Technical Infrastructure

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

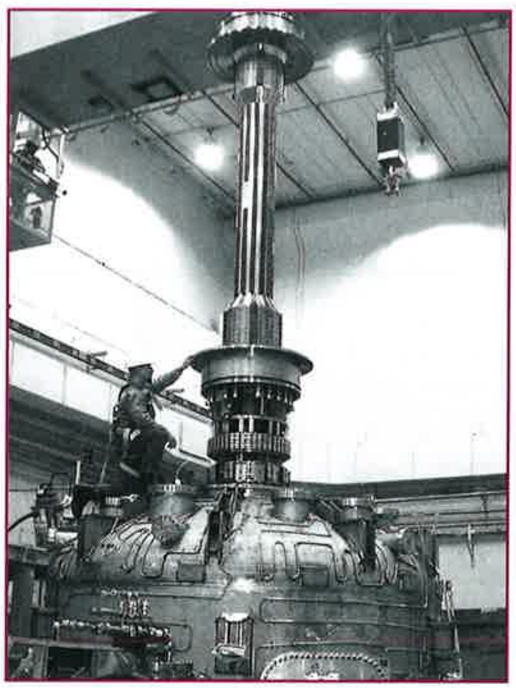


Figure 1. Installation of the NSTX center magnet structure.

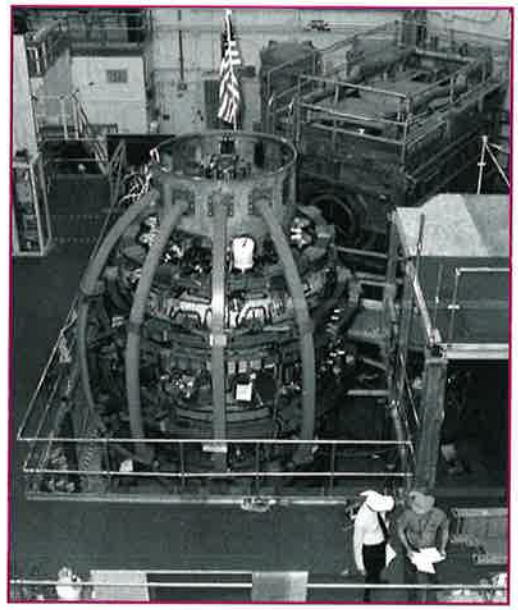


Figure 2. Completed NSTX device.

National Spherical Torus Experiment Construction

Final assembly and testing of the National Spherical Torus Experiment (NSTX) was completed and First Plasma accomplished in February 1999, ten weeks ahead of schedule and within budget. Following initial operations, the device was shut down to install the high-power plasma-facing components and upgrade diagnostics. Another major outage is planned for January 2000 to install a neutral beam injector which will provide up to five megawatts of heating power.

Tokamak Fusion Test Reactor

The Tokamak Fusion Test Reactor, a one-of-a-kind tritium-fueled fusion research device located in PPPL's D-Site complex, ceased operation in April 1997. During FY99 the safety and radiological cleanliness of the D-Site facility was successfully maintained while beginning to make the transition from caretaking to decontamination and decommissioning operations.

In addition, PPPL continued its collaboration with the Japanese Atomic Energy Research Institute, investigating the retention of tritium in carbon tiles resulting from high-power deuterium-tritium plasma operations. As part of this collaboration, PPPL staff, dressed in bubble suits, entered the TFTR vacuum vessel safely, and a large amount of data was collected. This data is being analyzed to determine the inventory of tritium maintained within the thin layer of plasma exhaust deposited on the surface of the TFTR limiter tiles. In addition to the ongoing analysis of the limiter tiles, staff worked on specialized tritium monitoring and tritiated waste solidification.

Figure 3. Diamond-wire rope and pulleys.

Also during FY99, PPPL had the opportunity to host the 17th Tritium Focus Group Meeting, attended by more than 50 participants representing most of the major tritium facilities in North America, Europe, and Japan.

TFTR D&D Preparations

The decontamination and decommissioning of the TFTR is scheduled to occur during a three-year period, beginning October 1999. The mission of the TFTR D&D Project is to:

- remove and store items which can be reused within the Department of Energy (DOE) complex;

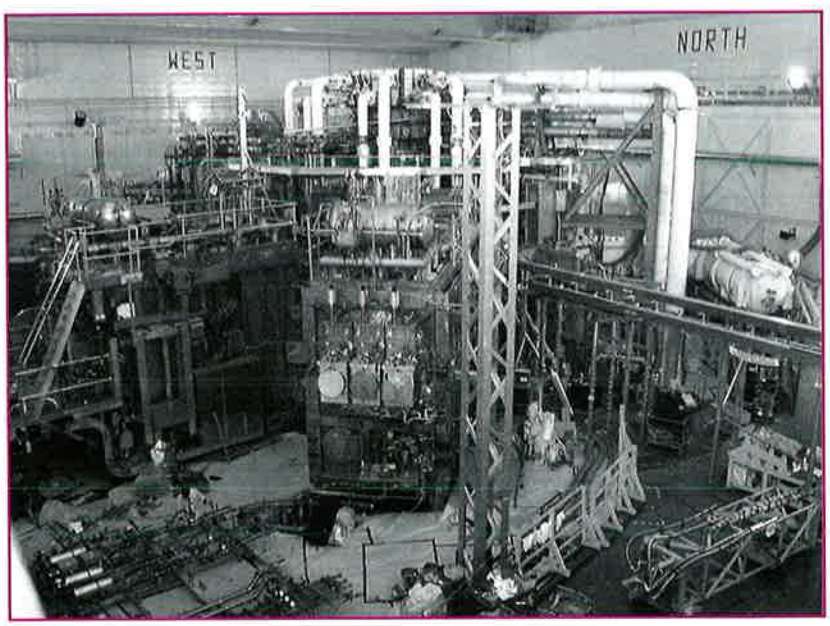


Figure 4. TFTR at the start of the D&D Project.

Figure 5. NSTX beamline undergoing modifications and installation.

- remove all remaining tritium contaminated and activated systems for disposal (except for the neutral beams);
- reclassify the D-site complex as a nonnuclear facility.

Starting in May, a core group began preparations for the October start-up of the TFTR D&D Project. The Work Breakdown Structure dictionary was updated and estimates were prepared for much of the work. Estimates of the quantities of radioactive waste resulting from the TFTR D&D were reviewed and updated. The Project Management Plan was also updated.

In June, several D&D experts within the DOE community were brought to PPPL to provide a two-day training session for engineers and crew leaders who will be working on TFTR D&D.

In July, a successful DOE Workshop on TFTR D&D was held at PPPL with a review committee comprised of the D&D specialists. This same committee will conduct a formal cost and schedule review in December 1999.

In late August, full-scale demonstrations of the diamond-wire cutting technique which will be used to segment the TFTR vacuum vessel were successfully completed at PPPL.

Neutral Beam Injection System for the National Spherical Torus Experiment

The Neutral Beam Injection Development Project focused on preparations for the planned NSTX outage in January 2000 when installation of the system will be completed and it will be commissioned. Final designs were completed for the protective plate armor to be installed in the NSTX vacuum vessel and the transition duct needed to connect the beamline to the NSTX torus. A prototype of the new gradient grid voltage divider, that eliminates the need for Freon coolant in the modulator regulator power supplies, was built and successfully tested through its full power range. In addition, work continued on the recommissioning of the internal beamline components, the fabrication of cryogenic lines, and the decontamination and refurbishment of the long-pulse ion sources reclaimed from TFTR for use on NSTX.

Cyber Security

The explosive growth of the internet has brought access to our site for an ever-increasing number of people. At the same time, the number of recorded hacker attacks on our site has also increased. Due to security breaches at other laboratories, as well as an overall increase in hacker attacks worldwide, DOE and Congress increased focus on computer security issues. Several new DOE orders regarding computer security were issued in FY99 for implementation in FY00 and beyond. In late FY99, PPPL established a Cyber Protection Technical Working Group and a Cyber Protection Review Board to manage the Cyber Protection Program. The process of preparing a "Cyber Security Action Plan" for PPPL was begun.

In FY99, several technical steps were begun to increase our level of protection, while continuing to allow for open collaborative research. A firewall was added and is currently being monitored on a daily basis to proactively block sites that are viewed as potential threats. Wide use of encrypted passwords was implemented. Further measures to increase security were planned. These include the implementation of virus scanning and site filtering software which will work with the firewall to better protect the Laboratory against incoming viruses in e-mail or ftp attachments, and from improper use of web browsers. We also plan to investigate implementation of secure key identification technology at PPPL. This will initially be implemented to restrict access to root accounts at PPPL, but will also be evaluated as a mechanism for requiring password identification through the PPPL firewall for all accounts. A network intrusion detector is also being planned to monitor incoming and outgoing PPPL traffic.

Y2K

FY99 saw the culmination of extensive Y2K planning and preparations. In accordance with DOE directives, PPPL's mission essential systems were validated as Y2K compliant. An Independent Validation and Verification of the systems was conducted. End-to-end tests were executed. Business continuity plans and contingency plans were prepared. All nonmission essential systems, which support the scientific research efforts at PPPL, were also inventoried and validated for Y2K compliance. Operating systems updates and patches were applied in preparation for the event. PPPL participated in DOE orchestrated Y2K drills, exercising our "Day-0" readiness plans.

National Compact Stellarator Experiment

Much of the engineering effort for the National Compact Stellarator Experiment (NCSX) in FY99 was in support of the development of advanced analytical computer codes for stellarator design. These codes, or "tools," as they are commonly called, are described in the NCSX section of this report. Work continued in parallel on the engineering design of the hybrid compact stellarator concept that began last year. This device, shown in Figure 6, would utilize much of the existing Princeton Beta Experiment-Modification (PBX-M) facility. The conversion requires the

Figure 6. The NCSX concept based on modifications to the PDX-M device.

installation of a new "core," consisting of a twisted donut-shaped vacuum vessel, and conformal magnetic windings surrounding the vessel. The conformal windings would be cooled by liquid nitrogen prior to an experimental pulse to lower their electrical resistance for higher performance.

During FY99, comparative studies were underway on two possible alternatives, which would not involve the use of PBX-M. The first alternative, shown in Figure 7, would use shaped-background coils around a core similar to the one that would be used in the modified PBX-M concept. The new background coils improve access and reduce the current density required in the conformal windings. In the second alternative, shown in Figure 8, the conformal winding would be replaced with a combination of shaped-background coils and poloidal field coils. This would improve access and be easier to fabricate. Both concepts are being analyzed to determine their feasibility.

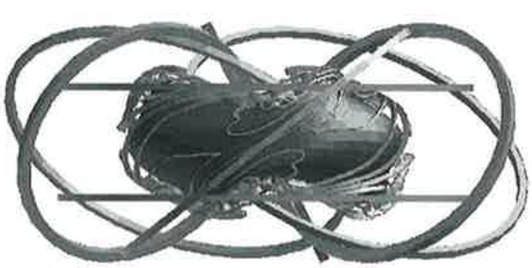


Figure 7. Side view of the first alternative for NCSX with shaped-background coils for improved access.

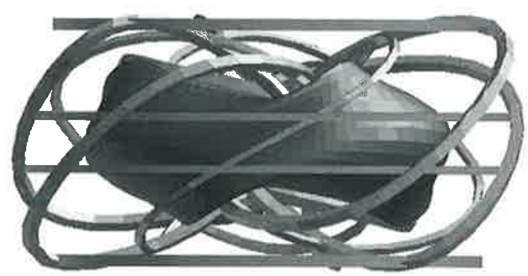


Figure 8. Side view of the second alternative for NCSX with shaped-background coils and external poloidal field coils. This eliminates the need for conformal windings.

Technology Transfer

One of the missions of the Princeton Plasma Physics Laboratory (PPPL) is the transfer of technology to other federal laboratories, private industry, and academic institutions. The Laboratory is currently collaborating with a number of industrial partners in research and development. These collaborations, which are predominantly Cooperative Research and Development Agreements (CRADAs), primarily involve near-term applications of science and technology developed for PPPL's fusion program. The PPPL Technology Transfer Office implements the Laboratory's efforts.

A CRADA, which is a contractual agreement between a federal laboratory and one or more industrial or university partners, is one of several vehicles by which technology can be transferred to the private sector or government agencies. A CRADA enables industry and PPPL researchers to work on programs of mutual interest. Costs and project results may be shared between the Laboratory and the research partner. In addition to CRADAs, the PPPL Office of Technology Transfer coordinates other programs to promote the transfer of technology to industry, including Work for Others, Employee Exchanges, and Licensing of Inventions and Technologies. In Work for Others, industry pays for work performed at PPPL, while in the Employee Exchange Program, researchers from industry assume a work assignment at the Laboratory, or PPPL staff work in the industrial setting. PPPL technology is licensed through Princeton University's Office of Research and Project Administration. The Laboratory works closely with the University for the patenting and protection of PPPL intellectual property.

The following projects were active in FY99.

The American Textile Partnership

The American Textile Partnership (AMTEX) is a multi-laboratory Master CRADA that spans the entire U.S. textile industry. AMTEX has a number of subtasks including the On-line Process Control Project. PPPL is collaborating with Dupont, BASF, Camac-Cookson, and Wellman, Inc. through the Princeton Textile Research Institute to develop a non-contact diagnostic instrument that can be

Figure 1. The combination of four helium-neon lasers for optical scattering by fibers.

Figure 2. Laser scattering by a fiber.

used in the factories of U.S. synthetic fiber manufacturers to assure that fibers conform to specifications. The measurements will be made optically on the production line in real time. PPPL had completed the second year of this effort with a proof-of-principle demonstration at the facilities of several industrial partners. In FY96 the program was suspended because of funding limitations.

In FY97 the project was restarted, and a laboratory devoted to the study of laser-fiber interactions was established at PPPL. Since that time, computer modeling codes have been developed that predict the relationship between fiber birefringence and the resultant pattern of laser light scattered from the fibers. The computer codes are highly predictive of experimental results obtained in the laboratory. PPPL is preparing to construct a commercial prototype of the On-Line Process Control System that will be taken into the field for trials on the spinning lines of commercial manufacturers in FY00.

Plasma Sterilization Project

The sterilization of thermoplastic food containers is widespread in industry. Limitations in existing sterilization techniques result in significant increases in production costs. For this reason, improvements in sterilization processes will have a large economic impact. The Plasma Sterilization Project is directed at developing a method for quickly sterilizing food, beverage, and other thermoplastic containers using a plasma discharge. The goal is to sterilize thermoplastic bottles with less than two seconds of treatment in a bottling-line environment.

Bacterial spores are the most difficult microbes to eliminate. PPPL's innovative plasma sterilization technique uses energetic ions for the destruction of microbial spores. However, the technique should be effective on other microbes as well.

During FY99, an experimental plasma chamber for spore testing was completed. In FY00, a series of tests on the spore samples will be conducted with various plasma conditions to determine the optimum plasma parameters for spore destruction, consistent with the needs of industry. These initial proof-of-principle tests will be performed on small aluminum tabs having bacterial spores on one side. In FY01, the range of parameters for effective sterilization will be determined. Hardware will be adapted to the configuration of a beverage or food container. Another series of experiments will be conducted to assess the effectiveness of plasma sterilization with different plastics and spore types. The evaluation will involve an analysis of the kill mechanism using scanning electron microscopy available on Princeton University's main campus.

Development of an RF Pasteurization Process

In FY99, PPPL and the U.S. Department of Agriculture (USDA) continued their interagency agreement to jointly develop new pasteurization methods that will use radio-frequency (rf) waves for pasteurizing raw liquid foods such as eggs, fruit juices, and milk. This Work-For-Others agreement between PPPL and the USDA came about when researchers at the USDA's Eastern Regional Research Center in Philadelphia identified the potential of rf radiation for pasteurization. Initial results and subsequent evaluation of microorganisms introduced into liquid foods indicated that rf radiation is an effective means for pasteurization

Radio-frequency waves offer advantages over the traditional pasteurization method of directly heating raw liquid foods. The direct method often heats foods unevenly, possibly resulting in incomplete pasteurization in lower temperature regions and in denaturing foods in overheated regions. Using rf waves of the appropriate wavelength may allow pasteurization without excessively heating liquid foods to temperatures that cause food deterioration.

The USDA's Eastern Regional Research Center is collaborating with PPPL because of the Laboratory's extensive experience in the application of rf and microwave radiation to the study of plasmas. The Laboratory has expertise in optimizing the absorption of rf and microwave energy into a receiving medium. The applicable PPPL capability includes the measuring of rf parameters, instrumentation, the design and fabrication of antennas, and the safe handling of these components.

During FY99, the PPPL team assisted USDA researchers in equipping their facility with the necessary rf power source and provided the expertise to enable the measurement of power deposited, power launched, and efficiency. In addition, the PPPL group optimized the rf launch configuration and helped monitor the effect of deposited power during the pasteurization process. PPPL will continue to provide support to the USDA in this area during FY00.

Figure 3. Next to the radio-frequency oven that is being used in the pasteurization experiments are members of the PPPL team, including (from left), Chris Brunkhorst, Elmer Fredd, and Dave Ciotti. Not pictured is Randy Wilson.

High-Resolution Imaging Spectrometer and X-ray Collimator

In FY99, PPPL resumed a collaboration with a small business, Radiation Sciences, Inc., to develop the technology for bending large crystals for use in double focusing X-ray spectrometers and similar instruments requiring high spectral and spatial resolution simultaneously. Such a spectrometer could be used as an X-ray diagnostic device in fusion experiments. In previous work, scientists and engineers from Radiation Science and PPPL demonstrated that it was possible to bend a very large circular crystal (200-mm diameter) into an optical-quality segment of a sphere and hold it in that shape for an extended period of time.

In FY99, the goal was to use the geometric characteristics of a spherical, double focusing crystal spectrometer such that a point source of X-rays can be collimated into parallel rays, or conversely, a parallel beam of X-rays can be focused at a point. The latter case makes it possible to build a high-resolution imaging spectrometer for a limited range of X-ray wavelengths that includes spectral lines of importance for plasma diagnosis. This spectrometer would provide simultaneous information on plasma conditions over a large volume. The diagnostic applications include Doppler measurements of the ion temperature and plasma rotation, and measurements of electron temperature, ionization equilibrium, and ion transport. The main advantage of this new type of X-ray spectrometer is that it would provide a spatially and spectrally resolved image of the plasma (on a two-dimensional detector) using only one, spherically bent crystal. The collimating property of the reverse configuration may have important implications for X-ray lithography from point sources such as laser generated plasmas. The development of the spectrometer will continue in FY00.

RF-Heated Plasma Thruster for Spacecraft Propulsion

During FY99, PPPL and Princeton Satellite Systems, Inc. entered into a CRADA for a systems study on the design for an innovative electric thruster. This novel propulsion concept employs radio-frequency electromagnetic fields to heat a plasma that is confined by a superconducting solenoidal magnetic coil. The plasma is expelled along the solenoidal field through a magnetic nozzle where it accelerates to supersonic speed, cools, and recombines into neutral gas, thus generating thrust. This has the potential to solve lifetime and thrust and power limitations of existing electric spacecraft propulsion systems. This propulsion concept can lead to high-thrust high-specific-impulse propulsion systems that would be useful within a decade. Applications include earth transfer orbit operations, lunar transfer vehicles, and manned and unmanned interplanetary missions.

During FY99, a systems design for the thruster was performed. System efficiency and specific-mass and specific-power computer models were developed, and a survey of space missions was initiated.

Particle Simulation Model for Chemical and Atomic Reactions

Applications of low-temperature high-density weakly ionized gases can be found in many branches of physics and engineering. Plasma etching devices in the semiconductor industry typically use such gases. In a past collaboration, PPPL and Charged Injection Corporation (CIC) jointly developed a computer code derived from plasma simulations to model electrostatically charged gases for novel industrial applications. Laser printers, electrostatic fire-fighting systems, and diesel engine nozzles are some examples of applications of charged electrostatic spray technology. In these applications, weakly ionized particles arising from gas breakdown in a high-density neutral gas, created by a driving electric field, play the essential role. The electrons gain energy from the field (source) and lose it to the atomic and chemical reactions (sinks) so that their energy distribution is far from equilibrium.

The original collaboration with CIC was well received by the physics community, and resulted in an American Physical Society invited paper. In the new collaboration, PPPL and CIC initiated the development of a new class of particle codes for the distribution of charged particles. To keep the total number of simulation particles tractable, these codes handle reacting charged gases by clumping electrons. Clumping is done in phase space to conserve momentum and energy.

During FY99, a code was under development in collaboration with Dr. Arnold Kelly of CIC. Once the code is completed, it will be very useful in modeling applications of reacting gases, including the CIC laboratory SPRAY TRIODE® and electron-beam-driven fire-fighting nozzles, where the number of real particles increases exponentially in time. CIC will evaluate the code's predictions by comparing results with experimental observations. This effort is expected to provide the foundation for further collaborative work with CIC.

Edge Turbulence Measurements by Laser-induced Fluorescence

Edge turbulence, a key factor in the performance of fusion devices, is poorly understood. In FY98 during the first phase of a Small Business Innovative Research CRADA with Fusion Physics and Technology, Inc. the development of a planar laser-induced fluorescence diagnostic was undertaken. This diagnostic was designed to measure ion turbulence and provide data that could be used to validate existing models of turbulence and edge transport. A tunable laser was used that would excite ion emission lines at specific wavelengths. The fluorescent light emitted at 90 degrees would be used to quantitatively model the signal-to-noise and signal-to-background ratios for experimentally relevant conditions. Various options to subtract the background emission were identified. The feasibility of measuring hydrogenic densities and velocities by laser fluorescence in the divertor region of fusion devices was investigated.

During FY99, PPPL and Fusion Physics & Technology built the diagnostic and by the end of the year, using the Magnetic Nozzle Experiment as a test-bed, preliminary testing had begun. This diagnostic will be used in physics experiments on the Current Drive Experiment-Upgrade and the Magnetic Reconnection Experiment.

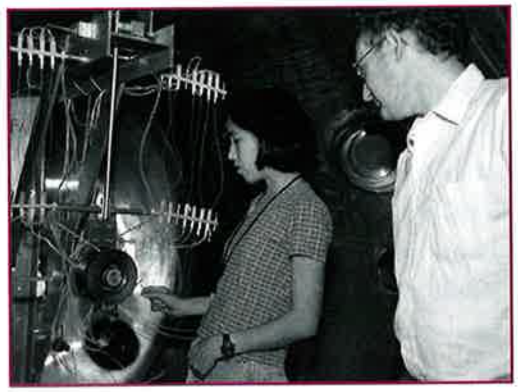
Fast Etching with Segmented Cathode Hall Accelerator

Currently, etching of silicon wafers for microelectrical and mechanical systems (mems) technology occurs on the order of a micron per minute or several hours for a wafer. A significant achievement in a number of industrial processes would be to substantially increase the etching rate as well as the selectivity. This Technology Maturation Project is a cooperative effort with Lucent Technologies. The goal of the project is to evaluate whether the PPPL Segmented Cathode Hall Current Thruster is capable of producing a neutral plasma flow with high current density, so that the thruster can be used as an accelerator of neutral plasma to etch silicon wafers and other materials.

The physical processes that occur when such a plasma impinges upon a silicon wafer can be expected to differ from the processes that occur in conventional plasma processing, using for example, inductively coupled plasmas, because of the different plasma environment in the vicinity of the wafer. In conventional etching, the material is bombarded by energetic flowing ions, while the surface is exposed to moderate-density cool plasma. In thruster etching, the surface is bombarded by energetic flowing neutral plasma, while the surface can be exposed only to very low-density neutral gas or plasma.

To determine whether thruster etching will be advantageous, the collaboration with Lucent was formed to evaluate this empirically. The Lucent team will direct attention to important practical process streams, provide wafers, and help to analyze the etching results. The segmented cathode thruster approach is particularly well suited to such a task because it provides the low plume divergence and plasma control that will be of paramount importance in industrial etching applications.

PPPL will operate the PPPL Hall Thruster, characterize the plasma flow, and position the silicon wafer in the accelerated plasma stream. Lucent will provide guidance on preferred operating regimes, provide suitable wafer targets, and will analyze the etch result. This Technology Maturation Project will provide background information for a more extensive collaboration with Lucent in the future.



Kai-Mei Fu (left) and Project Head Nathaniel Fisch inside the PPPL Segmented Cathode Hall Current Thruster which is located in the space that formerly housed the S-1 Spheromak.

Patents and Invention Disclosures

Patents Issued

Drum Bubbler Tritium Processing System
— Kieth Rule, Geoff Gettelfinger, and Paul Kivler

Patent Applications

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

Provisional Patent Applications

Energetic Ions for Sterilization
— John A. Schmidt

Invention Disclosures

Ion Heating in FRC by Application of Rotating Magnetic Fields
— Samuel A. Cohen

Stabilization of FRC Plasmas against Internal Modes by the Application of Rotating Magnetic Fields
— Samuel A. Cohen

Plasma Production of Ultraviolet Light for Sterilization
— Douglass S. Darrow and Philip Efthimion

Direct Coupling of Electron Bernstein Waves
— Philip Efthimion, J.C. Hosea, Gary Taylor, and R. Majeski

Segmented Cathode Hall Thruster
— Nathaniel J. Fisch and Yevgeny Raitses

A Variable-Frequency RF Source for Plasma Heating Equipment
— Nevell L. Greenough

Cavity Ring Down (CRD) Interferometry for Micro-plasma
— Hyeon K. Park and Elizabeth J. Foley

Current Sheet Plasma Confinement Device
— Stephen F. Paul

Method of using Superconducting Tiles to Form a Surface that Approximates that of a Solid Superconductor
— Wayne Reiersen and Allen Boozer

Advanced MagLev Configuration
— John A. Schmidt

Two-layer Stream Liquid Metal Protection for the First Wall of the Tokamak-reactor
— Leonid E. Zakharov, Nikolai Gorelenkov, and Roscoe White

The First Wall Device for Absorption of Non-localized Thermal Energy/Particle Flux from High Temperature Mirror-machine Plasma with use of B-directed Electro-magnetic Propulsion of Liquid Metal
— Leonid E. Zakharov, Dennis Mansfield, and Robert Woolley

The First Wall Device for Absorption and Transmission of Non-localized Energy/Particle Flux from High Temperature Tokamak Plasma with use of J-directed Electro-magnetic Propulsion of Liquid Metal
— Leonid E. Zakharov, Dennis Mansfield, and Robert Woolley

Lithium Breeder Device for Heat/Material Exchange in Intensive Flux of Fusion Neutrons
— Leonid E. Zakharov, Evgeni Muraviev, and Robert Woolley

Device for Absorption and Transmission of Intensive Localized Thermal Energy/Particle Flux from High Temperature Tokamak Divertor Plasma with use of Electro-magnetic Propulsion
— Leonid E. Zakharov, Martin Peng, and Robert Woolley

Device for J-directed Electromagnetic Propulsion of a Free-surface Liquid Lithium Stream along a Guide Plate in Tokamaks
— Leonid E. Zakharov and Robert Woolley

Device for B-directed Electromagnetic Propulsion of a Free-surface Liquid Lithium Stream along a Guide Plate in Mirror-machines
— Leonid E. Zakharov and Robert Woolley

Device for Intensive Heat/Material Exchange Driven by J-directed Magnetic Propulsion in the Conducting Fluid Contained in a Closed Volume and Embedded in the Toroidal Magnetic Field of a Tokamak
— Leonid E. Zakharov and Robert Woolley

Environmentally Clean and Compatible Tokamak Fusion Lithium-deuterium Reactor with Plasma Facing Liquid Lithium Stream and with Lithium Breeder both Driven and Controlled by J-directed Electro-magnetic Propulsion
— Leonid E. Zakharov, D. Mansfield, E. Muraviev, R. Woolley,
Yu.L. Igitkhanov, S. Krasheninnikov, S.V. Mirnov, A.I. Morozov,
V.S. Mukhovatov, G.V. Pereverzev, S. Putvinskii, and P.N. Yushmanov

Graduate Education

Program in Plasma Physics graduate students for academic year 1999-2000. From left: Luis Delgado-Aparicio, Barbara Sarfaty (Administrator), Troy Carter, Aleksey Kuritsyn, Kyle Morrison, Joshua Breslau, Sorin Zaharia, Daniel Clark, Andrei Litvak, Adam Rosenberg, Leonid Dorf, Elizabeth Foley, Hong Qin (alumni), Jef Spaleta.

The Princeton Plasma Physics Laboratory supports graduate education through the Program in Plasma Physics and the Program in Plasma Science and Technology.

Program in Plasma Physics

In the Program in Plasma Physics, students are admitted directly to the Program and are granted degrees through the Department of Astrophysical Sciences. With more than 200 graduates since 1959, the Program has had a significant impact on the field of plasma physics, providing many of today's leaders in the field of plasma research and technology in academic, industrial, and government institutions.

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

In FY99, there were 33 graduate students in residence in the Program in Plasma Physics, holding among them two Department of Energy Magnetic Fusion Science Fellowships, one Hertz Fellowship, one National Science Foundation Fellowship, two NASA Graduate Student Researchers Program Fellowships, and one Princeton University Honorific Fellowship.

Seven new students were admitted in FY99, two from Russia, one from China, one from Peru, and three from the U.S. Eight students graduated in FY99, six receiving postdoctoral positions at the following: Princeton Plasma Physics Laboratory, Lawrence Livermore National Laboratory, the National Center for Atmospheric Research at the University of Colorado at Boulder, Princeton University, the Institute for Theoretical Physics at University of California, Santa Barbara, and General Atomics. Two graduates took positions in private industry (Lucent Technologies and GE Medical Systems).

A fifth-year graduate student won the Princeton University Charlotte Elizabeth Proctor Honorific Fellowship in recognition of his distinguished work in the Program in Plasma Physics.

Recipients of Doctoral Degrees in Fiscal Year 1999.

Boldyrev, Stanislav A.
Thesis: "Burgers Turbulence and Passive Random Advection"
Advisors: A. Polyakov and John Krommes
Employment: Institute of Theoretical Physics at UC Santa Barbara

Chao, Edward
Thesis: "Pure Electron Plasma Dynamics and the Effects of Collisions with Background Neutral Gas Atoms"
Advisors: Stephen Paul and Ronald Davidson
Employment: GE Medical Systems

Fong, Bryan H.L.
Thesis: "Ballooning Modes in Laboratory and Space Plasmas"
Advisor: Steven C. Cowley
Employment: NCAR/HAO, University of Colorado at Boulder

Heeter, Robert F.
Thesis: "Alfvén Eigenmode and Ion Bernstein Wave Studies for Controlling Fusion Alpha Particles"
Advisor: Nathaniel J. Fisch
Employment: Lawrence Livermore National Laboratory

Malyshev, Mikhail V.
Thesis: "Advanced Plasma Diagnostics for Plasma Processing"
Advisor: Vincent Donnelly (AT&T) and Nathaniel J. Fisch
Employment: Lucent Technologies

Savchenko, Vladislav
Thesis: "Quantum and Radiation Effects in Plasmas"
Advisor: Nathaniel J. Fisch
Employment: Princeton University Department of Astrophysical Sciences

Snyder, Philip B.
Thesis: "Gyrofluid Theory and Simulation of Electromagnetic Turbulence and Transport in Tokamak Plasmas"
Advisor: Gregory Hammett
Employment: General Atomics

Trintchouk, Fedor
Thesis: "XUV Fluorescence in a Vacuum Arc Discharge by Resonant Optical Pumping"
Advisor: Szymon Suckewer
Employment: Princeton Plasma Physics Laboratory

Students Admitted to the Plasma Physics Program in Fiscal Year 1999.

Student	Undergraduate Institution	Major Field
Emily Belli	Cornell University	Engineering Physics and Mechanical Engineering
Andrew Burlingame	Ohio State University	Aeronautical and Astronautical Engineering
Luis Delgado-Aparicio	University Catolica Del Peru	Physics
Ilya Dodin	Nizhny Novgorod University, Russia	Physics
Roman Kolesnikov	Moscow Institute of Physics and Technology	Physics
Thomas Kornack	Swarthmore College	Physics and Linguistics
Chunqiang Li	Peking University	Space Plasma Physics

First year graduate students in the Program in Plasma Physics include, from the left, Roman Kolesnikov, Emily Belli, Ilya Dodin, Andy Burlingame, Tom Kornack, Luis Delgado-Aparicio.

Program in Plasma Science and Technology

Applications of plasma science and technology meld several traditional scientific and engineering specialties. The purpose of the Program in Plasma Science and Technology is to provide strong interdisciplinary support and training for graduate students working in these areas. The scope of interest includes fundamental studies of the plasmas, their interaction with surfaces and surroundings, and the technologies associated with their applications.

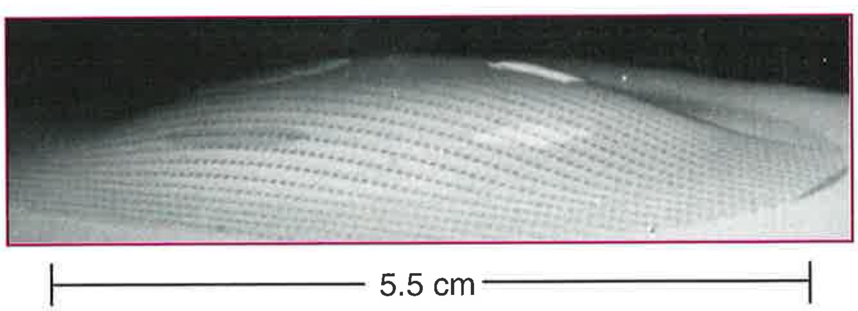
Plasmas are essential to many high-technology applications, such as gaseous lasers, in which the lasing medium is plasma. X-ray laser research is prominent in the Program in Plasma Science and Technology. Another example is fusion energy for which the fuel is a high-temperature plasma. Lower temperature plasmas are used for a growing number of materials fabrication processes, including the etching of complex patterns for microelectronic and microoptical components and the deposition of tribological, magnetic, optical (see figure), conducting, insulating, polymeric, and catalytic thin films. Plasmas are also important for illumination, microwave generation, destruction of toxic wastes, chemical synthesis, lasers, space propulsion, and advanced-design accelerators for fundamental particle research.

The Program in Plasma Science and Technology provides support for M.S.E. and Ph.D. students who concentrate on a specific research topic within the field of plasma science and technology while acquiring a broad background in relevant engineering and scientific areas. Princeton University departments in the Program are Astrophysical Sciences, Chemical Engineering, Chemistry, Civil Engineering, Computer Science, Electrical Engineering, Mechanical and Aerospace Engineering, and Physics. In 1999, eleven students received support from the Program; they coauthored more than a dozen refereed publications; five of these students received their Ph.D. degrees.

Two graduate students supported by the Program won awards for their thesis work. Kiran Pangal, now at Intel, won the Graduate Student Gold Medal Award from the Materials Research Society for his thesis entitled "Hydrogen-Plasma-Enhanced Crystallization of Hydrogenated Amorphous Silicon Films: Fundamental Mechanisms and Applications." Zhehui Wang, now at Los Alamos National Laboratory, won the Best Student Paper Award from the American Vacuum Society for a paper entitled "Geometrical Aspects of Hollow-Cathode Planar-Magnetron Sputtering."

A new grant, the Cooperative Research and Development Agreement, was awarded to a member of the Program's Interdepartmental Committee. The Agreement sponsored a joint research project with a local company and supported one student.

To maintain a strong Program in Plasma Science and Technology, increased efforts were made to develop appreciation for plasma physics among undergraduates. A sophomore seminar, entitled "All Plasmas Great and Small" was presented in Mathey College. One student from that class worked at PPPL on a plasma thruster project. The Program's interdepartmental faculty supervised independent research on plasmas by undergraduates.



Amorphous silicon islands deposited by plasma-enhanced chemical vapor deposition on polyimide foil after deformation to a spherical surface shape. These will become part of a spherically shaped infrared detector focal plane array.

Science Education

Undergraduate students who participated in PPPL summer programs during 1999 are, from left, (kneeling) Sabrina Turner, David Schuster, Jesse Hwang, Damon Tuney, Kai-Mei Fu, Amaria George; (middle) Jonathan Nazemi, Vyacheslav Lukin, Geoffrey Brumfiel, Shinya Kurebayashi, Tim Miller, Anthony Mrozckowski, Mike Mulligan, Karl Leuenroth, Adam Edwards; (back row) Brian Pierce, Eugenio Ortiz, Remik Ziemlinski, Jeff Nine, Steve Little, David Hannum, Brian Kirby, Thawatchai Onjun, and Warren Welch.

The goals of the Princeton Plasma Physics Laboratory (PPPL) Science Education Program are:

- to provide a comprehensive portfolio of initiatives that leverage the creativity and enthusiasm of teachers to enhance the science learning and understanding of America's children in grades K-12;
- to integrate research and education to improve teaching;
- to contribute to the training of the next generation of American scientists and engineers;
- to improve the scientific literacy of the community at large.

The science education programs allow PPPL staff to participate in science education and outreach through involvement with K-12 teachers, K-12 students, undergraduate students, and informal educational activities.

Integrated Mathematics and Science Project

During FY99, PPPL in conjunction with the National Science Foundation and the U.S. Department of Energy entered into a partnership with the Philadelphia School District. The program, coordinated through the school district's Office of Leadership and Learning, provides professional development for science and mathematics teachers.

During 1999, the Program consisted of four separate parts:

- A one-week workshop, the Summer Energy Institute, held at PPPL during the summer.
- A three-day workshop on the integrated use of mathematics and science held at a Philadelphia school. The workshop used the implementation of an energy audit to demonstrate the integration of mathematics and science in the curriculum.
- A follow-up meeting with participants was conducted by the Office of Leadership and Learning to assess the outcomes of the activities held during the summer and to plan future activities.
- School-year support and follow-up by PPPL scientists and staff.

The first phase of the partnership, the Summer Energy Institute, was designed to provide the content knowledge, pedagogy, and technology integration necessary for teachers to conduct research projects with students. During the Institute, the teachers were taught to use research as a vehicle for content enhancement and were provided the opportunity to experience constructivist learning. The Institute was developed in collaboration with the Philadelphia School District's Office of Leadership and Learning utilizing closely aligned national standards. The program enabled teachers to obtain the necessary skills to develop projects that would address the goals of "Reaching Higher: Graduation and Promotion Supports and Requirements," the District's newly developed educational standards.

Science, Mathematics, and Technology Collaborative

Started in FY99, the Science, Mathematics, and Technology Collaborative is a three-year program of sustained, intensive, high-quality professional development for teachers of grades 3 through 6. In this collaboration, Princeton University's Teacher Preparation Program, the Invention Factory Science Center, and PPPL are working in partnership with the school districts of the cities of Trenton and Burlington, and Florence Township Public Schools.

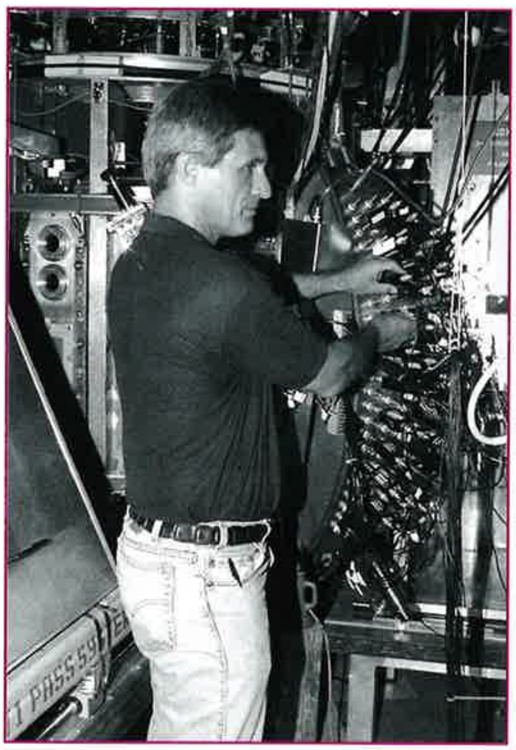
Each partner institution has a specialized, clearly defined role in the project that effectively uses its unique resources to enhance teacher professional development. Program activities are designed to further the implementation of the participating districts' vision, to strengthen the teaching of science, math, and technology, and to integrate these subjects with other core curriculum content areas. This should lead to an improved understanding and interest in science and math for the children in those districts. Accomplishments during FY99 include:

- The completion of an intensive, comprehensive needs assessment of teachers and administrators in all three districts.
- Thirty-five workshops reaching 133 teachers, exceeding the project's year-one goal. In addition, 30 teachers from other districts in Central New Jersey not in the program attended the workshops.
- A successful network of mentor teachers was formed. The mentors are working to disseminate project information and implement strategies to improve science teaching.

- Twenty teachers and 19 preservice teachers participated in summer institutes.
- Fifty teachers attended workshops on the use of the Internet as an effective classroom tool.
- A web site was created to facilitate teacher interchange on science matters.
- Preservice teachers attended the Quest Summer Institute at Princeton University and participated in workshops.

Plasma Camp

The Plasma Science and Fusion Energy Institute, known as "Plasma Camp," is an intensive two-week program of lectures, lab work, and curriculum design for high school physics teachers. The program began in the summer of 1998 and, in FY99, veteran teachers returned to PPPL and studied plasma behavior in the Current Drive Experiment-Upgrade (CDX-U).



Father Michael Liebl, a Plasma Camp participant who teaches at Mount Michael Benedictine High School in Elkhorn, Nebraska, conducts research on the CDX-U machine during the summer workshop.

The FY99 Plasma Camp was the first time that teachers actually ran an experimental fusion device and conducted research the same way scientists do. Working with PPPL researchers, teachers from Kansas, Nebraska, and New Jersey operated the hydrogen-fueled machine, evaluated the temperature and density of the plasma, and analyzed plasma impurities recorded with a soft X-ray pinhole camera. The experiments involved changing the magnetic field level to gauge the effect on the plasma. In addition to participating in the CDX-U experiments, three returning teachers assisted in the workshop and served as mentors to the new participants. Participants in the program are selected nationwide.

The goal of Plasma Camp is to help teachers develop curricular materials for introductory physics teaching, which make the subjects of plasma and fusion science accessible to high school students. One participant noted, "at the Plasma Institute, they teach us on a graduate level and create a stimulating atmosphere where we can develop curriculum materials appropriate for our students."

Outreach Efforts

During FY99, partnerships with local community organizations involved with improving science education and science literacy were continued. PPPL hosted the annual A+ for Kids Teacher Network's Summer Science, Mathematics, and Technology Institute. The theme of the FY99 Institute was "Technology in the Classroom." Middle and High School teachers from throughout New Jersey spent three days at PPPL exploring topics such as Internet Applications for Science and

Mathematics; Revitalizing Science Teaching Using Remote Sensing Technology-Meteorology; and Science, Industry & Education: Making the Connection.

PPPL hosted young women from the Foxcroft School in Virginia. Four PPPL women in science and technology participated in the program that included a tour of PPPL's experimental facilities, workshops, and a panel discussion. The staff encouraged the Foxcroft women to consider a range of career options now open to women.

In November, PPPL employees participated in the 1999 Plasma Expo and Science Teachers Day at the annual meeting of the American Physical Society-Division of Plasma Physics. More than 4,000 students attended the Expo and 138 teachers attended workshops during Teacher's Day. The goal of the annual Plasma Expo and Science Teachers Day is to 'build a bridge' between the plasma science community and the educational community.

FY99 marked the 15th anniversary of PPPL's popular Science-on-Saturday lecture series. William J. Hogan of the Lawrence Livermore National Laboratory kicked off the 1999 Series, which offered eight free lectures geared toward high school students, but open to the public at large. The goal of Science-on-Saturday is to improve science literacy by exposing children and adults to a broad range of science and science related issues. Approximately 2,150 individuals attended the 1999 series, a record number.

Undergraduate Research Programs

PPPL's long-standing National Undergraduate Fellowship Program and the recently implemented Department-of-Energy-sponsored Energy Research Undergraduate Laboratory Fellowship Program were conducted at the Laboratory during FY99. Through these programs, undergraduate science and engineering students are introduced to plasma science and technology through a one-week course in Plasma Physics, followed by participation in the on-going research of the Laboratory for nine weeks.

In addition to the research project, mentors provide guidance and support to students in matters related to course selection, graduate programs, and career options. During the summer of 1999, twenty-four students from colleges and universities throughout the United States participated in the programs. Students were selected competitively, based on their academic abilities, potential to do research work, and interest in graduate study.

Awards and Honors

Individual Awards

Joshua Breslau
1999 Charlotte Elizabeth Procter Honorific Fellowship
Princeton University

Darin Ernst
Outstanding Doctoral Thesis in Plasma Physics Award
American Physical Society-Division of Plasma Physics

Guo-Yong Fu
Kaul Foundation Prize for Excellence
in Plasma Physics and Technology Development
Princeton University

Long-Poe Ku
PPPL Distinguished Engineering Fellow
Princeton Plasma Physics Laboratory

Scott Larson
President's Standing Committee on the Status of Women Award
Princeton University

W. Wei-li Lee
PPPL Distinguished Research Fellow
Princeton Plasma Physics Laboratory

Ernesto Mazzucato
PPPL Distinguished Research Fellow
Princeton Plasma Physics Laboratory

Dale Meade
Leadership Award
Fusion Power Associates

Raffi Nazikian
Kaul Foundation Prize for Excellence
in Plasma Physics and Technology Development
Princeton University

George "Hutch" Neilson
Fellow
American Physical Society

James Taylor
Presidential Achievement Award
Princeton University

Harry Towner
EMS Recognition Award
Stark & Stark

Laboratory Awards

Award of Distinction
U.S. Small Business Administration
for PPPL's "Outstanding Efforts" in Providing
Contracting Opportunities to Small Businesses

Corporate Small Business Award
U.S. Department of Energy
for PPPL's "Outstanding Achievement" in Providing
Contracting Opportunities to Small Businesses

Dwight D. Eisenhower Award
U.S. Small Business Administration
for PPPL's "Outstanding Record" in Subcontracting to Small Businesses

Recognition Award
New Jersey Governor's Occupational Safety and Health Awards Program
for PPPL's "Outstanding Performance" for Safety

Recognition Award
New Jersey Governor's Occupational Safety and Health Awards Program
for NSTX Employees' "Outstanding Performance" for Safety

Recipients of the DOE Certificates of Appreciation for their efforts during the Integrated Safety Management System review were, from left (front row): John DeLooper, Al von Halle, and Joanne Bianco; (back row) George Ascione, Bill Slavin, DOE Princeton Group manager Jerry Faul (who presented the awards), Jerry Levine and Jim Graham. Not pictured are J.W. Anderson, Larry Dudek, Scott Larson, Dave O'Neill, Mike Viola, and Mike Williams.

The Year in Pictures

On February 12, PPPL staff watched a monitor in the Control Room as the National Spherical Torus Experiment (NSTX) achieved first plasma. From left are Tom Egebo, Raffi Nazikian, Ken Young, Ron Strykowsky, Steve Sabbagh (seated), Charles Gentile, Eric Fredrickson, PPPL Director Rob Goldston (seated in front wearing suspenders), Martha Redi, Hutch Neilson, and NSTX Program Director Martin Peng (far right at front).

Secretary of Energy Bill Richardson came to PPPL on February 26 for a ceremony celebrating the beginning of experimental operations on the National Spherical Torus Experiment (NSTX). Cutting a ribbon to mark the occasion are, from left, Laboratory Director Rob Goldston, N. Anne Davies, Associate Director for Fusion Energy Sciences at the DOE Office of Science, Representative Rush Holt (NJ-12th), Richardson, Representative Rodney Frelinghuysen (NJ-11th), Princeton University President Harold Shapiro, and Princeton Township Mayor Phyllis Marchand.

Princeton author Richard Preston captivated a standing room only crowd at PPPL with his discussion about "The Shadow of Biological Weapons" on March 20 during the Laboratory's final talk for the 1999 Science on Saturday lecture series. Preston is a journalist and the author of the best selling nonfiction book, "The Hot Zone," a true story about an outbreak of the Ebola virus near Washington, D.C. Science on Saturday is an annual wintertime series of free lectures geared toward high school students, but open to everyone.

On April 22, nearly 300 students, teachers, and children of PPPL staff came to the Laboratory for this year's Pollution Prevention Awareness activities and Take Our Children to Work Day. The day featured poster contest displays and awards, science demonstrations, talks, and — for the offspring of staff visiting for Take Our Children to Work Day — hands-on experience in various areas of PPPL. Shown are students trying out a plasma ball during the demonstrations in the Lobby.

Harold P. Furth, former Director of PPPL and one of the "giants" of fusion, was honored during a day-long symposium on June 7 at PPPL. More than 100 people from the national and international fusion community, as well as from the U.S. Department of Energy and Princeton University, came to the Laboratory to celebrate Furth's life and scientific achievements. Furth retired on July 1 and became Professor Emeritus of Astrophysical Sciences at Princeton University. Furth holds a gift he received at a dinner held in his honor.

This year, experiments began on the Hall Thruster, a plasma-based propulsion system for space vehicles. Next to the Hall Thruster are, from left (back row), Kai-Mei Fu, PPPL technical associate Dick Yager, PPPL physicist Yevgeny Raitses, visitor Amnon Fruchtman, and Project Head Nathaniel Fisch; (front row) Adam Edwards, Eugenio Ortiz, and Princeton University graduate student Andrei Litvak. Fu, Edwards, and Ortiz are Energy Research Undergraduate Laboratory Fellowship students who were at PPPL for 10 weeks during the summer.

The Laboratory honored thirty-three inventors for Fiscal Year 1998 during the annual Patent Recognition Dinner on June 29 at Princeton University's Prospect House. Those attending the dinner and receiving awards were, from left (front row), Charles Skinner, Henry Kugel, Manfred Bitter, and Kenneth Hill; (second row) Yevgeny Raitses, Wolfgang Stodiek, and A. Lane Roquemore; (third row) Amnon Fruchtman, Cynthia Phillips, Szymon Suckewer, and Robert Woolley; (fourth row) Schweickhard von Goeler, James Gorman, David Mikkelsen, and John Schmidt.

In September, the Laboratory celebrated the successful completion of the NSTX construction tasks and the restart of plasma operations. Some members of the NSTX Operations team pose by the project display in the Lobby. From left are Mike Anderson, Bill Blanchard, Glenn Pearson, Ray Camp, Joe Winston, Colin McFarlane, Tom Czeizinger, Jerry Gething, and Bob Herskowitz.

PPPL Financial Summary by Fiscal Year (Thousands of Dollars)

	FY95	FY96	FY97	FY98	FY99
Operating Costs					
Fusion Energy Sciences					
TFTR Physics/Data Analysis	$14,207	$13,004	$13,607	$4,955	$317
TFTR Operations	46,938	33,792	13,497	—	—
TFTR Shutdown/Caretaking	2,047	8	12,368	3,292	2,952
TFTR D&D	—	—	—	—	371
Subtotal TFTR	$63,192	$46,804	$39,472	$8,247	$3,640
NSTX	—	$1,163	$1,441	$3,241	$13,737
NCSX	—	1,073	702	2,524	2,840
Theory and Computation	3,295	2,683	2,929	4,003	5,161
Off-site Collaborations	2,279	1,253	4,028	9,241	9,281
Off-site University Research Support	—	—	—	985	697
CDX-U	758	699	479	802	680
MRX	166	125	39	165	221
Science Education Programs	429	301	440	691	652
ITER	2,138	2,981	3,546	3,677	488
TPX	43,145	(1,255)	(1,062)	(224)	(116)
PBX-M	4,138	9	—	—	—
Other Fusion	1,544	1,107	1,430	2,220	2,715
Change in Inventories*	(76)	(90)	(35)	(50)	(35)
Total Fusion Energy Sciences	$121,008	$56,853	$53,409	$35,522	$39,961
Environmental Restoration and Waste Mgt	$5,728	$3,581	$4,066	$3,735	$3,564
Computational and Technology Research	300	391	157	101	92
Basic Energy Sciences	—	—	—	302	534
High Energy Physics	—	—	—	73	80
University and Science Education	331	279	92	—	—
Energy Management Studies	124	136	13	3	58
Total DOE Operating	$127,491	$61,240	$57,737	$39,736	$44,289
Work for Others					
Korea Basic Science Institute	—	$186	$1,837	$2,039	$871
All Other	797	693	1,199	2,218	1,755
TOTAL OPERATING COSTS	$128,288	$62,119	$60,773	$43,993	$46,915
Capital Equipment Costs					
TFTR	$469	$546	$241	—	—
NSTX	—	—	3,412	12,268	8,503
All Other Fusion	458	71	32	—	970
Environmental Restoration and Waste Mgt	127	125	75	(1)	58
TOTAL CAPITAL EQUIPMENT COSTS	$1,054	$742	$3,760	$12,267	$9,531
Construction Costs					
General Plant Projects - Fusion	$2,066	$2,158	$473	$454	$798
General Plant Projects - ERWM	163	—	—	—	—
Safety and Fire Protection Improvements	817	332	34	—	—
Radioactive Waste Handling Facility	1,066	560	1	—	—
Energy Management Projects	71	66	255	45	15
Tokamak Fusion Test Reactor	—	—	—	—	(2)
TOTAL CONSTRUCTION COSTS	$4,183	$3,116	$763	$499	$811
TOTAL PPPL	$133,525	$65,977	$65,296	$56,759	$57,257

**Change of the inventory levels on hand at the end of the fiscal year compared to the previous fiscal year (excludes write-offs).*

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Off-Site Research
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Plasma Science and Technology
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Stephen C. Jardin, Deputy

Experiment
Joel C. Hosea

Engineering and Technical Infrastructure
Michael D. Williams

Business Operations
Edward H. Winkler

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

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

PPPL Staffing Summary by Fiscal Year

	FY95	FY96	FY97	FY98	FY99
Faculty	7	7	6	6	3
Physicists	91	89	88	87	89
Engineers	118	105	76	74	74
Technicians	215	198	137	136	139
Administrative	91	81	66	68	69
Office and Clerical Support	37	28	19	18	19
Total	559	508	392	389	393

Collaborations

Laboratories

A.F. Ioffe Physical-Technical Institute, St. Petersburg, Russian Federation
Argonne National Laboratory, Argonne, IL
Association Euratom-CEA, Cadarache, France
Association Euratom-CRPP-EPFL, Lausanne, Switzerland
Association Euratom-FOM, Nieuwegein, Netherlands
Associazione Euratom-ENEA, Frascati, Italy
E.O. Lawrence Berkeley National Laboratory, Berkeley, CA
Ecole Royal Militaire, Brussels, Belgium
Environmental Measurements Laboratory, U.S. DOE, New York, NY
Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID
Institute for Nuclear Research, Kiev, Ukraine
Institute for Plasma Research, Ghandinagar, India
Institute of Plasma Physics, Kharkov, Ukraine
Istituto di Fisica del Plasma, Milan, Italy
Forschungszentrum, Jülich GmbH, Germany
ITER Joint Work Site, Garching, Germany
ITER Joint Work Site, Naka, Japan
Japan Atomic Energy Research Institute, Naka Fusion Research Establishment, Ibaraki, Japan
Japan Atomic Energy Research Institute, Tokai Research Establishment, Ibaraki, Japan
JET Joint Undertaking, Abingdon, Oxfordshire, United Kingdom
KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
Korea Atomic Energy Research Institute, Taejon, Republic of Korea
Korea Basic Science Institute, Taejeon, Republic of Korea
Lawrence Livermore National Laboratory, Livermore, CA
Los Alamos National Laboratory, Los Alamos, NM
Max Planck Institüt für Plasmaphysik, Garching, Germany
Max Planck Institüt für Plasmaphysik, Greifswald, Germany
Max Planck Institüt für Quantenoptik, Garching, Germany
National Institute for Fusion Science, Toki, Japan
New Jersey Department of Environmental Protection, Trenton, NJ

Oak Ridge National Laboratory, Oak Ridge, TN
Pacific Northwest National Laboratory, Richland, WA
Russian Research Centre, Kurchatov Institute, Moscow, Russian Federation
Sandia National Laboratories, Albuquerque, NM
Sandia National Laboratories, Livermore, CA
Southwestern Institute of Physics, Chengdu, China
Textile Research Institute, Princeton, NJ
Troitsk Institute of Innovative and Thermonuclear Research, Troitsk, Russian Federation
UKAEA, Government Division, Fusion, Culham, United Kingdom
U.S. Department of Agriculture, Eastern Regional Research Center, Philadelphia, PA
Westinghouse Savannah River Site, Aiken, SC

Industries

Advanced Energy Systems, Medford, NY
BASF, Charlotte, NC
Bechtel Energy and Consulting, San Diego, CA
Boeing Company, St. Louis, MO
Bristol-Myers Squibb, Lawrenceville, NJ
Camac-Cookson Fibers, Bristol, PA
Charged Injection Corporation, Monmouth Junction, NJ
CompX, Inc., Del Mar, CA
DuPont Chemical Corporation, Wilmington, DE
Fusion Physics and Technology, Inc., Torrance, CA
General Atomics, San Diego, CA
Lodestar, Boulder, CO
Lucent Technologies, Murray Hill, NJ
Mission Research Corporation, Newington, VA
Ontario Hydro, Toronto, Ontario, Canada
Princeton Electronic Systems, Princeton Junction, NJ
Princeton Scientific Instruments, Inc., Princeton, NJ
Qualprotech, Oakville, Ontario, Canada
Raytheon Engineers and Constructors, New York, NY
Schlumberger EMR Photoelectric, Princeton Junction, NJ
Stone and Webster, Cambridge, MA
Wellman, Inc., Charlotte, NC

Universities and Educational Organizations

American Association of Engineering Societies, Washington, DC
American Physical Society, College Park, MD
Auburn University, Auburn, AL
The Australian National University, Canberra, Australia
A+ for Kids, Plainsboro, NJ
Bordentown High School, Bordentown, NJ
Bridges to the Future, Lawrenceville, NJ
Burlington City Schools, Burlington, NJ
Caltech, Pasadena, CA
Carnegie Science Center, Pittsburgh, PA
Center for Technological Education Holon, Israel
The College of New Jersey, Trenton, NJ
Coalition for Plasma Science
Columbia University, New York, NY
College of William and Mary, Williamsburg, VA
The Contemporary Physics Education Project, Palo Alto, CA

Council on Competitiveness,
Washington, DC
Drexel University,
Philadelphia, PA
The Education Fund of Trenton,
Trenton, NJ
The Federal Laboratory Consortium,
Washington, DC
Fisk University, Nashville, TN
The Foxcroft School, Arlington, VA
Florida A&M University, Tallahassee, FL
Florida State University, National
High Magnetic Field Laboratory,
Tallahassee, FL
Florence Public Schools, Florence, NJ
Fort Discovery: The National Science
Center, Augusta, GA
Georgia Institute of Technology,
Atlanta, GA
Grinnell College, Grinnell, IA
Harvard-Smithsonian Center for
Astrophysics, Cambridge, MA
Hiroshima University, Hiroshima, Japan
Hopewell Valley Central High School,
Pennington, NJ
Improving America's Schools Act
Advisory Council, Trenton, NJ
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Institute for Fusion Science, Austin, TX
Invention Factory Science Center,
Trenton, NJ
Johns Hopkins University,
Baltimore, MD
Korea Advanced Institute of Science
and Technology, Taejeon,
Republic of Korea
Kyushu University, Fukuoka, Japan
Lehigh University, Bethlehem, PA
LeTourneau University, Longview, TX
Liberty Science Center, Elizabeth, NJ
Massachusetts Institute of Technology,
Cambridge, MA
Mid-Atlantic Eisenhower Consortium,
U.S. Department of Education,
Philadelphia, PA
Nagoya University, Nagoya, Japan
The National Science Foundation,
Washington, DC
New Jersey Department of Education,
Trenton, NJ
New Jersey Institute of Technology,
Newark, NJ
New Jersey Technology Council,
Plainsboro, NJ
New York University, New York, NY
Oak Ridge Institute for Science
and Engineering, Oak Ridge, TN
Peddie School, Hightstown, NJ
Pennington High School,
Pennington, NJ
Philadelphia Public School System,
Philadelphia, PA
Plainsboro Public Library,
Plainsboro, NJ
Pohang University of Science
and Technology,
Pohang, Republic of Korea
Princeton Center for Leadership
Training, Princeton, NJ
Princeton Satellite Systems,
Princeton, NJ
Princeton University, Princeton, NJ
Rensselaer Polytechnic Institutue,
Troy, NY
Shady Side Academy, Pittsburgh, PA
Sigma Xi, the Scientific Research
Society, Princeton, NJ
Stevens Institute of Technology,
Hoboken, NJ
Steinert High School, Hamilton, NJ
Swarthmore College, Swarthmore, PA
Technische Universitat Graz,
Graz, Austria
Trenton Public Schools, Trenton, NJ
University of Bochum,
Bochum, Germany
University of California, Davis, CA
University of California, Irvine, CA
University of California,
Los Angeles, CA
University of California, San Diego, CA

University of Illinois, Urbana, IL
University of Maryland, College Park, MD
University of Maryland, Baltimore County, MD
University of Massachusetts, Lowell, MA
University of Montana, Missoula, MT
University of Paris, Paris, France
University of Pittsburgh, Greensburgh, PA
University of Provence, Marseilles, France
University of Texas, Austin, TX
University of Tokyo, Japan
University of Toronto, Toronto, Canada
University of Washington, Seattle, WA
University of Wisconsin, Madison, WI
Watchung Hills Regional High School, Watchung, NJ
Westminster College, New Wilmington, PA
Yale University, New Haven, CT

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*First author is from another institution. PPPL co-authors are underlined.
†Paper presented at conference in fiscal year 1999; proceedings to be published.
§Submitted for publication in fiscal year 1999.

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§Bernabei, S., Bell, M.G., Budny, R., Fredrickson, E.D., Gorelenkov, N.N., Hosea, J.C., Majeski, R., Mazzucato, E., Phillips, C.K., Schilling, G., and Wilson, J.R., "Nature of Monster Sawteeth and Their Relationship to Alfvén Instabilities in Tokamaks," Phys. Rev. Lett. **84** (February 2000) 1212-1215; Bernabei, S., Budny, R., Fredrickson, E.D., Gorelenkov, N.N., Hosea, J.C., Majeski, R., Phillips, C.K., Schilling, G., and Wilson, J.R., "On the Nature of Monster Sawteeth during ICRF Heating," Princeton Plasma Physics Laboratory Report PPPL-3345 (May 1999) 17 pp.

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Abbreviations, Acronyms, and Symbols

2-D	Two-dimensional
3-D	Three-dimensional
Alcator C-Mod	A tokamak at the Plasma Science and Fusion Center at the Massachusetts Institute of Technology
ALPS	(Energy) Advanced Liquid Plasma-facing Surface (a U.S. Department of Energy Program)
AMTEX	American Textile Partnership
APEX	Advanced Power Extraction (a U.S. Department of Energy Program)
B_t	Toroidal Magnetic Field
BEST	Beam Equilibrium Stability and Transport Code
C-Mod	A tokamak in the "Alcator" family at the Plasma Science and Fusion Center at the Massachusetts Institute of Technology
CDX-U	Current Drive Experiment-Upgrade at the Princeton Plasma Physics Laboratory
CIC	Charge Injection Corporation
cm	Centimeter
CRADAs	Cooperative Research and Development Agreements
CY	Calendar Year
D&D	Decontamination and Decommissioning
D-D	Deuterium-deuterium
D-T	Deuterium-tritium
DIII-D	Doublet-III-D; a tokamak at General Atomics in San Diego, California
DOE	(United States) Department of Energy

EAEs	Ellipticity-induced Alfvén Eigenmodes
EBW	Electron Bernstein Wave (Heating)
ECCD	Electron Cyclotron Current Drive
ECE	Electron Cyclotron Emission
ECH	Electron Cyclotron Heating
EFIT	An equilibrium code
ELMy	Edge Localized Modes
ER/WM	Environmental Restoration and Waste Management
eV	Electron Volt
FIRE	Fusion Ignition Research Experiment (a national design study collaboration)
FPT	Fusion Physics and Technology, Inc.
FTP	File Transfer Protocol
FY	Fiscal Year
GA	General Atomics in San Diego, California
H-mode	High Confinement Mode
HHFW	High Harmonic Fast Waves
I_p	Plasma Current
ICRF	Ion Cyclotron Range of Frequencies
IDSP	Ion Dynamic Spectroscopy Probe; an optical probe used to measure local ion temperature and flows during magnetic reconnection
ITER	International Thermonuclear Experimental Reactor
JAERI	Japan Atomic Energy Research Institute
JET	Joint European Torus (JET Joint Undertaking) in the United Kingdom
JFT-2M	A small Japanese tokamak
JT-60U	Japanese Tokamak at the Japan Atomic Energy Research Institute
kA	Kiloampere
keV	Kiloelectron Volt
kG	Kilogauss
KMB	Kinetic Ballooning Mode
KSTAR	Korea Superconducting Tokamak Advanced Research device being built in Taejon, South Korea
kV	Kilovolt

kW	Kilowatt
LHD	Large Helical Device; a stellarator operating in Japan
LIF	Laser-induced Fluorescence
MA	Megampere
MAST	Mega Amp Spherical Torus
MHD	Magnetohydrodynamic
MHz	Megahertz
MIT	Massachusetts Institute of Technology in Cambridge, Massachusetts
MLM	Multilayer Mirror
MNX	Magnetic Nozzle Experiment at the Princeton Plasma Physics Laboratory
MRX	Magnetic Reconnection Experiment at the Princeton Plasma Physics Laboratory
ms, msec	Millisecond
MW	Megawatt
NASA	National Aeronautics and Space Administration
NBI	Neutral Beam Injection (Heating)
NCSX	National Compact Stellarator Experiment (a national design study collaboration)
NSO	Next Step Option
NSTX	National Spherical Torus Experiment at the Princeton Plasma Physics Laboratory
OFES	Office of Fusion Energy Sciences (at the U.S. Department of Energy)
ORNL	Oak Ridge National Laboratory, Oak Ridge, Tennessee
OS	Optimized Shear
PBX-M	Princeton Beta Experiment-Modification at the Princeton Plasma Physics Laboratory (no longer operating)
PF	Poloidal Field
PPPL	Princeton Plasma Physics Laboratory in Princeton, New Jersey
PSACI	Plasma Science Advanced Scientific Computing Initiative
Q	The ratio of the fusion power produced to the power used to heat a plasma
QA	Quality Assurance
QA	Quasiaxisymmetry

rf	Radio-frequency (Heating)
RWM	Resistive Wall Modes
ST	Spherical Torus
START	Small Tight Aspect Ratio Tokamak at Culham, United Kingdom
T	Temperature
TEXTOR	Tokamak Experiment for Technologically Oriented Research in Jülich, Germany
TF	Toroidal Field
TFTR	Tokamak Fusion Test Reactor (1982-1997) at the Princeton Plasma Physics Laboratory
Tore Supra	Tokamak at Cadarache, France
TSC	Transport Simulation Code
USDA	United States Department of Agriculture
USDOE	United States Department of Energy
W7-AS	An operating stellarator in Germany
W7-X	A stellarator being built in Germany
Y2K	Year 2000

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