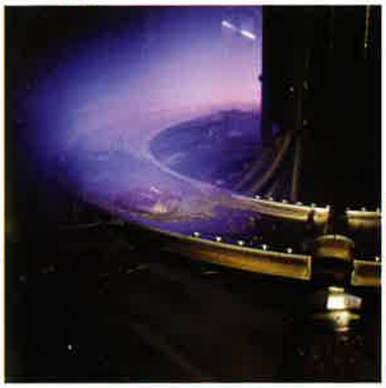

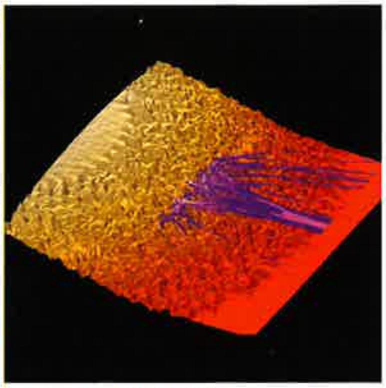

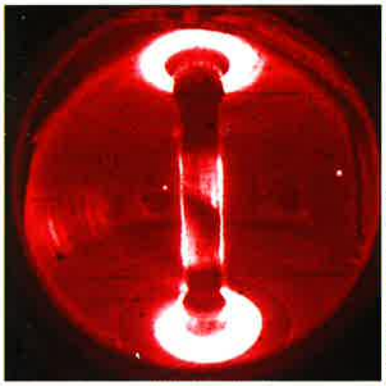

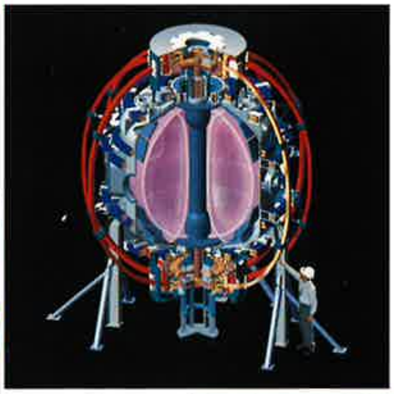

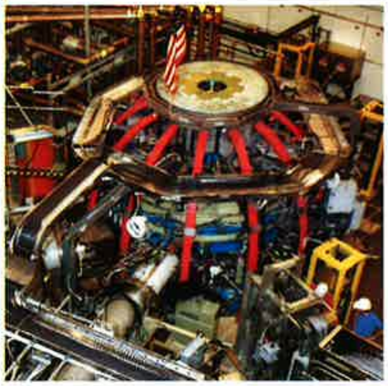

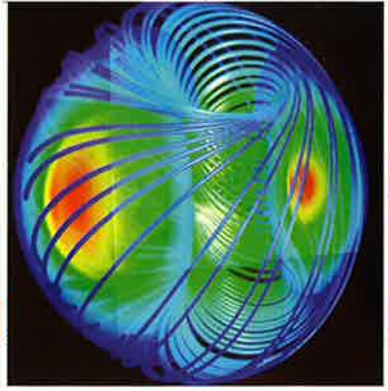

PPPL
PRINCETON PLASMA
PHYSICS LABORATORY

FY2001 Annual Highlights

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 was 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, came into operation in 1999 ahead of schedule and on budget.

Princeton University manages PPPL under contract with the U.S. Department of Energy. The fiscal year 2001 budget was approximately $76.1 million. The number of full-time regular employees at the end of the fiscal year was 485, not including approximately 93 subcontractors, 48 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 plasma thrusters 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

Clockwise from the upper left: (1) Argon glow discharge cleaning of toroidal lithium limiter used for liquid-lithium research on the Current Drive Experiment-Upgrade. (2) A visualization of incoming microwaves (purple) reflecting off microturbulence in a plasma. (3) An artist's rendition of the National Spherical Torus Experiment. (4) An aerial view of the Princeton Plasma Physics Laboratory. (5) An artist's rendition of the National Compact Stellarator Experiment. (6) A visualization of National Spherical Torus Experiment magnetic field lines. (7) The Princeton Plasma Physics Laboratory's Lyman Spitzer Building. (8) A fast digital visible-light camera image of a hot NSTX plasma reaching 20 million degrees Celsius in temperature. The rings of light on the top and bottom indicate cooled plasma due to strong interactions with graphite tiles designed to handle intense plasma heat and particle fluxes. The bands of light in the middle occur where the plasma grazes the graphite tiles that protect the center post magnets. The rest of the plasma appears dark because it emits primarily X-rays. (9) At the center — the National Spherical Torus Experiment.

This publication highlights activities at the Princeton Plasma Physics Laboratory for fiscal year 2001 — 1 October 2000 through 30 September 2001.

Mission

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 energy source.

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

Vision

Deepening the understanding of plasmas and creating key innovations to 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

During FY2001, Princeton Plasma Physics Laboratory (PPPL) researchers made rapid progress in understanding the physics of plasmas — the hot, ionized gas that will fuel fusion power plants in the 21st Century. PPPL is leading two substantial collaborative on-site projects to develop innovative plasma confinement configurations — the National Spherical Torus Experiment (NSTX) and the National Compact Stellarator Experiment (NCSX). I am pleased to report that these collaborations and others, both on and off-site, are making considerable strides in the science and technological innovation required for practical fusion energy.

During FY2001, NSTX shifted into high gear, achieving 1.4 million amperes of plasma current — well above the design goal of 1 million amperes. Furthermore, NSTX achieved a toroidal beta (a key measure of cost-effectiveness) of 27%, not expected until the end of FY2002. Plasma confinement was above empirical expectations, as had been predicted theoretically. We are, obviously, very excited about these results.

Another satisfying set of developments included a successful NCSX Physics Validation Review, followed by approval of the Compact Stellarator program for proof-of-principle status by the Fusion Energy Sciences Advisory Committee (FESAC). Members recognized the Compact Stellarator's potential to resolve critical issues for magnetic fusion, including both plasma disruptions and efficient steady-state operation. Together these reviews line up NCSX for construction funding in FY2003 and first plasma in FY2007. The presence of two proof-of-principle experiments, NSTX and NCSX, at PPPL will greatly increase the breadth of our scientific endeavor, as well as its reach toward practical fusion energy.

Robert J. Goldston

Our off-site collaborations have also been very successful. At DIII-D (General Atomics) in San Diego, PPPL played a leading role in experiments to suppress resistive wall modes and neoclassical tearing modes. At C-MOD (Massachusetts Institute of Technology) in Boston, we helped to improve the ion-cyclotron heating system and to interpret transport data — as we did at the JT-60U experiment in Japan, where we also contributed to decisive improvements in their negative-ion neutral-beam systems. Perhaps most surprising was the discovery we facilitated at the Joint European Torus (JET) in England that the plasma current in the core of a tokamak does not go negative, even with strong negative drive, but rather forms a region of zero current — a "current hole." Our theoretical team has already developed a good physical explanation for this phenomenon.

Indeed, PPPL's activities in theory and computation have born fruit this year in dramatic ways. The macrostability research team has identified new physics that may play an important role in the high stability of rapidly rotating NSTX plasmas. As just noted, the team has also identified a physical mechanism to explain the "current holes" observed in JET and JT-60U. This result promises to allow a more rapid start-up scenario for the spherical torus as well. Very importantly, extensive macrostability calculations supported the successful design effort on NCSX. In the microturbulence area, calculations performed on the new 5-tera-flop IBM-SP machine at the National Energy Research Supercomputer Center (Lawrence Berkeley National Laboratory) in Berkeley showed favorable confinement scaling at larger system size, a positive result. Theory has also been reaching out to experiment, with detailed simulations of experimental measurements of gas-puff imaging and microwave reflectometry. Reaching further, new calculations of coronal mass ejections show promise that ideas developed within the magnetic fusion energy effort can contribute to understanding solar flares. Furthermore, delta-f methods developed for magnetic fusion energy are being successfully applied to ion-beam plasmas for heavy-ion fusion applications.

Smaller on-site experiments have been very productive as well. The Magnetic Reconnection Experiment examined collisional plasmas, which show good agreement with classical reconnection rates and perpendicular resistivity. The Current Drive Experiment-Upgrade (CDX-U) has shown performance improvements with liquid-lithium plasma-facing components. Our plasma-thruster work is breaking into new regimes of "micro-thruster" operation, relevant for propelling clusters of small satellites. We are especially pleased that a Paul Trap Simulator Experiment will come on line soon to provide PPPL with experimental capabilities to study the nonlinear physics of intense ion beams for inertial fusion energy applications.

The Tokamak Fusion Test Reactor (TFTR) decommissioning project is moving forward safely, on schedule and on budget. We anticipate this project will be finished as planned in FY2002, leaving the TFTR Test Cell clear for future experiments and providing valuable lessons for future fusion decommissioning activities.

What does the future hold? We are delighted that fusion was highlighted as an attractive future energy source in the National Energy Plan, which came out in May 2001. Furthermore, fusion has been very favorably discussed in both House and Senate Energy bills. Hopefully one result of this increased political interest may be that the U.S. will be able to join the international (Europe, Japan, Canada, Russia) negotiations to construct the International Thermonuclear Experimental Reactor burning plasma and fusion technology experiment, so that we can define an exciting role for ourselves. In FY2002, the fusion community will once again gather at Snowmass, CO, this time to consider the options for a burning plasma experiment, both international and domestic. PPPL is contributing strongly to the underlying technical assessments.

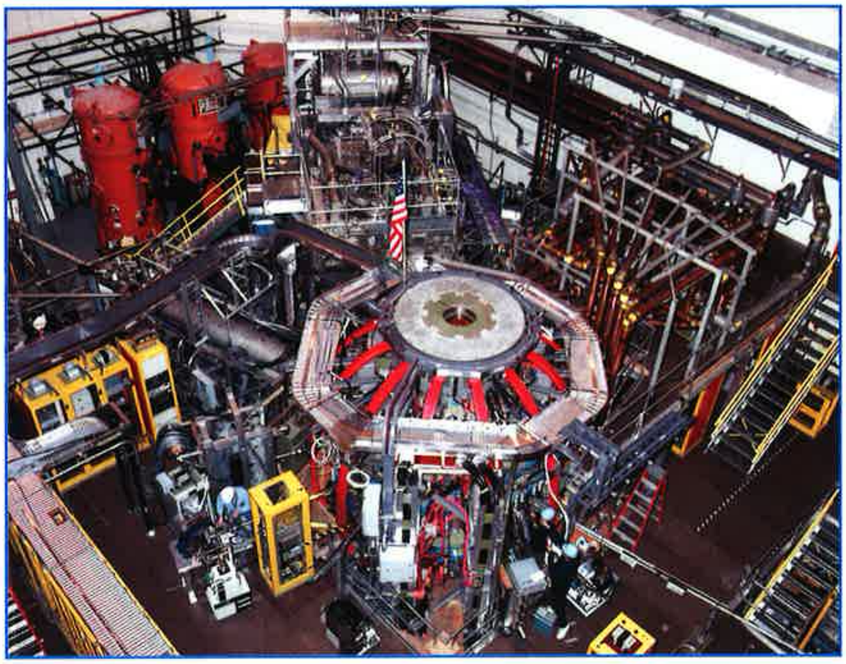
From our perspective, we see a strong fusion program, based around the thrusts defined by FESAC in 1999 and reconfirmed recently in the Office of Fusion Energy Sciences Integrated Program Plan:

- Fundamental Understanding of Magnetically Confined Plasmas
- Configuration Optimization
- High Performance and Burning Plasma
- Technology and Materials
- Fundamental Understanding of Inertially Confined Plasmas
- Development of Inertial Fusion Energy Drivers

We are excited about PPPL's present roles and future opportunities in each of these areas. Under the category of *Fundamental Understanding,* we are proud of our present accomplishments, but we also see great opportunities to help expand advanced computing and sophisticated plasma diagnostics in the fusion program. Under *Configuration Optimization,* we see NSTX and NCSX as leading proof-of-principle optimization experiments in the U.S. We see the TFTR Test Cell as a natural location for a next domestic step toward *High Performance,* perhaps for an innovative approach such as defined by NSTX or NCSX. Based on our experience with TFTR, the Laboratory is well positioned to play a leading role in a *Burning Plasma* experiment. CDX-U represents a first step for PPPL toward *Technology and Materials* and we are also very pleased that the Princeton University Materials Institute has begun to study, through advanced computing, materials for fusion. PPPL as a member of the Virtual National Laboratory for Heavy Ion Fusion, through its studies of laser-plasma interactions, and in collaboration with the Naval Research Laboratory, will play an important role in the *Fundamental Understanding and Development of Inertial Fusion Energy* as well.

So — in summary — this has been an extraordinary year, and the future holds even more excitement in the development of fusion science and energy — over a very broad frontier.

National Spherical Torus Experiment



National Spherical Torus Experiment

The National Spherical Torus Experiment (NSTX) is a proof-of-principle experimental facility designed to explore the physics of toroidal magnetic confinement in plasmas with low toroidal aspect ratio. In NSTX the aspect ratio, which is the ratio of the major radius of the torus to its minor radius, can be as low as 1.3. This magnetic configuration has been theoretically predicted to offer benefits, particularly in greater magnetohydrodynamic stability and possibly in reduced losses of plasma energy, over tokamaks with conventional aspect ratio. The cross section of the NSTX device is shown in Figure 1. In a spherical torus plasma where the size of the minor radius approaches that of the major radius, the plasma cross section in a plane through the axis approaches a half circle and, seen in three dimensions from the outside, the plasma appears almost spherical.

FY2001 was an exciting period for NSTX as its capabilities were developed and exploited to produce plasmas in new regimes and to study these plasmas with a widening array of diagnostic instruments. Plasma operations on NSTX were conducted on 74 days with commissioning and calibration operations on another five

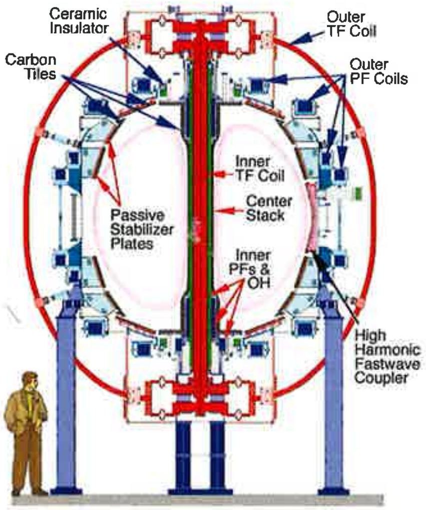


Figure 1. Schematic cross section of the NSTX device.

days. A total of 1,696 plasma discharges with current exceeding 100 kA were run over the period. Two extended periods of maintenance and repair activity were undertaken: the first from mid-December 2000 through mid-May 2001 (for repair of the central solenoid and the inner toroidal-field conductors) and the second from early August 2001 continuing through the end of the fiscal year (for diagnostic installations and upgrades).

Among other highlights, FY2001 saw the achievement in NSTX of a record plasma current, 1.4 MA, as well as record heating power by both neutral-beam injection and radio-frequency (rf) waves. As a result of these achievements and the apparently good confinement of the NSTX plasmas relative to the predictions of empirical scaling relations, both the plasma stored energy and toroidal beta (the ratio of the average plasma fluid pressure to that of the toroidal magnetic field at the plasma center) reached new high levels, revealing a variety of plasma phenomena, several observed for the first time in NSTX, and some apparently unique to the low aspect ratio configuration.

In the following sections, the progress in operational capability during FY2001 and the results of research along various lines important to the assessment of this magnetic confinement concept are described.

NSTX Facility

FY2001 started just after the achievement of a major milestone for NSTX, the installation and first operation of a three-source neutral-beam line originally from the Tokamak Fusion Test Reactor (TFTR) project. During FY2001, the neutral-beam system became the foundation for most experiments in NSTX. Within two weeks of operation in FY2001, NSTX had achieved a toroidal beta above 20% using only two of the three neutral-beam sources, and within another six days, the first high-confinement mode transitions had been observed. This success opened the possibilities for a wide range of pioneering physics experiments.

One result of heating with neutral-beam injection (NBI) early in the pulse was to reduce the poloidal flux consumption through a combination of reduced plasma resistivity due to the higher electron temperature and a reduction of deleterious magnetohydrodynamic (MHD) instabilities during the current ramp-up phase, possibly as a result of the plasma rotation induced by the NBI. This reduction in flux consumption opened the possibility that NSTX could be operated at currents above its original design goal of 1 MA, which had already been reached about a year before. Engineering analysis of the effects of operating with increased plasma current were carried out and, after review, the Project received approval to increase the maximum allowable plasma current to 1.5 MA. At the end of May 2001, the plasma current was successfully increased to 1.43 MA. This increased range of current was instrumental in achieving record toroidal beta of 27% at the end of the FY2001 experimental run.

In December 2000, the toroidal-field (TF) coil was tested to its full design current of 71 kA, to produce a toroidal magnetic field of 0.6 T at the nominal plasma major radius of 0.85 m. In addition, later in FY2001, both the neutral-beam heating and the high-harmonic fast-wave (HHFW) heating systems reached their design goals of 5 MW and 6 MW, respectively, for power delivered to the NSTX plasma. In addition, the HHFW system operated with independent control and in situ measurement of the phase of the individual antennas fed by the six rf sources. The accomplishments in power and antenna phase control fulfilled two project milestones for the HHFW system.

In December 2000, some technical problems were also encountered. Water leaks developed in the cooling tubes of the TF coil inner legs and an insulation fault occurred in the ohmic-heating (OH) coil. Both problems were traced to defects in the original manufacturing of the magnets. The TF inner-leg leak problem was largely fixed with epoxy injection treatments (developed for TFTR) and one larger remaining leak was fixed mechanically during the summer outage of 2001. In order to insure coil safety against any future potential leaks, a Fluorinert® (fully fluorinated hydrocarbon liquid) TF cooling system was implemented during the summer outage. For the OH solenoid, a repair of the insulation problem was performed by removing the solenoid and inner TF bundle from the machine without breaking the high vacuum. This preservation of high vacuum enabled a quick restart of plasma operations in May 2001 to complete a very productive 12 week experimental run.

From May 22, when plasma operation resumed after the repairs, until August 3, when the FY2001 experiments ended, NSTX operated on 43 days, achieving up to 45 plasma discharges in a standard operating shift and up to 50 discharges on one of eight days with extended operation.

In August 2001, the vacuum vessel was vented for installation and repair of internal components and diagnostic systems. In particular, many of the internal magnetic sensors, both flux measurement loops and magnetic field measurement coils, were refurbished or, in some cases, replaced with more robust designs. New port covers were provided to accommodate planned diagnostic systems and upgrades. At the same time, a more permanent repair of the leak in the TF coil cooling tube was undertaken.

Diagnostic Development

Several new diagnostic systems became operational in FY2001. The evolving diagnostic capability has contributed greatly to the research program and allowed a wide range of experiments to be run. The new and upgraded diagnostics are grouped by the primary area of physics study to which they contribute.

Confinement Diagnostics

An interim system was installed for measuring the ion temperature and toroidal velocity profiles at 17 spatial locations by Charge-exchange Recombination Spectrometry (CHERS). This instrument measures the Doppler broadening of line emission from intrinsic carbon impurities excited by charge-exchange with fast neutrals injected by the neutral beams. The first measurements with this instrument were made in November 2000. Its capabilities were progressively enhanced and it became a standard diagnostic by the end of the experimental run.

The Multi-point Thomson Scattering (MPTS) diagnostic for the electron temperature and density profiles, which had made its first measurements in June 2000, was upgraded by the addition of a second laser to operate at 60 measurements per second, with the possibility of syncopated operation of the lasers to provide high time resolution (<1 msec separation of time samples) for reproducible transient phenomena, such as MHD instabilities.

A Neutral Particle Analyzer (NPA), originally from the Advanced Toroidal Facility at Oak Ridge National Laboratory, was installed on NSTX viewing on a line-of-sight across the plasma midplane at a tangency radius of 0.7 m in the direction counter-parallel to the plasma current. This instrument is capable of detecting neutral deuterium and hydrogen atoms escaping from the plasma with energies from 0.25 to 300 keV, which spans the range from thermal ions to above the neutral-beam injection energy, with a time resolution of 1 msec. The ion temperature deduced from the NPA data has generally agreed well with that from the CHERS measurement.

A three-channel microwave reflectometer was commissioned by collaborators from the University of California at Los Angeles. This instrument was used primarily in a frequency swept mode for measuring the density profile in the outer region of the plasma, but it could also be operated at fixed frequencies for fluctuation measurements. The far-infrared tangential interferometer and polarimeter (FIReTIP) being developed by collaborators at the University of California at Davis produced the first density data from two of its channels during the latter part of the FY2001 experimental campaign.

A system was commissioned to determine the plasma diamagnetism by accurately measuring the magnetic flux displaced from the TF coil by the plasma. The measured diamagnetic flux can then be used as an input to the analysis of the plasma equilibrium by the EFIT code, giving an additional constraint on the plasma energy. This system is capable of measuring the diamagnetic flux with a time resolution of 2 msec and an accuracy of about ±2 mWb, which corresponds to a change in the plasma energy perpendicular to the toroidal direction of about 3 kJ for a toroidal field of 0.3 T.

A detector for fast ions lost from the plasma after being born or scattered onto unconfined orbits was commissioned. Its signals during NBI heating were compared with predictions based on classical injection physics and scattering processes.

MHD Stability Diagnostics

During the outage to repair the center-stack coils, a set of detectors for low-frequency magnetic perturbations or "locked-mode coils" was installed on NSTX. These are three matched pairs of coils mounted opposite each other toroidally at the midplane just outside the vessel and designed to detect perturbations in the radial component of the poloidal magnetic field. After careful calibration to remove their residual couplings to the poloidal- and toroidal-field coils, these coils were used in the latter part of the FY2001 experimental campaign, fulfilling a diagnostic milestone for the Project. These coils revealed that slowly rotating or locked modes were present in many NSTX plasmas and contributed to degradation or, in some cases, to rapid collapses of confinement. The locked-mode detectors also revealed that poloidal-field coil #5 was misaligned with respect to the machine axis, which resulted in a significant error field in the plasma region. This error field, which had a dominant component with toroidal mode number n = 1, may have contributed to the locking of underlying MHD perturbations in the plasmas. Complementing the locked-mode detectors, a set of magnetic pick-up coils (Mirnov coils) for high frequency fluctuations was installed and became operational in FY2001.

Impurity Spectroscopy

Our knowledge of the impurity content of NSTX plasmas improved considerably during the year with the installation of spectrometers spanning the range from the visible (the VIPS-2 instrument), through the vacuum ultraviolet region (the SPRED instrument) to the extreme ultraviolet (the GRITS instrument). These spectrometers revealed that carbon remained the dominant intrinsic impurity and confirmed that metallic impurities played a minor role in most conditions, although they could be detected in the aftermath of abnormal events or instabilities.

Edge Diagnostics

In collaboration with the Los Alamos National Laboratory, a manifold was installed inside the vacuum vessel at the outboard midplane to inject gas into the plasma edge from a row of small jets in a line roughly perpendicular to the local magnetic field in normal plasma conditions. A fast visible camera with filters for emission lines from deuterium or helium was mounted to view this same edge region along lines of sight roughly parallel to the magnetic field. During gas puffing from the injector, two-dimensional images of the spatial distribution of the edge light emission in the plane perpendicular to the local field were obtained with a 10 µsec exposure time and a frame rate of 1 kHz. These revealed information about the structure of the pronounced fluctuations in the plasma edge and, particularly, the occurrence of persistent, moving structures, commonly called plasma "blobs," in the edge region which seem to be responsible for much of the edge transport. In order to measure their frequency spectrum, the fluctuations in the edge revealed by the gas puff were also viewed by a linear array of seven photomultipliers with a response time of approximately 5 µsec.

A camera was installed consisting of one-dimensional arrays of CCD detectors viewing the filtered deuterium or carbon line emission with high time and spatial resolution from a major-radial line across the divertor. This camera was able to resolve the structure of the emission from the divertor strike points and the changes that occurred at H-mode transitions and the subsequent edge-localized mode instabilities.

The first measurements were made with an infrared camera of the surface temperature of tiles in the plasma contact regions of the lower divertor plates and on the center column. The camera has good spatial resolution, 10 mm, on the surfaces and adequate frame rate, 30 Hz, to provide the first estimates of the surface heat fluxes in NSTX during auxiliary heating.

Experimental Results

The experiments conducted in fiscal year 2001 were organized by five Experimental Task (ET) groups, covering the main NSTX research areas of High-Harmonic Fast-Wave Heating, Coaxial Helicity Injection, Boundary Physics, MHD Stability, and Plasma Transport and Turbulence. These ET groups developed NSTX Experimental Proposals (XPs) which were reviewed by the NSTX team and approved and scheduled by the project management. Some experiments had an enabling or cross-cutting character and benefited more than one ET group or the entire program. In all, 26 experimental proposals received experimental run time, ranging from a half to several shifts of operation, during the FY2001 experimental campaign. In addition to these experiments, eight "Machine Proposals," which are aimed to develop operational capabilities of the device, were conducted. Machine proposals are also used to conduct some routine tasks such as boronization of the vacuum vessel and the subsequent assessment of its effects on the plasma.

Operation of NSTX with auxiliary heating by both neutral-beam injection and High-harmonic Fast-Wave radio-frequency power became routine. About 740 plasma discharges had NBI heating and about 270 had HHFW heating of more than 50 kJ. Note that many of the experiments devoted primarily to HHFW heating also made use of NBI because of its beneficial effect on the start-up and flux consumption and also to measure the ion temperature using the CHERS diagnostic.

High-Harmonic Fast-Wave Heating

During FY2001, the HHFW heating improved dramatically in its effectiveness and reliability for both helium and deuterium plasmas. In helium plasmas with current 0.8 MA, toroidal field 0.44 T and moderate density, $n_e(0) \approx 4 \times 10^{19}$ m^{-3}, HHFW power of 3.4 MW launched in the heating phasing produced a central electron temperature of 1.1 keV and an ion temperature of 0.6 keV measured by the CHERS diagnostic. With the antenna elements excited in the heating phasing, the spectrum of launched waves peaks at a parallel wavenumber $k_{||} \approx 14$ m^{-1}. Calculations indicate that the HHFW power is overwhelmingly absorbed on the electrons in these conditions. The measured temperatures are consistent with transport similar to that in comparable plasmas heated by NBI. On the other hand, in deuterium plasmas with similar current, field, and HHFW phasing but with lower density [$n_e(0) \approx 3 \times 10^{19}$ m^{-3}] and HHFW power (2.5 MW), very peaked electron temperatures profiles with a remarkably high central temperature, $T_e(0) \approx 3.7$ keV, occurred, as seen in Figure 2. The central ion temperature was measured by X-ray spectroscopy to be 1.5 keV at this time. The large electron temperature gradient suggests the formation of an electron transport barrier, i.e., a region of reduced elec-

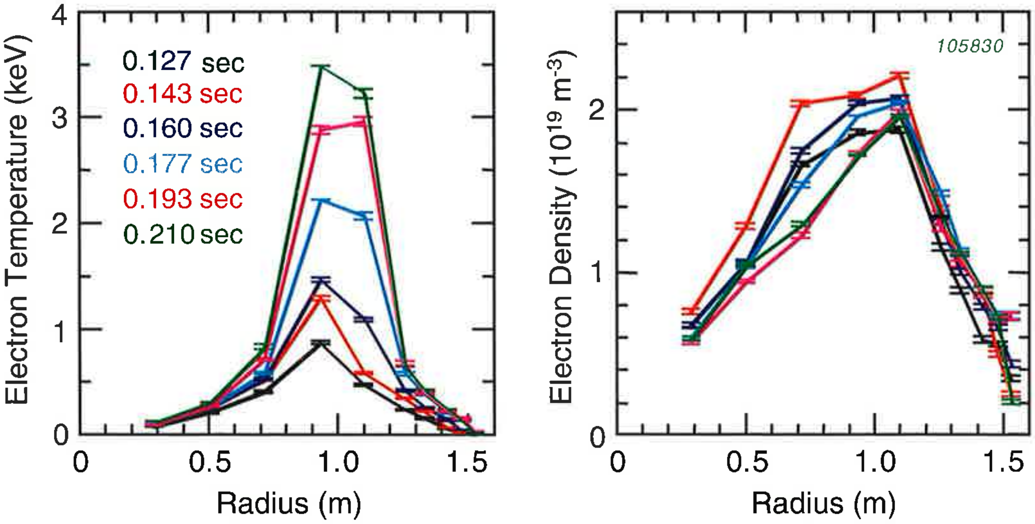


Figure 2. Successive electron temperature and density profiles at intervals of 17 msec in a deuterium discharge with 2.5 MW of high-harmonic fast-wave power injected in the heating phasing, that is with a parallel wavenumber $k_{||} \approx 14$ m^{-1}.

tron thermal diffusivity, inside a normalized minor radius r/a ≈ 0.5.

Although the HHFW power predominantly heats the electrons, absorption of these waves by the energetic ions introduced by NBI can also occur. During heating of a deuterium plasma by 3 MW of HHFW and 1.5 MW of NBI power, the Neutral Particle Analyzer measured an energetic tail on the majority deuterium ion distribution extending to about 140 keV in energy, well above the primary NBI energy of 80 keV. Understanding and controlling this competing absorption mechanism will be important in developing the current-drive capabilities of the HHFW.

Unlike NBI heating, which requires significant plasma current to confine the injected fast ions, HHFW heating can be applied to low current plasmas. In 0.4 MA plasmas, high values of the poloidal beta, up to 1.0, were produced by HHFW power of 3.2 MW. Under these conditions, up to 40% of the plasma current was driven by the bootstrap effect.

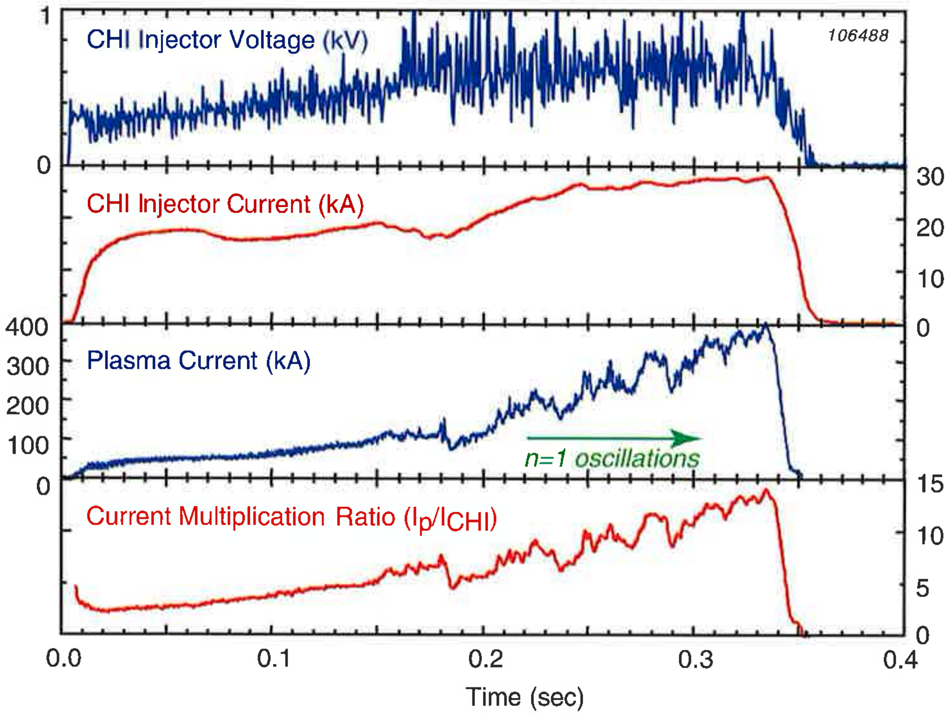
Coaxial Helicity Injection

Coaxial Helicity Injection (CHI) is a technique for generating toroidal plasma current by injecting a poloidal plasma current from electrodes inside the vacuum chamber connected to an external power supply. The technique has been previously applied successfully to small purpose-built devices. If CHI can be developed for larger devices, it would be possible to dispense with the expensive central solenoid in future spherical tori (STs).

Experiments in NSTX in FY2001 showed that CHI can indeed be applied to a large ST for generating a substantial toroidal current. The experiments succeeded in producing 390 kA of toroidal plasma current without using the ohmic solenoid and using only about 28 kA of injector current, as shown in Figure 3. The driven toroidal currents are consistent with our understanding of current multiplication. The toroidal current produced by CHI initially flows on open magnetic field lines connecting the injector electrodes. For CHI to be successful in the ST, some of this current must be transferred by the process of magnetic reconnection onto the closed field lines needed for confining plasma. Indications were obtained that the MHD instabilities believed to accompany such reconnection were occurring in the NSTX discharges. The duration of the CHI discharges in NSTX was up to 330 msec, more than an order of magnitude longer than previously obtained by this technique. The duration was limited by the occurrence of absorber arcs, which are unwanted discharges across the secondary insulating gap between the coaxial electrodes. The experiments have indicated the need for changes to the absorber insulator to reduce the propensity for the formation of absorber arcs. This development effort is being coordinated with the engineering team.

Boundary Physics

An experiment was conducted to produce the high-confinement mode (H-mode) in NSTX. H-mode transitions, evidenced by a sudden decrease in the hydrogen Balmer-alpha line emission from the plasma edge, occurred in divertor discharges heated by both NBI and HHFW. The H-mode was confirmed by the subsequent rise in the radial gradient of the plasma density just inside the plasma boundary, indicating the formation of an edge transport barrier. The H-mode phases varied in duration between 0.5 and 120 msec. H-mode phases both with and without edge-localized mode (ELM) instabilities were observed, with the longest ELM-free period lasting up to 65 msec. The confinement time in the ELM-free



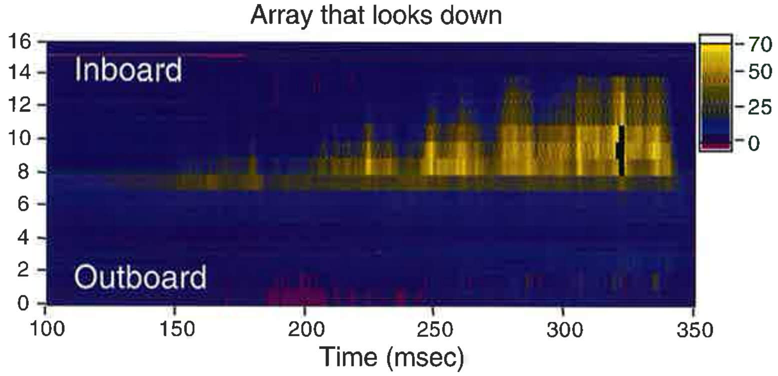


Figure 3. (a) Waveforms of the main discharge parameters during a coaxial helicity injection (CHI) discharge. The period is indicated during which coherent oscillations are observed with toroidal mode number n = 1. These oscillations may accompany the formation of closed magnetic flux by magnetic reconnection. (b) Color contour plot of the intensity of soft X-ray emission during a coaxial helicity injection plasma discharge. The emission is measured by a vertically viewing fan of detectors sensitive to X-rays above approximately 50 eV in energy. The X-ray emission appears to come from a region on the inboard side well above the injector region.

discharges increased by a factor of 2 to 3 above the low-confinement mode (L-mode) reference case, to a maximum of 120 msec. The time evolution of representative plasma quantities and the profiles of the electron temperature and density during the H-mode phase are shown in Figure 4. The power threshold for the occurrence of the H-mode was measured in NBI-heated discharges to be about 2 MW in terms of total heating power and 1 MW in terms of power outflow through the last closed flux surface, which is between 16 and 33 times the predicted power threshold from the International Thermonuclear Experimental Reactor

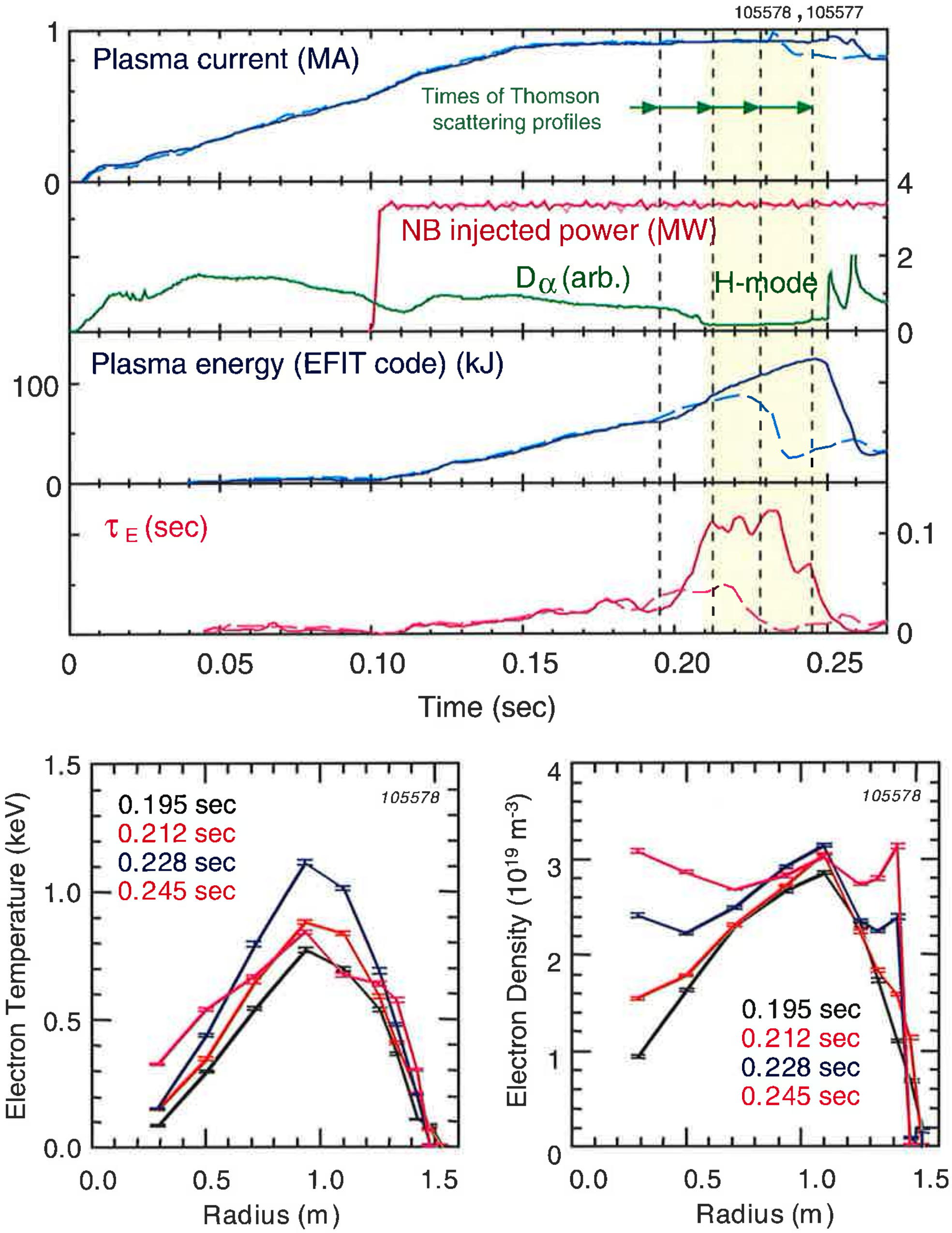


Figure 4. (Top) Time evolution of plasma parameters in an NSTX discharge which undergoes an H-mode transition (solid) compared to a neighboring discharge which did not (dashed). The H-mode phase is indicated by the yellow shading. (Bottom) Evolution of the electron and density profiles through the H-mode phase.

(ITER) international scaling. The suppression of plasma turbulence following the H-mode transition was confirmed for the region just inside the boundary by a reduction in the fluctuations measured by the microwave reflectometer and for the region surrounding the boundary by the gas-puff imaging diagnostic.

Initial experiments were conducted to determine the heat flux to the divertor target in auxiliary heated discharges by measuring the surface temperature of the graphite tiles with the infrared camera. During 4 MW of NBI heating, heat fluxes at the outer divertor strike point, which received the majority of the power, reached

6 MWm^{-2} although the average flux was much lower. The peak flux increased with heating power, as expected, and the width of the power deposition region decreased to about 40 mm. The total divertor heat flux accounted for only about 25% of the heating power.

Following the success of boronization by a glow discharge in a 90/10 percent mixture of helium/deuterated trimethylboron (TMB), respectively, in improving plasma purity in NSTX, an experiment was conducted in which the helium-TMB mixture was used to fuel normal plasma discharges and thereby replenish the boron coating in real time. Compared to reference discharges run just before the TMB fueling, the radiated power was reduced by 50% in fiducial discharges after the fueling. Also high-confinement mode transitions were observed after the fueling experiment, but not in the preceding reference discharge.

MHD Stability

Through NBI heating, NSTX plasmas reached $\beta_T = 2\mu_0\langle p\rangle/B_{T0}^2 \approx 25\%$, defined in terms of the applied toroidal magnetic field, B_{T0}, for $B_{T0} = 0.3$ T and plasma current $I_p = 1.2$ MA. This corresponds to a Troyon-normalized beta, $\beta_N = \beta_T a B_{T0}/I_p \approx 4\%$ m·T/MA (a is the plasma minor radius). This value of β_N, which is above the limit encountered in standard tokamaks with conventional aspect ratio, confirms the expected high utilization efficiency of the ST with respect to the applied toroidal field. Interestingly, when expressed in terms of the volume-average β, $\langle\beta\rangle = 2\mu_0\langle p\rangle/\langle B^2\rangle$, where $\langle B^2\rangle$ is the volume average of the square of the total magnetic field, the Troyon-normalized limit for the NSTX data becomes $\langle\beta_N\rangle = \langle\beta\rangle a B_{T0}/I_p \approx 2\%$ m·T/MA, very similar to the limit for this parameter observed in conventional tokamaks, indicating that the same underlying theoretical framework can be applied to both confinement systems. The achieved values for β_T and $\langle\beta\rangle$ are plotted in Figure 5 against the normalized plasma current I_p/aB_{T0} to show the Troyon scaling of the β-limit.

The values of β_T and β_N were increased to their highest values by shaping the plasma cross section to increase its triangularity to $\delta \approx 0.5$ for an elongation κ

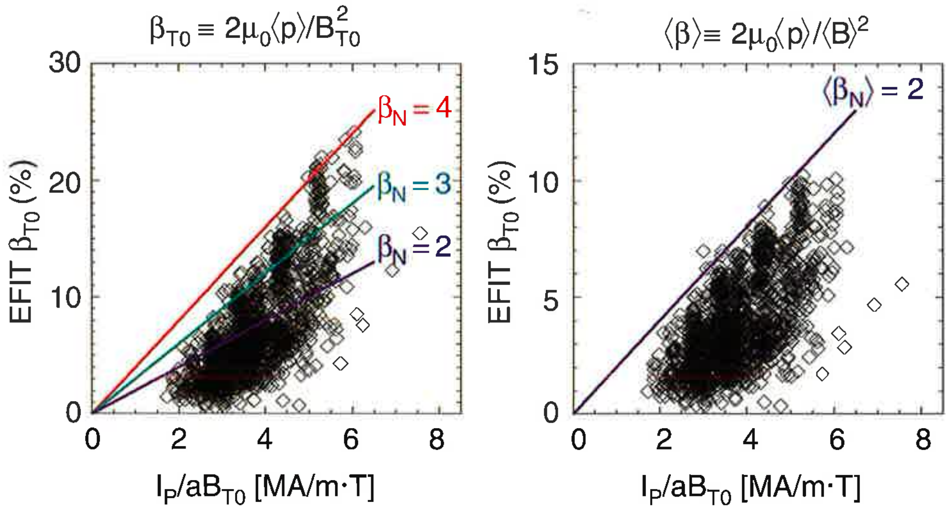


Figure 5. Measured β_T (tokamak definition) and $\langle\beta\rangle$ (volume-average definition) for NSTX plasmas plotted against the Troyon-normalized plasma current I_p/aB_{T0}. These data are from analyses of the plasma equilibrium with the EFIT code based on magnetic measurements.

≈1.75. In a controlled scan of the plasma shape, the normalized β-limit was found to decrease by about 30% as the elongation was increased further to 2.2 at fixed δ of 0.4. The observed instabilities had characteristics of internal kinks with toroidal mode numbers $n = 1, 2$, and 3. Theoretical analysis of the data from this scan reproduced the dependence on κ and predicted well the observed onset times for instabilities with poloidal mode numbers $m = 2$ and 3. Puzzles remain, however, in that onset of the usually virulent $n = 1$ mode did not cause an immediate plasma collapse and all the modes rotated with a frequency similar to that measured spectroscopically at the plasma edge rather than the core prior to beta collapse.

In addition to the ideal internal-kink instabilities mentioned above, other classes of MHD instabilities have been observed in NSTX plasmas. One of these is the neoclassical tearing mode (NTM) which occurs below the threshold for ideal instability when the perturbed bootstrap current in the vicinity of a magnetic surface having a rational value of the MHD safety factor, q, causes an otherwise stable perturbation of the plasma current to grow. As expected theoretically, the NTM was observed in NBI-heated plasmas when the value of the poloidal-β, which determines the magnitude of the bootstrap current, reached $\beta_p \approx 0.4$. The structure of the plasma perturbations detected by the soft X-ray arrays during an NTM agreed very well with theoretical simulations of the mode growth.

Experimentally, the β_N limit increases, then saturates with increasing peaking of the current profile (corresponding to higher values of the internal inductance parameter ℓ_i), and decreases with increasing peaking of the pressure profile. The theoretical stability of the plasmas has been assessed using the equilibrium configuration and the profiles of pressure and current calculated by the EFIT code from experimental data. The threshold for instability of ideal low-n modes in the absence of any stabilizing effect from a conducting wall (the "no-wall limit") agrees quantitatively with the experimental threshold for fast beta collapses. For the bulk of the plasmas from the fiscal year 2001 experimental run, the coupling of the plasma to the walls and, therefore, the expected wall stabilizing effect were quite weak.

In dedicated experiments to increase the coupling to the wall and its stabilizing effect, the so-called "resistive wall mode" was observed when the ideal no-wall limit was exceeded. This is an instability which would not occur if the walls were perfectly conducting, but can grow because of the interaction between the toroidally rotating plasma and the eddy currents induced in walls with finite resistivity. Analysis of the results suggests a route to increase β_N and β_T further in NSTX. A broad pressure profile will allow higher stable beta without wall stabilization if sufficiently high $\ell_i \sim 0.7$ can be maintained while keeping the central safety factor $q(0)$ above one. At high β, global modes develop long poloidal wavelength on the outboard side making them amenable to wall stabilization, so that ℓ_i can be either allowed to fall under the action of the bootstrap current or reduced through current drive to avoid the destabilizing condition $q(0) < 1$.

In typical NSTX conditions, the initial velocity of the energetic ions introduced by NBI exceeds the Alfvén wave velocity in the plasma, so it was expected that various Alfvén resonant modes could be excited by the NBI. A broad spectrum of high-frequency fluctuations was indeed observed during NBI in the signals from magnetic pick-up (Mirnov) coils outside the plasma. The spectrum extended in frequency from about 0.4 MHz up to 2.5 MHz, the latter being the maximum detection frequency of the coils and about 1.2 times the typical deuterium ion cyclotron frequency at the plasma boundary near the pick-up coils. In detail, the spectrum consisted of a series of narrow, discrete, equally spaced peaks, either quasi-continuous or showing bursts in time.

The modes were also detected by a microwave reflectometer but, as yet, no quantitative measurements of their amplitudes are available. These modes have been identified as compressional Alfvén eigenmodes (CAE) excited by a Doppler-shifted resonance with the fast injected ions. Their frequency was shown to scale with the Alfvén velocity as the magnetic field and the plasma density were varied during the NBI pulse. The excitation of the CAE was shown to be very sensitive to the NBI energy. There was concern that the CAE might cause losses of fast ions through scattering onto unconfined orbits, but measurements with the lost-ion detector have not revealed any anomalous losses associated with the CAE.

Plasma Transport and Turbulence

One of the first tasks of the Plasma Transport and Turbulence group was to assess the confinement of energetic ions during NBI heating. The dependence of the heating on both the injection angle and the plasma current followed the expectations of the classical orbit model. Both the decay of the neutron rate from beam-target deuterium-deuterium fusion reactions following brief pulses of NBI and the flux of escaping fast ions measured by the lost-ion probe also followed these expectations. No significant anomalous loss processes were apparent in MHD-quiescent plasmas.

In terms of global confinement, some interesting trends are evident in the NSTX data from the FY2001 experimental run. In Figure 6, the energy confinement times deduced from the plasma stored energy and input power calculated by the EFIT magnetic analysis code are plotted against the predictions from two standard tokamak scaling relations. The NSTX data for plasmas without any H-mode transitions exceed the L-mode scaling by up to a factor 2 and even the H-mode scaling by up to a factor 1.4. Following H-mode transi-

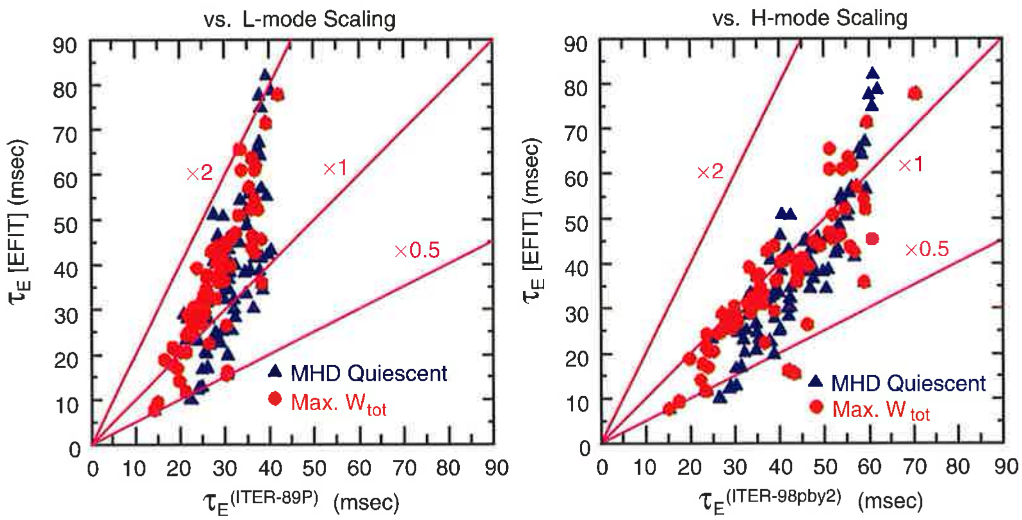


Figure 6. Comparison of the NSTX confinement results for non-H-mode plasmas with the standard tokamak scalings, ITER-89P (L-mode) and ITER-H98pby2 (H-mode).

tions, the confinement time can transiently double in NSTX. The H-mode data have not yet been included in the confinement plot because these plasmas have not yet reached steady-state. The different trends evident in the NSTX data suggest that the tokamak scalings, which were developed from tokamaks all with much higher aspect ratio, will have to be modified to account for the ST data.

In plasma conditions typical of NSTX, the neutral beams are injected above the so-called critical energy and therefore are expected to heat the electrons preferentially. It was therefore surprising that ion temperatures significantly higher than the electron temperature were measured during NBI heating. In addition, high toroidal rotation velocities, up to 250 km/sec, were measured by the CHERS diagnostic. Figure 7 shows an example of the measured plasma profiles for a 1.2 MA plasma with 4.8 MW of NBI heating. The high ion temperatures suggest, at the least, that ion confinement is very good in NSTX plasmas. This has been confirmed by the first analyses of the plasma transport with the TRANSP code. In most NSTX cases, the TRANSP analysis, assuming a model of classical beam thermalization, calculates a negative power conducted through the ion channel in the outer regions of the plasma. Ion thermal diffusivities approaching neoclassical levels have been shown to be consistent with the measured ion temperature if a significant portion of the classical heating power is shifted from the electrons to the ions. This suggests that anomalous heating and/or energy transfer mechanisms may be operating in these

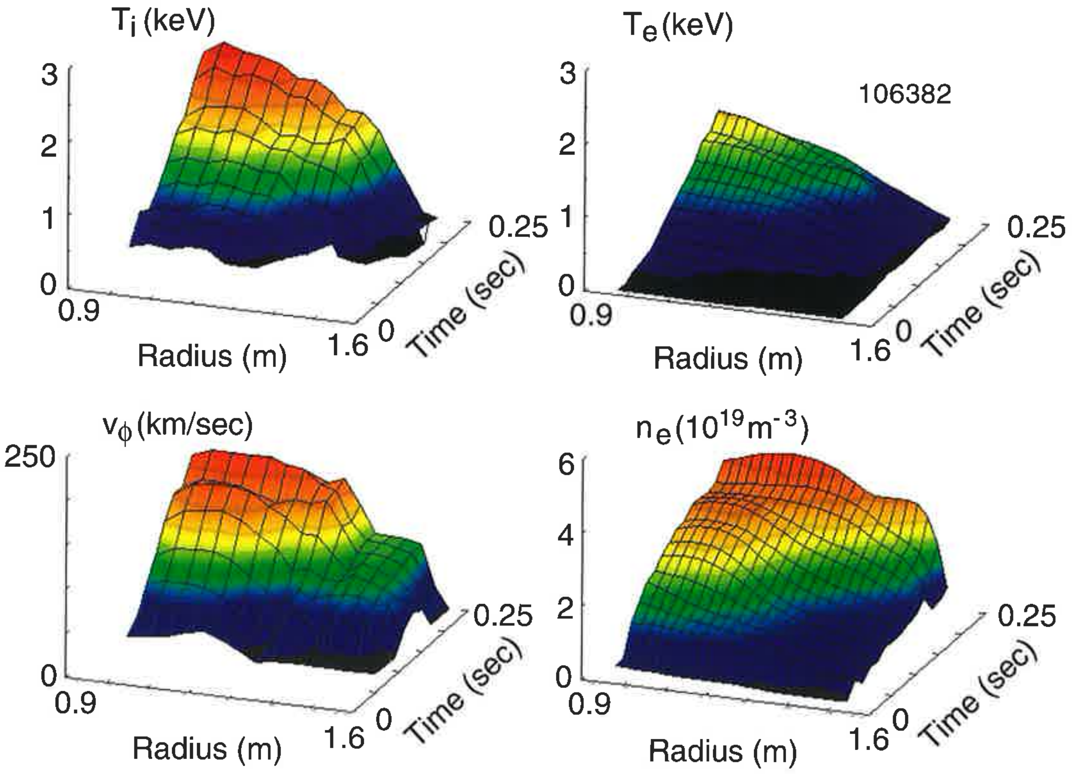


Figure 7, Profiles of the ion temperature (T_i) and plasma toroidal rotation (v_ϕ) measured by CHERS and the electron temperature (T_e) and density (n_e) measured by Thomson scattering in a plasma heated by 4.8 MW of neutral-beam-injection.

unique conditions. Further experiments are planned to resolve this anomaly. It should be noted that there was generally good agreement between the total plasma energy deduced from magnetic measurements by the EFIT equilibrium analysis code and that calculated by TRANSP by integrating the measured profiles of the electron and thermal ion pressures and the profile of the fast ion pressure calculated self-consistently from the measurements.

Complementary data on the ion particle transport were obtained by measuring the time evolving profile of the soft X-ray emission after injecting a brief puff of neon gas at the plasma edge. The neon diffused rapidly in the outer portion of the NSTX plasma but much more slowly in the core, at a rate comparable to that expected for neoclassical theory.

Development of Analysis Capability

Ray tracing modeling has been carried out for HHFW discharges where the electron and ion heating profiles were evaluated with measured plasma profiles and reconstructed EFIT equilibria. Two codes, CURRAY and HPRT, gave very similar results for cases with HHFW heating alone, and with HHFW and NBI heating including the energetic beam ions.

Initial current-drive modeling with HHFW has been carried out using the adjoint technique in CURRAY, and driven-current density profiles were computed at various time slices in the discharge. This capability will be implemented in TRANSP for detailed analysis of future high-performance discharges.

In order to define MHD stability boundaries precisely and to enable the design of an active MHD stabilization system, four widely used ideal-stability codes, PEST1, PEST2, DCON, and GATO were benchmarked against each other using standard NSTX discharge parameters. Initial differences in results for both the global beta limits and the mode structure of the instabilities were resolved so that all the codes eventually agreed satisfactorily.

The TRANSP code was upgraded by implementing a more accurate finite-Larmor-radius correction to the beam Monte-Carlo package. This provides more accurate calculations of the neutral-beam-heating profile in typical NSTX conditions. Other accomplishments include upgrades of full orbit-tracking codes and upgrades of the NCLASS neoclassical transport package. Work was initiated on applying a phase-space boundary approach to assess quickly fast-particle loss and on analytic modifications to neoclassical theory in the regime unique to the ST where there is high plasma flow and in which the ion gyroradius becomes comparable to the density gradient scale length. A suite of database tools was developed allowing users to create and analyze data sets of different types.

Plans for FY2002 to FY2003

The NSTX is scheduled to conduct experiments for a total of 12 weeks during FY2002. The experimental campaign will start in February 2002 after the completion of several major engineering tasks and diagnostic installations during the outage which had begun in August 2001.

Major upgrades to the facility will include a new cooling system for the TF conductors using Fluorinert® liquid and a high-temperature bakeout system using helium as the working fluid. Cooling the TF conductors with Fluorinert®, a fully fluorinated hydrocarbon which is an electrical insulator, will protect against the possibility of compromising the insulation of the coils in the event of any further leaks in the inner TF conductors. Also undertaken during the outage is a realignment of the PF5 coil and the installation of a gas injector at the midplane on the center column. The realignment of the PF5 coil bundles is expected to reduce substantially the error fields in the plasma region which are believed to have caused the frequent "locking" of MHD perturbations during the previous experimental run. The inboard gas injector will allow comparisons of fuelling efficiencies for gas introduced in very dissimilar regions magnetically and is expected to contribute to the study of H-mode plasmas.

The diagnostic upgrades include the installation of a fast reciprocating probe for studying the edge region, providing angular scanning of the Neutral Particle Analyzer, increasing the number of spatial channels for the Thomson Scattering Diagnostic to 20, and installing new, more robust magnetic sensors, a prototype bolometer for the divertor region, and an imaging X-ray detector. A new fast data acquisition system will be installed for the real-time control computer which will allow more comprehensive control of the plasmas based on real-time equilibrium analysis to be implemented.

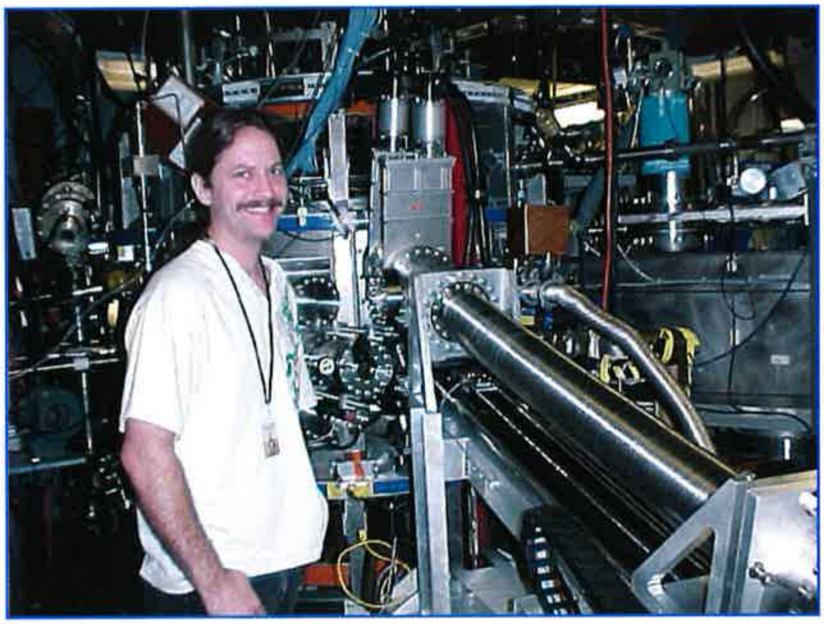
During the FY2002 experimental campaign, experiments will be conducted to measure and analyze the global stability of high-β NSTX plasmas, to assess the effects of very high-β and plasma flow on plasma transport and to test the effectiveness of using HHFW power to drive plasma current via direct interactions with the electrons and/or fast ions. In addition, experiments will continue to study CHI for initiating the plasma current.

At the conclusion of the FY2002 experiments, the NSTX facility will enter an outage for about four months, during which a new insulator for the CHI absorber will be installed. This will involve removal of the center stack of the machine. Several diagnostics will be installed or upgraded, including the collection optics for the Motional Stark Effect diagnostic to measure the internal poloidal magnetic field and an upgrade for the CHERS diagnostic to 51 spatial channels.

During FY2003, it is hoped to operate NSTX for an expanded period of 21 experimental run weeks. Using the newly installed diagnostics, measurements will be made of the edge heat flux at high heating power to assess the impact on plasma facing components. The upgraded insulator in the CHI absorber will permit experiments to assess the effectiveness of using a combination of noninductive techniques, CHI, radio-frequency, and NBI current drive, and the bootstrap current, to assist in start-up and sustainment of plasma pulse lengths up to 1 sec. A microwave radiometer with a steerable antenna will be used to characterize emission from the plasma due to intrinsic thermal Electron Bernstein Waves (EBW) in order to estimate requirements for a possible EBW heating and current drive system.

In the area of stability, experiments will be carried out to explore and characterize plasmas simultaneously with high-beta and high-energy confinement and to maintain these plasmas for durations greater than the energy confinement times. During the FY2003 experimental run, it is also planned to install a set of external coils to apply small correction fields to test suppression of the growth of the resistive wall modes.

Current Drive Experiment-Upgrade



Russ Doerner of the University of California at San Diego in front of the Current Drive-Experiment Upgrade with the liquid lithium rail limiter.

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

Reactor designs for inertial fusion reactors have relied for some time on the concept of a flowing liquid wall in order 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 stabilization of plasma instabilities to unprecedented high values of the plasma beta.

The very low recycling wall provided by liquid lithium also 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 (TFTR), 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) was the world's first spherical torus (ST) to operate with liquid-lithium plasma-facing components (PFCs). The liquid-lithium PFC program involves collaborations with numerous universities and national laboratories, including the University of California at San Diego (UCSD), 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 also participating through the Energy Advanced Liquid Plasma-facing Surface (ALPS) and Advanced Power Extraction (APEX) programs of the U.S. Department of Energy.

Facility Description

A schematic of CDX-U is shown in Figure 1. All power supplies (with the exception of two capacitor banks) are presently preprogrammed 12-phase supplies, controlled by digital-to-analog waveform generators. An upgrade to the ohmic power supply will extend the pulse length to 35 msec, from the present 15-20 msec. The CDX-U has a plasma major radius R = 34 cm, minor radius a = 22 cm, and aspect ratio A = R/a ~ 1.4. The interior of the vessel has been modified to accommodate the internal lithium PFCs. Ancillary systems (an argon glove box, small vacuum chambers for testing lithium systems, etc.) have been assembled to support the lithium experiments on CDX-U.

Experiments with Lithium Limiters

The first experiments involving the use of solid and liquid lithium as a plasma limiter in CDX-U took place in FY2000, utilizing a lithium covered rail 5 cm in diameter and 20 cm long, which was developed at UCSD. The lithium limiter was inserted or removed via a double gate valve airlock system to prevent exposure of the lithium to air. When the limiter was fully inserted, it formed the upper limit-

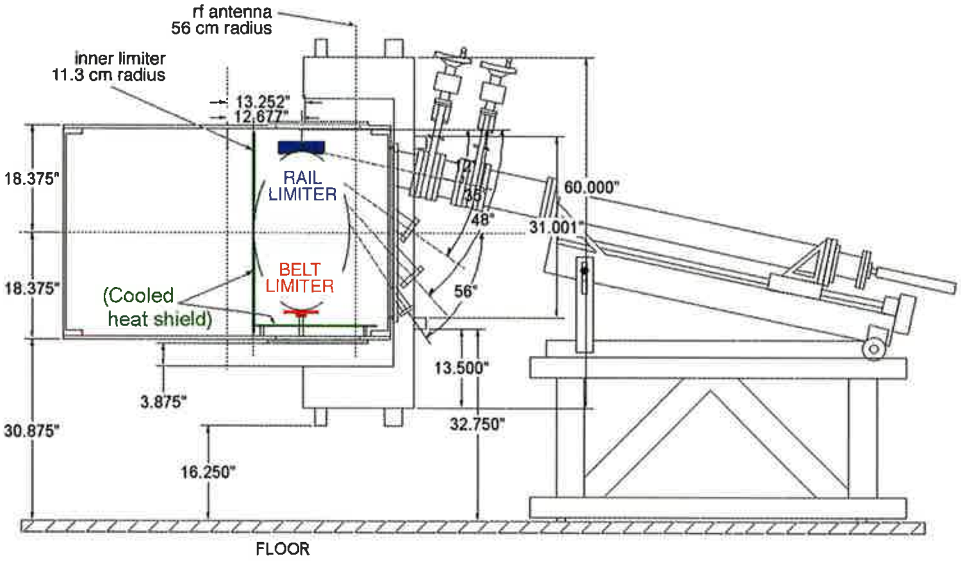


Figure 1. Elevation of CDX-U showing the UCSD rail limiter and the toroidal belt limiter.

ing surface for the discharge and was intended to define the last closed flux surface for the discharge. When the limiter was retracted, ceramic boron carbide rods formed the upper limiting surface for the discharge. The limiter had an internal heater and was operated in contact with the plasma over the temperature range of 20 - 300 °C.

The rail limiter experiments demonstrated that a ST plasma could successfully operate with a liquid-lithium PFC, and were instrumental in identifying and resolving numerous problems and safety concerns with lithium operations. However, the surface area of the rail limiter was small (approximately 300 cm^2, less than half of which is in contact with the plasma), and so the effects of the lithium-coated limiter on the discharge itself were minimal. In FY2001 the lithium PFC experiments on CDX-U entered a second phase, when the toroidal liquid-lithium belt limiter was placed in operation.

The toroidal belt limiter is shown in Figure 1. It consists of a shallow, heated toroidal tray with a radius of 34 cm and a width of 10 cm, which is filled with lithium to a depth of a few millimeters. When completely filled with lithium, the belt limiter presents an exposed area of 2,000 cm^2 to the plasma. Operation of CDX-U with the lithium belt limiter yielded clear indications of the ability of a liquid-lithium limiter to reduce impurities. Figure 2 shows the effect of the limiter on the oxygen impurity.

Liquid lithium has a high chemical affinity for hydrogen and its isotopes, so it is expected that plasma recycling would be strongly reduced at a liquid-lithium PFC. This effect is clearly shown in Figure 3, which compares D_α emission (which is proportional to the recycling coefficient) at the lithium-filled tray for room temperature and liquid lithium.

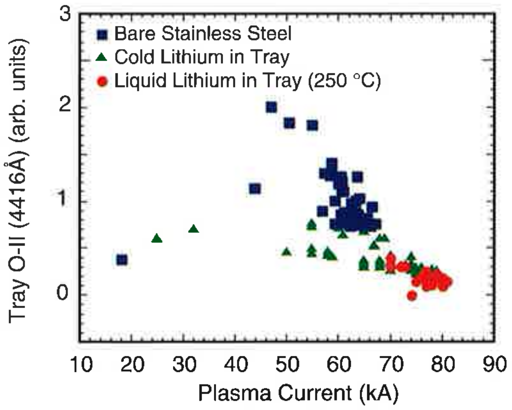


Figure 2. Variation of oxygen emission with a bare stainless steel tray, a cold lithium-filled tray, and a liquid-lithium-filled tray.

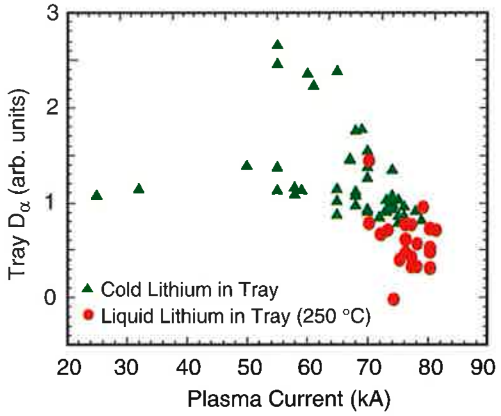


Figure 3. D_α emission at the tray with cold, solid lithium and hot lithium.

Operation with lithium PFCs and lithium wall coatings has been observed to increase the maximum plasma current which can be obtained in CDX-U, reduce volt-second consumption, and significantly modify plasma fueling.

Future Plans

In 2002, a second-generation lithium tray with a treated surface which is designed to promote a more uniform lithium fill in the limiter will be installed in CDX-U. A new liquid-lithium filler system for the tray is under development by UCSD, and will also be installed in 2002, along with new gas-fueling systems. Additional discharge cleaning techniques will be implemented to provide a cleaner surface for interaction with the plasma, and further reduce recycling at the limiter, perhaps to zero.

In 2003 a flowing lithium limiter will be introduced. The main objective of these experiments will be to provide a fresh lithium surface prior to every plasma discharge. A magnetohydrodynamic drive scheme will be used to internally recirculate the liquid lithium over the limiter surface.

Finally, a proposal to investigate a tokamak with completely nonrecycling walls is under development.

Collaborations and Graduate Studies

The liquid-lithium wall effort has introduced a major new component into CDX-U collaborations. The first liquid-lithium system installed in CDX-U was a rail limiter designed and constructed by collaborators at UCSD. They participated closely in the experiments with this limiter. UCSD has assumed responsibility for the new lithium-filling system for the CDX-U tray. It is planned that a postdoctoral research fellow from UCSD will be on site at PPPL full time to work on the lithium experiments.

Researchers at Sandia National Laboratories have contributed surface analysis of wall samples, and have also provided and set up an infrared camera to monitor surface temperature of the lithium during plasma discharges. Numerous other scientists in the ALPS and APEX initiatives have been participants in the experiments and will continue to be involved.

The CDX-U group and the plasma spectroscopy group at Johns Hopkins University 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 Torus experiment at Culham Laboratory in England.

A number of collaborations with Oak Ridge National Laboratory (ORNL) are underway. These include a collaboration on spectroscopic diagnostics of lithium and impurity concentrations at the lithium limiter. These diagnostics have proved invaluable in determining the effects of lithium on the edge plasma. Other collaborations with ORNL involving fueling techniques are also underway.

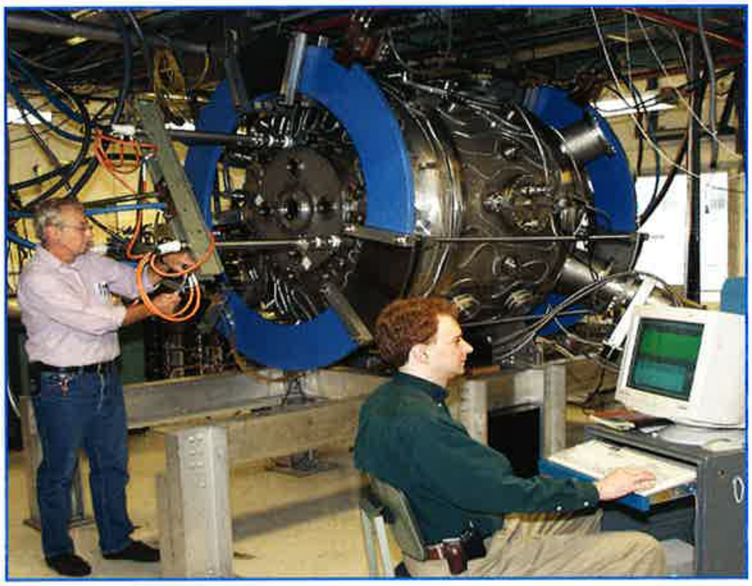
A primary role of CDX-U at the Princeton Plasma Physics Laboratory (PPPL) has always been to serve as a training ground for graduate students in experimental plasma physics. Tobin Munsat (Princeton University) completed a doctoral dissertation on electron transport in ST plasmas early in 2001. Brent Jones (Princeton University) is currently completing his Ph.D. dissertation on electron Bernstein wave emission in CDX-U. Jeffrey Spaleta (Princeton University) has begun his thesis research, which involves radio-frequency heating of ST plasmas at moderate harmonic number. During the summer of 2001, CDX-U hosted several undergraduate students, including M. Maiorano from Rutgers University, B. Miller from Dartmouth College, and S. Smith from Oklahoma State University.

The CDX-U has been a significant part of the PPPL Plasma Science and Fusion Energy Institute, a summer training program for high school science teachers.

Since CDX-U 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. We hope to continue this strong commitment to education in FY2002 and beyond.

Magnetic Reconnection Experiment



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 — can occur in virtually all magnetized plasmas, both in the laboratory and in nature (Figure 1).

Despite its omnipresence, reconnection is not a well-understood phenomenon. In laboratory fusion plasmas, such as those in tokamaks, reconnection manifests itself as "sawtooth" oscillations in electron temperature and ultimately degrades plasma confinement. In nature, reconnection plays an important role in the evolution of solar flares, coronal heating, and in the dynamics of the Earth's magnetosphere. Reconnection at the dayside magnetopause, shown in Figure 2, often is considered as the onset or trigger for such events as auroral substorms and geomagnetic storms. In recent years, the solar satellite TRACE has provided the best evidence to date that reconnection is involved in solar flare energy release. However, the rate of energy release is a mystery, unaccountable by the present understanding of reconnection physics. The observed "fast reconnection" has made magnetic reconnection a very active area of research.

Experiments on MRX have provided crucial data with which the theoretical and

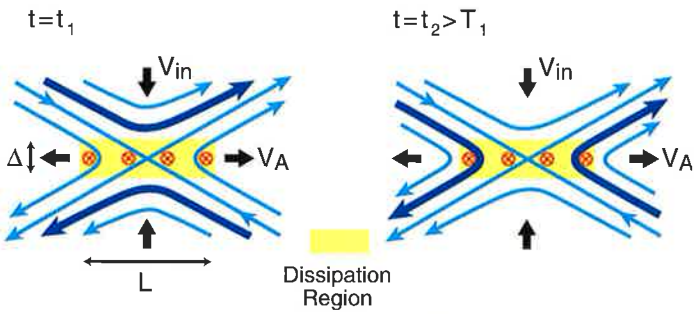


Figure 1. Evolution of the magnetic field lines during reconnection.

observational research communities can compare their work. Cross-disciplinary interactions have led to fertile discussions and useful reassessments of the present understanding. Indeed, experimental research on MRX has initiated a renewed interest in magnetic reconnection unseen for some decades.

The small size and rich plasma physics of MRX make it an ideal facility 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 MRX is the comprehensive analysis of magnetic reconnection both locally and globally in solar and magnetospheric relevant plasmas. The analysis focuses on the coupling between microscale features of the reconnection layer and global properties such as driving force, 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.
- Study the importance of three-dimensional effects in reconnection.
- 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 and Past Major Results

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.

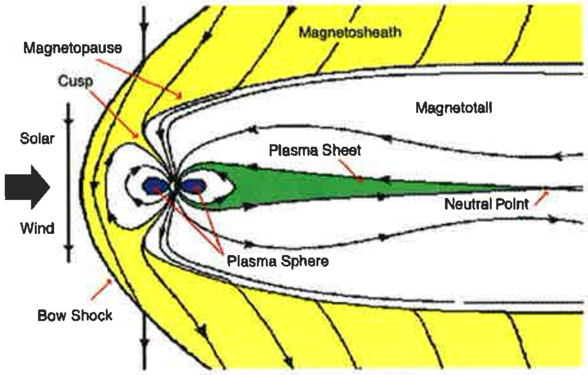


Figure 2. Illustration of magnetospheric reconnection at the dayside of the magnetopause (when the incoming magnetic field of the solar wind is southward).

Qualitative differences in the reconnection layer arise depending on the presence of the toroidal field.

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 the local magnetic field vector).

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

Null-helicity experimental data indicated a reconnection speed consistent with a generalized Sweet-Parker model, which includes the effects of plasma compressibility, finite pressure in the downstream region of the field lines, and nonclassical plasma resistivity. Compressibility allows more incoming plasma to accumulate in the current sheet, leading to a slight enhancement in reconnection speed over the classical Sweet-Parker speed. Conversely, finite downstream pressure hinders the outgoing plasma, leading to a reduction in plasma outflow speed and hence reconnection speed. The measured plasma resistivity was found to be enhanced over the classical Coulomb-collision value by up to a factor of ten; this enhancement is thought to play a crucial role in determining the reconnection rate. Figure 3 shows the experimentally measured reconnection rate plotted as a function of the generalized Sweet-Parker number 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.

Nonclassical Ion Heating during Reconnection

Conversion of magnetic field energy to plasma kinetic energy is a primary consequence of reconnection. This process is

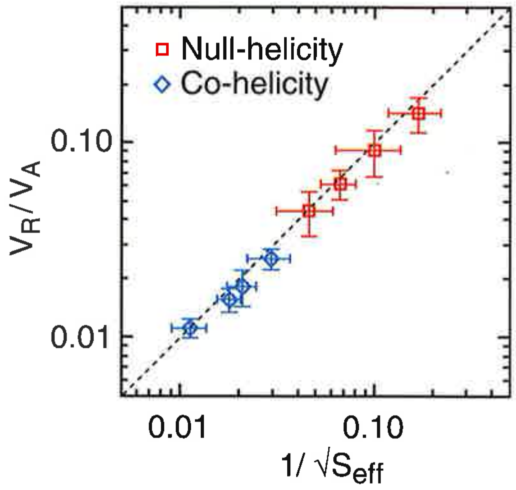


Figure 3. Experimentally measured reconnection rate (in flow speed V_R divided by Alfvén speed V_A) in MRX.

believed to play an important role in coronal heating, solar flares, and acceleration of auroral jets in the magnetosphere. Solar observations and in situ satellite measurements show the existence of extremely energetic particles. However, the direct cause and effect between reconnection and the acceleration and/or heating of these energetic particles is unknown due to the extreme challenge of diagnosing a single reconnection event adequately and at the same time observing local plasma acceleration and heating that is concomitant with the reconnection event. In the MRX laboratory experiment, this has been done.

In collaboration with Dr. G. Fiksel from the Madison Symmetric Torus group 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 3 was observed during reconnection phase, while the ion temperature was basically flat when no reconnection was induced. Spatially 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 and found to be consistent with a slower reconnection rate compared to the null-helicity case. Experimentally, it was observed that the ion energy increase correlates well with resistivity enhancement, suggesting that the same fast reconnection mechanism(s) also directly heats ions.

Study of Current Sheet Profiles

In 1962, E.G. Harris presented an elegant one-dimensional solution for the equilibrium profiles of a collisionless current sheet. Since then, many theoretical and numerical studies of magnetic reconnection have used the Harris magnetic field profile, $B(x) \sim B_0 \tanh(x/\delta)$. However, this profile had not been observed in real plasmas.

In MRX, the precise profile of the magnetic field in the current sheet has been measured by a very high-resolution magnetic probe array (5-mm spatial resolution). The measured magnetic profiles fit very well the Harris solution, as shown in Figure 4. This agreement is remarkable, since the Harris theory does not take into account the electric fields and dissipation associated with reconnection. The sheet thickness δ is found to be approximately 0.35 times the ion skin depth, which agrees with a generalized Harris theory incorporating nonisothermal 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.

Recent Results

Fluctuations Studies in Current Sheets

Current sheets formed in MRX contain strong gradients in plasma density and

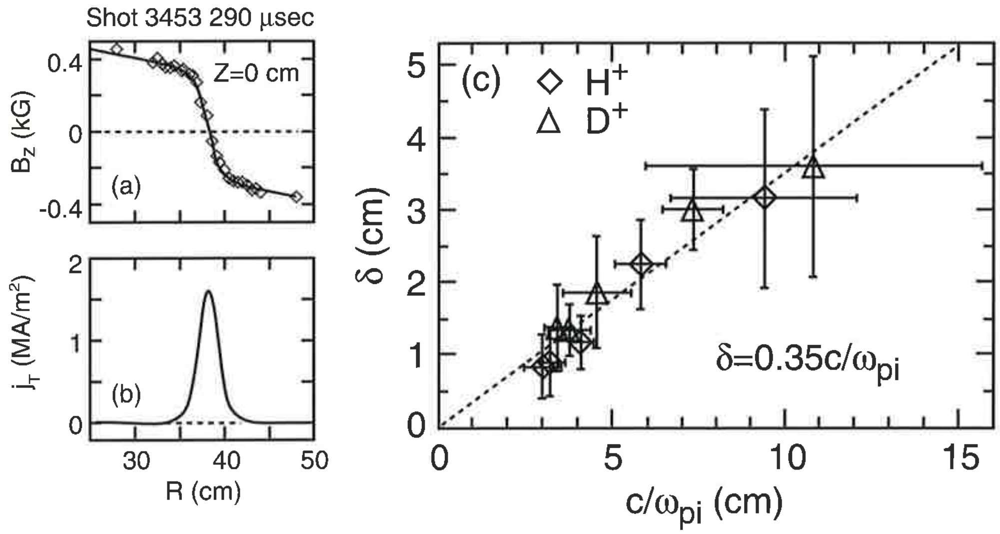


Figure 4. (a) Radial profile of reconnecting magnetic field (B_z) measured by a high-resolution magnetic probe array. (b) Current sheet inferred from B_z measurements. (c) The thickness of the current sheet is proportional to the ion skin depth, c/ω_{pi}.

strong cross-field currents, both of which can drive unstable fluctuations and result in turbulence. The role of turbulence in magnetic reconnection has been a controversial subject in the theoretical literature with some claiming that it is necessary to provide anomalous resistivity for fast reconnection, while others claim that it is not essential and may even slow the process. There have been very few experimental studies of turbulence in current sheets, and none has investigated fluctuations in current sheets in MHD plasmas, where the ion gyroradius is much smaller than the experimental apparatus.

Experiments studying electrostatic and magnetic fluctuations in MRX have found the presence of strong fluctuations in the lower-hybrid frequency range. Figure 5 shows an example of raw fluctuation signal, along with a time trace of the plasma current. These fluctuations are observed during current sheet formation and reconnection, and have a broad frequency spectrum located near the lower-hybrid frequency, as shown in the inset of Figure 5. The spectrum of the observed fluctuations is consistent with theoretical predictions of the lower-hybrid drift instability (LHDI), an instability driven by strong density gradients and cross-field currents in MRX.

The role of the LHDI in the reconnection process in MRX was explored by studying the spatial and temporal behavior of the fluctuation amplitude and by studying the dependence of the fluctuation amplitude on the current sheet collisionality. The observed radial profile of the fluctuations is consistent with several theoretical predictions that the LHDI

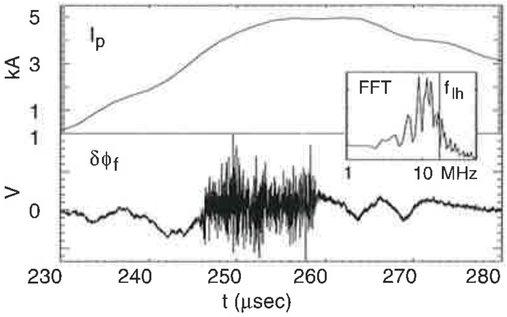


Figure 5. Traces of plasma current and measured floating potential signal, along with a frequency spectrum of the signal. Current sheet formation and reconnection occur roughly from t = 240 µsec to 280 µsec.

should not penetrate to the high-beta null point. The temporal behavior of the fluctuation amplitude provided further support for the conclusion that the electrostatic LHDI (E-LHDI) is not essential to reconnection in MRX. The amplitude was observed to drop dramatically during reconnection, while the reconnection rate (electric field) was steady. The mechanism for the drop in amplitude is still not fully understood, but this observation makes it difficult to claim that the E-LHDI is providing anomalous dissipation during reconnection in MRX. Finally, a study of the effect of collisionality in the current sheet on the fluctuation amplitude was performed. The normalized fluctuation amplitude was found to be fairly insensitive to the collisionality in MRX current sheets. Significant LHDI amplitude persists in high-collisionality current sheets where the reconnection rate is classical. These findings suggest that the E-LHDI does not play an essential role in determining the reconnection rate in MRX.

Measurement of the Transverse Spitzer Resistivity

Coulomb collisions among charged particle species were historically the first mechanism of transport in plasmas to be described by a quantitative theory. In magnetically confined plasma devices, this "classical" mechanism is often strongly modified by particle orbit effects, or is completely dominated by turbulent transport. Nevertheless, the classical value of electrical resistivity, among other transport coefficients, is universally used as an important reference value and the lower bound whenever transport or dissipation phenomena are discussed.

For plasmas where Coulomb collisions dominate all other dissipation processes, including wave and turbulence effects, the resistivity is determined by the collisional drag on electrons moving against the background of ions. If a strong magnetic field is applied perpendicular to the electric field direction, the current is not due to direct acceleration of electrons by the electric field, but is diamagnetic in origin. The transverse, or cross-field resistivity, was calculated by L. Spitzer, Jr. It turned out to be approximately twice as large as the resistivity without the presence of the magnetic field, since the transverse electron distribution function is not as distorted as in unmagnetized plasma where the current is carried by energetic electrons experiencing less frequent collisions.

However, this theoretical prediction had not been verified experimentally. The difficulty of such measurement is due to the E × B drift resulting from the application of the transverse electric field. In typical plasma, two terms on the left-hand side of Ohm's Law, $E + v \times B = \eta j$ (where η is the plasma resistivity and j is the current density), very nearly cancel each other. An attempt to experimentally evaluate Ohm's Law fails to produce a reliable estimate of η since it involves taking a difference of two nearly identical numbers. One way to make the measurement feasible is to suppress the cross-field flow. This is achieved in MRX where an electric field is applied perpendicular to the reconnecting magnetic field. Oppositely directed magnetic field lines merge through the neutral sheet as a pressure gradient is created perpendicular to both E and B and a neutral sheet current is induced.

Transverse resistivity is measured as a function of the fill pressure of hydrogen and helium gases. The measured resistivity is remarkably close to the classical value in the range of pressures above approximately 5 mTorr. Below 5 mTorr, the resistivity quickly becomes anomalous. The normalized resistivity is plotted in Figure 6 as a function of the collisionality param-

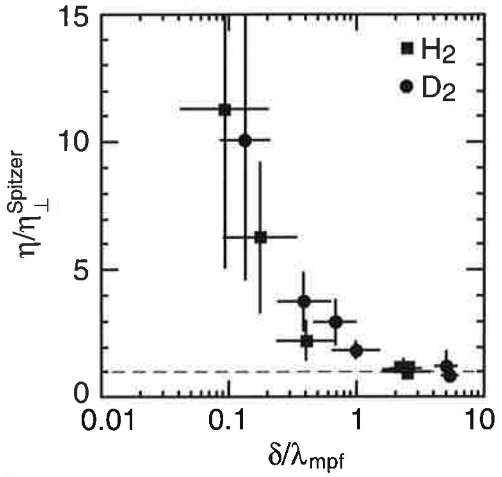


Figure 6. Resistivity anomaly factor as a function of the collisionality parameter δ/λ_{mfp}.

eter δ/λ_{mfp}, where δ is the thickness of the neutral sheet and λ_{mfp} is the mean-free-path. In a highly collisional region of reconnecting plasma, where the mean-free-path for Coulomb collisions is smaller than the thickness of the neutral sheet, measured resistivity agrees with the calculated Spitzer value to within 30% uncertainty. To our knowledge, this is the most accurate measurement of the transverse Spitzer resistivity to date. The observed resistivity follows the $T_e^{-3/2}$ dependence characteristic of Coulomb collisions (Figure 7) and shows no significant electron density dependence. As the mean-free-path increases beyond the thickness of the neutral sheet, the resistivity is enhanced by up to an order of magnitude greater than the Spitzer value, indicating that dissipation mechanisms other than Coulomb collisions become dominant.

Future Work

The search for the mechanism behind fast reconnection in MRX current sheets will continue in order to ascertain the role of non-MHD effects in the current sheet. The role of nondissipative Hall terms in reconnection in MRX will be investigated through high-resolution studies of current sheet structure. It also is planned to carry out a more systematic study of magnetic fluctuations, other than E-LHDI in the MRX current sheet. Any relationship between these fluctuations and the reconnection rate or ion heating will be the subject of future research. Advanced diagnostics will be used for these studies, including the use of planar laser-induced fluorescence to obtain two-dimensional images of the ion density in MRX current sheets. Further studies of the global MHD aspects of reconnection and the importance of three-dimensional perturbations to the current sheet geometry are planned. The results of these efforts should bring a better understanding of the important process of magnetic reconnection.

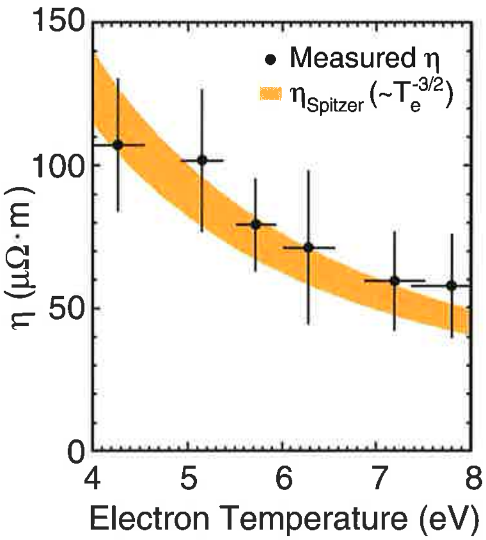


Figure 7. Electron temperature (T_e) dependence of the measured resistivity (filled circles) and calculated from measured electron temperature and electron density (shaded area). The one-σ range shown incorporates the statistical uncertainty of the electron temperature measurement and the electron density variations in the data set.

Fusion Theory and Advanced Computing

During FY2001, 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 fusion as an attractive, technically feasible energy option. The work described below highlights how theory drives progress in the fusion program. Continued enhancements in understanding the basic mechanisms associated with toroidal confinement enables these advances. In addition, improvements in operating regimes in magnetically confined plasmas and in diagnostic techniques have stimulated more realistic comparisons of experimental results with theoretical models. This is expected to generate more reliable physics-based models that should accelerate the pace of technical advances. Key results from experimental facilities would be more efficiently and reliably obtained, and attractive new approaches and designs for new facilities would emerge more readily.

The PPPL Theory Department continued to add to its internationally appreciated contributions of key seminal concepts as well as to its innovative development and maintenance of the most comprehensive set of toroidal design and analysis codes. It fulfills its mission in an efficient manner by:

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

Achieving the goals of the PPPL Theory Department requires continued advances in analytical capabilities together with the validation and active applications of the best existent theoretical tools for interpretation and design. Contributions to the areas highlighted below are reminders of the lead role theory can play in the fusion program.

Three-dimensional Nonlinear MHD

The capabilities of the three-dimensional extended magnetohydrodynamic (MHD) code, M3D, have continued to be significantly improved in collaboration with New York University and the Massachusetts Institute of Technology to enable more realistic analysis of advanced tokamaks and alternate concept devices. In particular, the two-fluid model and Particle/MHD hybrid model within M3D have been updated to massively parallel processing structure. Along with the basic MHD model, these capabilities have been applied to study spherical tori, tokamaks, and stellarators.

M3D code studies of internal reconnection events (IREs) in the National Spherical Torus Experiment (NSTX) indicate that IREs are similar to disruptions. IREs occur in at least two ways: due to stochasticity and due to localized steepening of pressure-driven modes. In cases where stochasticity plays a major role, the IREs are similar to the more familiar "sawtooth" crash, as shown in Figure 1.

M3D code simulation results of equilibria with strong toroidal flow were found to be consistent with the interpretation that the experimentally observed shift of the density relative to the temperature profile is due to the centrifugal force of the plasma rotation. Linear and nonlinear simulations indicate that the strong toroidal flow is stabilizing and that, as illustrated in Figure 2, it can lead to a saturated steady state. Here the magnetic field lines, density contours, and a temperature iso-surface are depicted. Unlike the usual sawtooth crash, the density and pressure tend to peak inside the magnetic island. Together with strong sheared toroidal flows, this causes the mode saturation.

Recent experiments in the Joint European Torus (JET) and the Japanese Tokamak (JT-60), with a fast current ramp-up and external current drive, exhibit a central region with virtually zero current density. M3D simulations of these "current-hole" discharges indicate that the current clamping is due to sawtooth-like crashes, but with n = 0 (where n is the toroidal mode number) rather than n = 1. Figure 3 shows flux contours and the toroidal current profile during a crash.

Simulation studies of stellarators using a two-fluid model of M3D indicate that the diamagnetic drift of the equilibrium is strongly stabilizing for MHD modes with toroidal mode number about

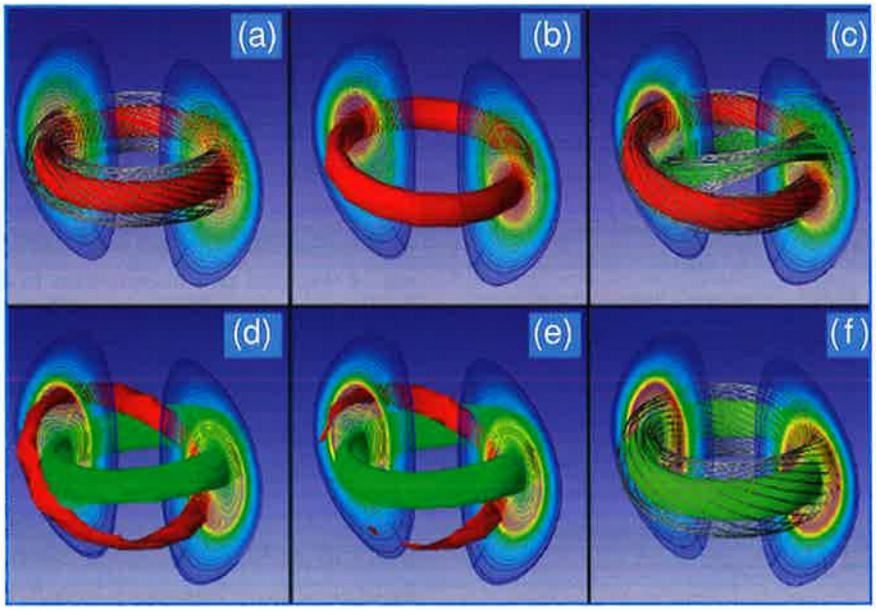


Figure 1. M3D code simulation of the temporal evolution of an internal reconnection event in the National Spherical Torus Experiment.

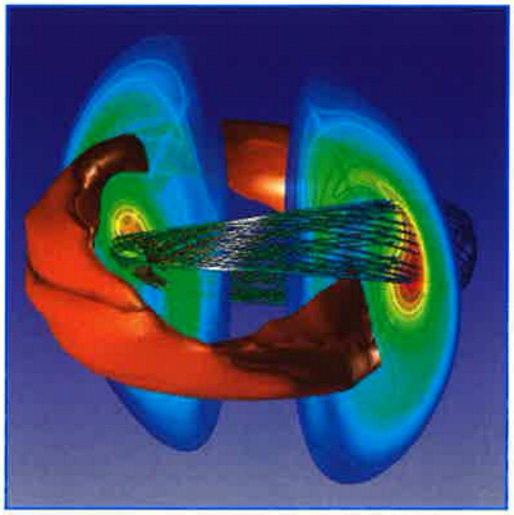


Figure 2. Magnetic field lines, density contours, and temperature iso-surface from M3D simulation of a steady-state plasma with strong toroidal flow.

ten or higher. Since these high-n modes are the most unstable ones (due to the toroidal modulation of stellarators), these simulation results may explain why, though seldom observed in actual experiments, most standard MHD calculations for stellarators indicate instability to resistive ballooning and resistive interchange. The Particle/MHD hybrid model of the M3D code has also been used to study toroidal Alfvén eigenmodes (TAE) in stellarators. By examining a sequence of equilibria starting from a tokamak and ending in stellarator, the 3-D (three-dimensional) geometry of stellarators was found to be substantially stabilizing for TAE modes.

Turbulent Transport Simulations and Analysis: Gyrokinetic Simulations

The gyrokinetic particle simulation efforts have continued, centered around advances in model improvement and associated applications for the three-dimensional full-torus gyrokinetic toroidal code (GTC) in general geometry. Fully utilizing the available power of the newly configured 5-teraflop IBM-SP massively parallel computer at the National Energy Research Supercomputer Center, new large-scale transport scaling studies with respect to device size have been carried out for electrostatic ion-temperature-gradient turbulence with adiabatic electron dynamics. These first-principles nonlinear simulations, which used up to one billion particles and hundreds of millions of spatial grid points, have just become feasible with the implementation of an efficient global

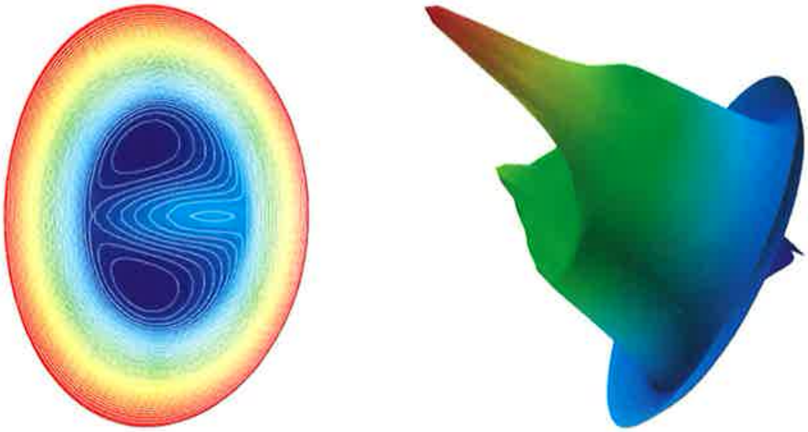


Figure 3. Flux contours (left) and toroidal plasma current profile (right) from M3D simulation of current-hole discharges relevant to the JET and JT-60U experiments.

field-aligned mesh, together with access to the 5-teraflop IBM-SP.

Results of these simulations, varying device size (represented by tokamak minor radius a) normalized by the ion gyroradius (ρ_i) while keeping other dimensionless plasma parameters fixed, show that the fluctuation characteristics (correlation lengths and autocorrelation time) obey a gyro-Bohm scaling in the presence of zonal flows. The local transport coefficient (χ_i) exhibits a gradual transition from a Bohm-like scaling, χ_B=cT/eB (c, T, e, B are, respectively, the speed of light, electron temperature, electron charge magnitude, and magnetic field strength), for device size corresponding to present-day tokamak experiments to a gyro-Bohm scaling, $\chi_{GB} = \chi_B \rho_i / a$, for larger fusion devices, as illustrated in Figure 4. The transition occurs at a much larger size than expected from linear ion-temperature-gradient theory of profile variation effects. The new simulations include a heat-bath/source to prevent profile relaxation and are in a regime far away from marginal stability. These findings show that extrapolations based on empirical scalings or mixing length rules are not reliable and that advanced simulations can supplement and eventually replace the extrapolation methods for projecting future machine performance by directly addressing parameter regimes inaccessible through conventional analyses or by existing experimental data.

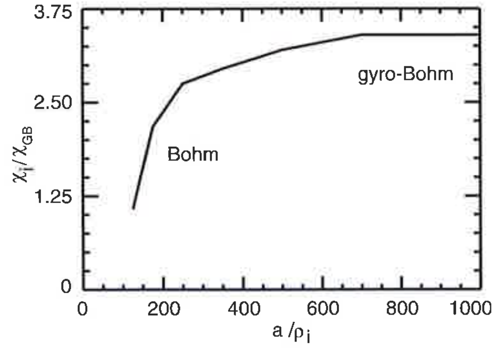


Figure 4. Size-scaling results from full-torus global gyrokinetic simulations of microturbulence due to toroidal ion-temperature-gradient-driven instabilities.

Laser-plasma Interactions

Inertial confinement fusion is an alternative to magnetic confinement fusion as a path to a practical fusion power. In the inertial fusion process, a spherical deuterium-tritium target of a few millimeters diameter is imploded by some external radiation.

Lasers are a practical way to deliver the required levels of radiation. The lasers heat up the outer shell of the target which becomes ionized and expands outward in the form of a plasma. As a counter-reaction, the inner core of the target implodes to very high density — a thousand times its initial density — leading to a high rate of fusion reactions. Above an intensity threshold, the laser beam can nonlinearly generate fluctuations in the hot tenuous plasma at the outer edge of the pellet. These instabilities can have a number of deleterious effects, including uncontrolled scattering of the laser energy into unwanted regions of the target, thereby destroying the required high degree of irradiation symmetry needed to compress the target core to high density. As a countermeasure, high-power inertial confinement fusion laser beams are routinely "degraded" by passing them through time-varying phase-distorting plates at the end of the amplifier chain. These plates effectively decorrelate the beams both temporally and across the lens plane, with the result that in the target region, randomly irregular intensity patterns ("hot-spots" or "speckles") are introduced. The goal is to vary the location of the intensity maxima sufficiently rapidly so that, at any location, they disappear before appreciably nonlinear scattering occurs.

Part of the difficulty in analyzing this situation is that the dynamics of the instabilities depend on the shape of the electron distribution function, which is influenced by energy transport across the laser hot-spots. Because these hot-spots can be comparable in size to the electron collisional mean-free-path, analysis of energy transport necessitates solving the full Boltzmann transport equation. PPPL theory efforts have recently addressed this key issue for a wide range of parameters in the case of both single and multiple hot-spot geometries. The electron distribution function has been parameterized in terms of the two fundamental dimensionless quantities governing the physics: the ratio of mean-free-path to speckle radius and the strength of the laser drive. Additionally, quantitative limitations on the accuracy of widely used results from linearized analysis of the transport equation have been determined.

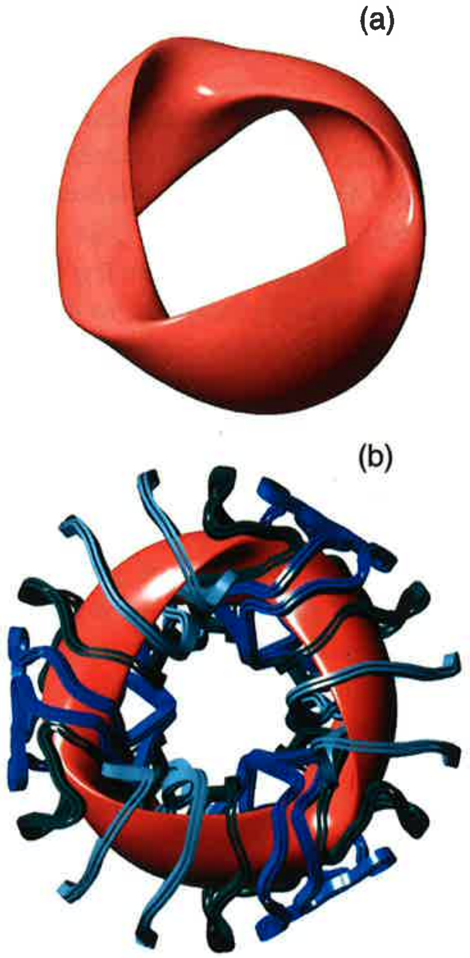


Figure 5. Advanced stellarator codes have been effectively utilized to design the National Compact Stellarator Experiment (NCSX) via optimization of confinement and constructability properties. Shown is (a) the NCSX reference plasma configuration and (b) the NCSX plasma and modular coils.

Stellarator Theory

The PPPL Theory Department has had a lead role in addressing and resolving critical physics issues relating to the proposed National Compact Stellarator Experiment (NCSX) in preparation for the NCSX Physics Validation Review. Progress was made in developing sophisticated new numerical diagnostics for the PIES and aforementioned M3D codes, and in implementing an improved stellarator optimization algorithm. Highlights in these areas include:

Equilibrium Flux Surfaces

An algorithm was developed and implemented for designing stellarators with good flux surfaces (Figure 5). This is a problem that is fundamental to stellarator physics and is also of critical importance to NCSX. The algorithm has been applied successfully to remove the islands in the NCSX reference fixed-boundary configuration, and to design coils for this configuration which yield free-boundary equilibria with good surfaces.

MHD Stability

A systematic MHD stability analysis of the proposed NCSX reference configuration was carried out using high numerical resolution. It was shown that free-boundary equilibria of NCSX exist that are stable to all MHD modes including

Mercier modes, ballooning modes, external kink modes, and the vertical mode.

Global Stellarator Optimization

A global "differential evolution" optimization algorithm was implemented in the stellarator optimizer. The global optimizer is found to require less human intervention and adjustment in the optimization process than the standard algorithm.

NCSX Robustness and Flexibility

A substantial effort was invested to demonstrate the ability of NCSX coils to support the wide range of variation in plasma configuration about the reference baseline equilibrium necessary to achieve the scientific goals of NCSX.

New computational capabilities were developed and utilized for flexibility and robustness studies. These included an equilibrium code-based free-boundary optimizer that determines coil currents that produce free-boundary equilibria consistent with a chosen set of plasma profiles and desired physics properties. The desired physics properties include good quasi-axisymmetry (QA) (measured by low values of effective helical ripple amplitude) and beta limits in excess of 3% for a wide range of assumed plasma profiles. It was possible to demonstrate that:

- there is a wide operating space of plasma current and beta values for which plasmas supported by NCSX coils are stable to kink and ballooning modes with low helical ripple amplitude,
- NCSX plasma performance is robust with respect to substantial variations in plasma current and pressure profile shape,
- substantial changes in the external rotational transform and magnetic shear can be induced by varying currents in the NCSX coils, and
- NCSX coils have the flexibility to control the degree of quasi-axisymmetry allowing exploration of the physics of quasi-axisymmetry plasmas.

Plasma Boundary Physics

The DEGAS 2 neutral transport code was used to simulate neutral deuterium and helium light emission in the "gas puff imaging" plasma turbulence visualization experiments on Alcator C-Mod and NSTX (Figure 6). This research established that the spatial structure of the emission pattern directly reflects that of the underlying plasma turbulence. Hence,

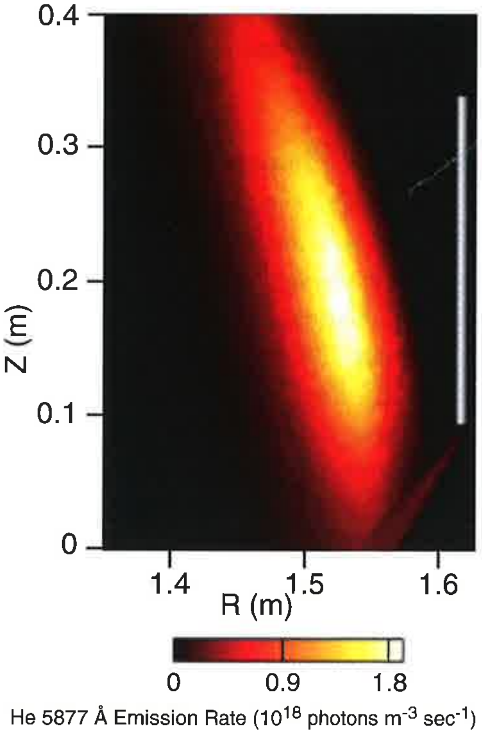


Figure 6. DEGAS 2 simulation of the poloidal variation of emitted light from neutral helium puffed into the edge of the NSTX device via the gas manifold indicated in gray on the right. The computations were performed with time-averaged plasma profiles from a "low-confinement mode" discharge.

a wavenumber analysis of the emission patterns will yield spectra that can be directly compared with those obtained from plasma turbulence codes. Contrary to expectations, the dependence of the emission rate on the electron temperature was found to be just as strong as the electron density dependence under typical conditions of these experiments. Consequently, the actual plasma density and temperature profiles cannot be directly inferred from the emission profiles.

New features developed over the last two years for DEGAS 2 include: (1) elastic scattering atomic physics processes, including self-collisions of the neutrals; (2) new tools for defining two-dimensional geometries and plasma backgrounds; (3) the ability to monitor conservation of neutral mass, momentum, and energy; and (4) extensive updates to the User's Manual and other documentation, as well as two new examples, to illustrate the usage of these new capabilities.

Field-reversed Configuration Stability Calculations

Stability properties of field-reversed configurations (FRCs) were studied using a 3-D nonlinear hybrid and MHD code (HYM). This code has been upgraded to include options for two-fluid (Hall-MHD) simulations, realistic boundary conditions, and detailed particle phase-space diagnostics. The n = 1 tilt instability mechanism and stabilizing factors were investigated including effects of the particle loss along the open field lines and Hall stabilization. It has been demonstrated that resonant ion effects are responsible for instability in the large-Larmor-radius, strongly kinetic regime, and the nonlinear saturation in this case occurs due to nonlinear change in the ion-distribution function. Small-Larmor-radius calculations (Figure 7) show linear growth comparable to that of the MHD model, but considerably slower nonlinear evolution, which can provide an explanation of the

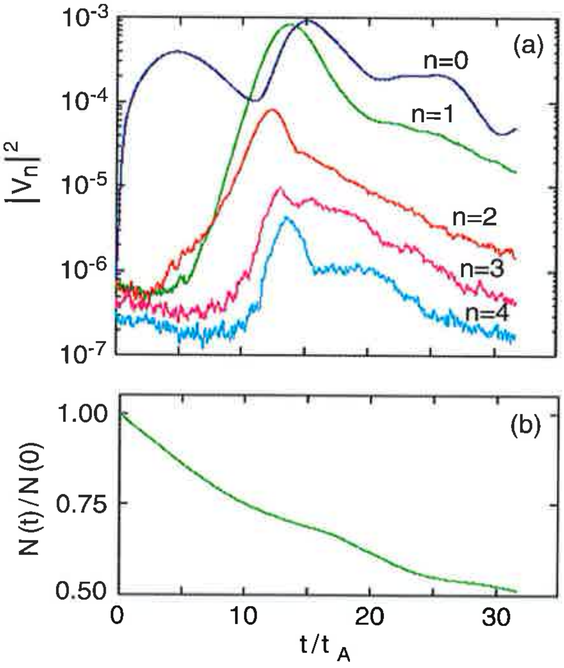


Figure 7. Results from nonlinear hybrid simulations of field-reversed configuration plasmas: (a) energy plots for n = 0 to 4 modes and (b) total number of particles in the configuration.

experimentally observed FRC behavior. Hall stabilization is found to be relatively small and not sufficient to explain the stability. A numerical scheme, which allows a switch between delta-f and full-f particle simulation, was implemented in order to follow the dynamics of the unstable global modes from the linear phase to the large-amplitude, strongly nonlinear phase. The HYM code was also upgraded to allow for spherical torus geometry, and it is used to study the excitation of compressional Alfvén modes (CAE) by the fast neutral-beam ions in the National Spherical Torus Experiment.

The High-resolution Display Wall

PPPL's high-resolution display wall, which was installed in FY2000 has continued to be an active venue for scientific discussions and major presentations. In FY2001, it was further upgraded, including the installation of three new projectors (each with a 4 by 3 aspect ratio and 1024 by 768 pixels). This new configuration enables a 16 by 9 aspect ratio for the wall for a total of 9.4 M pixels (upgraded from 7.1 M pixels). Another major upgrade involved the computer equipment, with the new machines now comprised of 1.5-GHz Pentium IV processors (upgraded from 733-MHz processors). Each of the 13 machines has 60 GB of disk storage for a total of 780 GB on the cluster. A Myrinet network provides the necessary support for the display wall software. There was considerable effort to have theory codes run on this cluster. Small parallel jobs were run for rapid prototype development.

An effort was undertaken this year to develop an automated screen alignment system for the display wall. This system will use a modified version of software supplied by Princeton University's Computer Science Department. The mechanical parts of the mount were replaced with stepper motors, with each motor able to move the image less than 0.1 pixel per revolution. In collaboration with Rutgers University students, designs of circuit boards and software to control the projectors were also completed. A remote-control-panel graphic-user-interface was provided. All 12 projectors can now be easily operated from one computer.

As part of the National Fusion Collaboratory project, an access grid node was set up in PPPL's display wall. This required three additional computers with audio hardware that connects the eight microphones in the room with the participants on the access grid. Additional information about the access grid can be found at: http://www-fp.mcs.anl.gov/fl/accessgrid/.

Modeling of Advanced Diagnostics

To gain a better understanding of the complex processes impacting plasma turbulence, theorists, computer scientists, and experimentalists have recently developed a massively parallel processor (MPP) simulation of the actual microwave reflectometry diagnostic. As illustrated in Figure 8, the new MPP code models the actual incoming microwaves reflecting off a plasma which evolves as its turbulence grows. This is interfaced with the latest large-scale microturbulence simulation results described earlier in this report. The characteristic turbulent correlation length can be extracted from this reflectometer simulation and compared with that deduced from the original microturbulence simulation. This innovative capability can cost-effectively aid in the interpretation of the reflectometry data, help utilize existing diagnostics more efficiently, improve these tools and design future experiments. For example, recent extensive simulations have shown that use of O-X correlation reflectometry to determine the magnetic field in the Fusion Ignition Research Experiment is only feasible when the density fluctuation level is extremely low (less than 0.1%). This simulation capability can also be used to help examine whether imaging of turbulence is feasible in large-scale plasma devices and, if so, how an array of receivers might be optimally deployed.

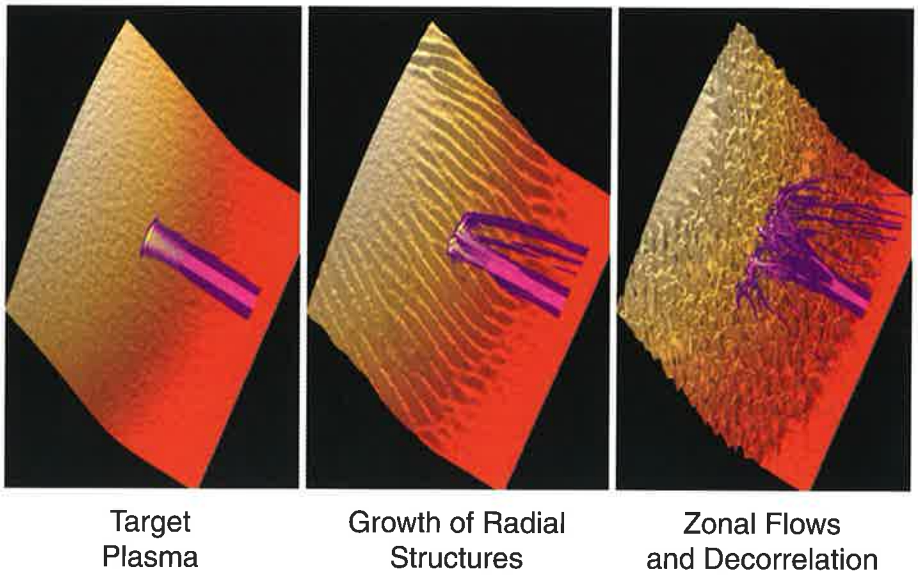


Figure 8. Interfacing of massively-parallel-processing (MPP) simulation of microwave reflectometry diagnostic with large-scale microturbulence simulation results.

Off-site Research

Princeton Plasma Physics Laboratory (PPPL) scientists and engineers participate in research programs on leading facilities worldwide, acquiring information from a diverse set of configurations and bringing PPPL's integrated experience and tools to bear in addressing key fusion science issues. The PPPL researchers work as partners on integrated teams either at the remote facility or via remote access to the experimental equipment and data.

Joint experiments on multiple facilities allow researchers to compare and contrast phenomena at different scales and in different configurations and to extend innovations and discoveries to other facilities. PPPL researchers bring to the remote collaborations much more than their individual expertise and effort. In fact, they engage PPPL's institutional strengths, especially in areas such as experiment design, diagnostics, data analysis, experiment and theory comparison, engineering design, and operations support.

Advances have been achieved in the following areas, in many cases by coordinated PPPL research on multiple facilities:

- Resistive-wall modes, in which high-pressure plasmas can become unstable due to the electrical resistivity of the nearby metallic walls, are a key research topic on DIII-D (Doublet-III D, General Atomics). PPPL participated extensively in this research and supplied feedback-control power supplies, sensors, and theoretical tools. Using a combination of magnetic control and plasma rotation, the team stabilized the mode for more than one second, well above the magnetohydrodynamic (MHD) limit without a conducting wall.

- Turbulence and transport have been studied on several devices, including turbulence measurements on JT-60U (Japanese Tokamak-60U, Japan); benchmarking and application of transport models on C-Mod (Alcator C-Mod, Massachusetts Institute of Technology), JET (Joint European Torus, England), and JT-60U; operation of a gas-puffing imaging diagnostic and upgrade of the microwave reflectometer on C-Mod; novel modes for improving confinement by radio-frequency waves in C-Mod; and internal transport barrier studies on C-Mod and DIII-D.

- Neoclassical tearing mode studies via feedback stabilization with the PPPL-supplied electron cyclotron launcher on DIII-D and Motional Stark Effect diagnostic on JET.

- "Current hole" experiments on JET via integrated diagnostic measurements of the current profile and MHD stability studies.

- Wave-particle interaction-studies via ion-cyclotron-frequency waves on

C-Mod; flexible electron-cyclotron wave launching on DIII-D, design of a lower-hybrid wave launcher for C-Mod, and design of components of a prototype ion-cyclotron antenna in support of JET.

- Preparations for studies of inside-launch pellet injection on JET by design of a spectrometer that views the pellet as it penetrates the discharge.
- Studies of energetic-particle-induced waves on JT-60U and DIII-D.
- Optimization of a negative-ion-based neutral-beam on JT-60U.

Doublet-III-D Collaborations

PPPL's collaboration in the DIII-D program at General Atomics in California has allowed PPPL scientists and engineers to share in some of the most notable tokamak physics achievements of the past year. These results included active magnetic stabilization of resistive-wall modes (RWMs) for more than one second at pressures well above the free-boundary MHD stability limit and feedback stabilization of m/n = 3/2 neoclassical-tearing modes (NTM) by electron-cyclotron current drive (ECCD). PPPL physicists also reported and contributed to many other scientific results, and PPPL engineering and technical staff provided vital support for the DIII-D facility.

Stability

Substantial progress was made in FY2001 in physics understanding and active control of resistive-wall modes in DIII-D. These experiments are a joint effort of PPPL, Columbia University, and GA, and they are a major component of the DIII-D tokamak research program. If these slowly growing, long wavelength, pressure-driven MHD instabilities can be effectively controlled, it will be possible to operate advanced tokamaks at pressures approaching the ideal wall stability limit. Experiments in FY2001 demonstrated that active magnetic control, coupled with rapid toroidal plasma rotation, can indeed stabilize resistive-wall modes in high pressure plasmas.

Experiments in FY2000 were described in a PPPL first-author invited paper at the 42nd Annual Meeting of the American Physical Society Division of Plasma Physics in October 2000. Those experiments used large-area external sensor loops to detect radial magnetic field perturbations arising from the growth of RWMs. Various logic schemes were used to generate commands for powering three diametrically opposed pairs of correction coils arrayed along the DIII-D equator outside the poloidal-field coils. The experiments conclusively demonstrated closed-loop feedback stabilization of resistive-wall modes, although achievable pressures were limited by system oscillations caused by uncompensated coupling between the sensors and the active coils and vacuum vessel eddy currents. Nevertheless, it was possible to control a mildly unstable RWM for about one second.

During the DIII-D maintenance period in the first quarter of FY2001, PPPL installed an extensive new set of sensor loops and magnetic probes inside the vacuum vessel underneath the protective carbon tiles. The installation was motivated by modeling predictions that the new internal sensors should be more effective than external sensors in controlling resistive-wall modes. Figure 1 shows a portion of the new large-area saddle loops and Figure 2 shows a poloidal magnetic field probe. The photos, taken during in-

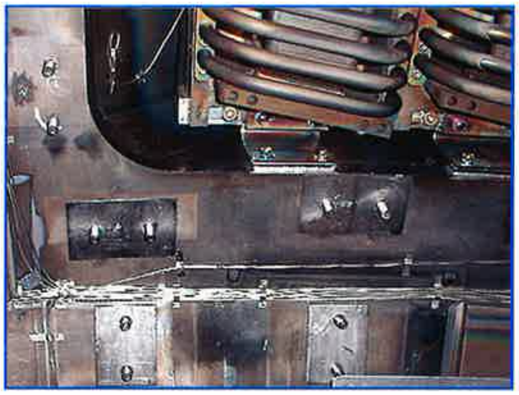


Figure 1. A portion of the new large-area saddle loops (the small silverish wires) for measuring magnetic radial-field fluctuations in DIII-D.

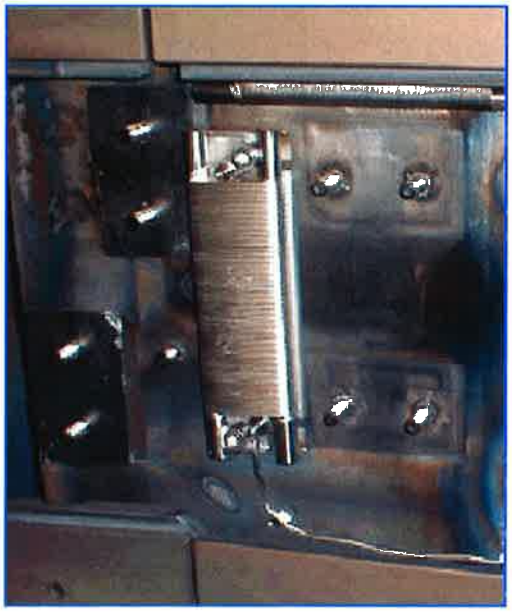


Figure 2. One of the poloidal magnetic field probes being installed in DIII-D.

stallation, show the inner wall of the DIII-D vacuum vessel with the carbon tiles removed.

Experiments in 2001 have demonstrated dramatic improvements in active control capability, owing largely to the new set of internal magnetic sensors. The new sensors, together with preexisting external sensors and a toroidal array of X-ray cameras, have also afforded better characterization of the previously observed and theoretically predicted global kink nature of resistive-wall modes. Closed-loop feedback stabilization experiments using the internal sensors also support predicted improvements in mode control with respect to previously published results using external sensors.

The new experimental results were reported in a PPPL-first-author paper at the European Physical Society meeting in June 2001, and subsequently highlighted in the "Search and Discovery" section of the September 2001 issue of *Physics Today*. The experiments show that, in plasmas with pressures at or above the no-wall ideal-MHD stability limit, rapid toroidal rotation can enhance the stabilizing effect of a surrounding conductive wall and delay the onset of resistive-wall modes or, in some cases, prevent them altogether.

When the braking arising from small magnetic error fields is reduced, either by feedback or preprogrammed control of currents in correction coils, the plasma rotation can be sustained by torque applied by neutral-beam heating. Figure 3 shows data for a case where a slow plasma current ramp was used to reliably trigger an RWM at about 1,400 msec in the absence of feedback stabilization. With δB_p feedback, beginning at 1,300 msec, the discharge was sustained for almost a second at pressures nearly twice the no-wall stability limit, indicated by the dashed line in Figure 3(a). The toroidal rotation frequency, shown in Figure 3(b), is essentially constant until the end of the discharge. The plasma terminates in a rapid disruption, suggesting proximity to the stability limit for a perfectly conducting wall. The correction coil currents demanded by the feedback system are shown in Figure 3(c). Similar stabilization results were obtained when the cur-

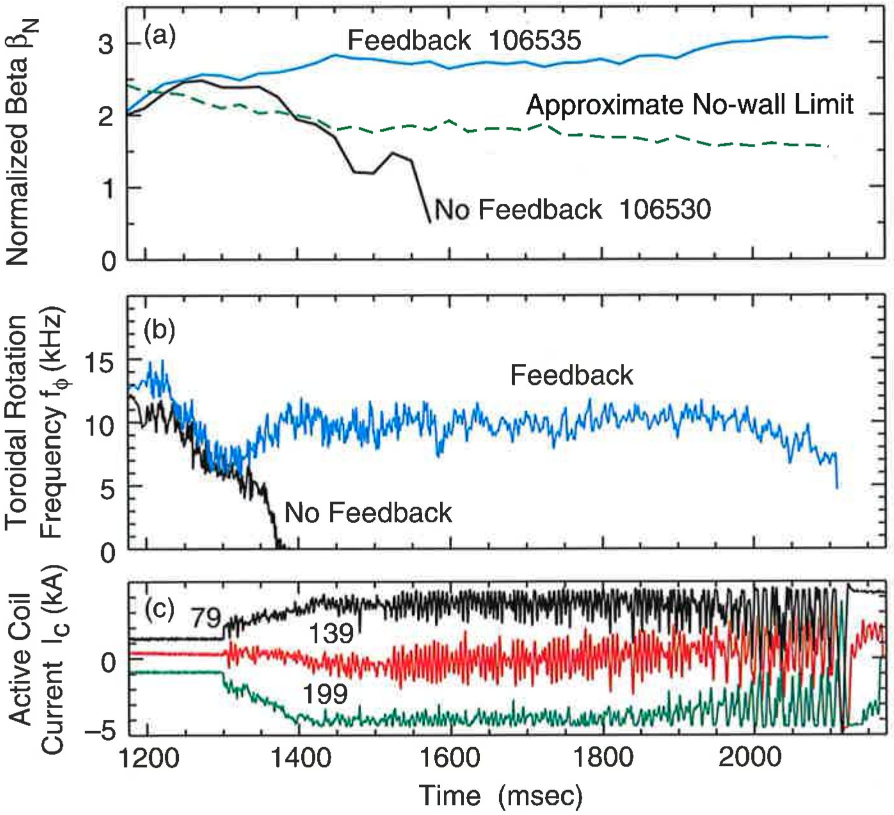


Figure 3. (a) Normalized plasma pressure β_N, (b) toroidal rotation frequency at the half-radius point, and (c) currents in the three pairs of active coils for plasma discharge106535 with internal δB_p feedback. For comparison, β_N and rotation frequency are also shown for plasma discharge 106530 without feedback.

rents in the correction coils were preprogrammed to match the slow time behavior of coil currents in the feedback case, indicating that the principal effect of closed-loop feedback for this plasma condition is dynamic correction of small magnetic error fields. The feedback system senses the resonant plasma response to static nonaxisymmetric field errors and adjusts the correction coil currents so as to minimize the plasma response.

To provide a framework for modeling the feedback stabilization of external modes in toroidal plasma discharges, the VACUUM code has been modified and coupled with the GATO stability code. The code includes the effect of a resistive shell and contributions from feedback coils and sensor loops. The result of a VACUUM-GATO study to characterize an effective set of feedback coils is summarized in Figure 4. The figure shows the calculated perturbations at the wall as a function of the fractional poloidal coverage provided by the active coils. The curves are labeled by the number of equal length segments into which a given poloidal coverage is divided. The figure shows that a single coil segment covering about 13% of the poloidal circumference is 40% as effective as an ideal shell, and that 6 or 7 segments covering 30% poloidally can be 90% as effective as an ideal wall. These predictions, together with simulations by collaborators from Columbia University with the finite-element code VALEN, are being used in the design of an expanded set of active coils to be installed inside the

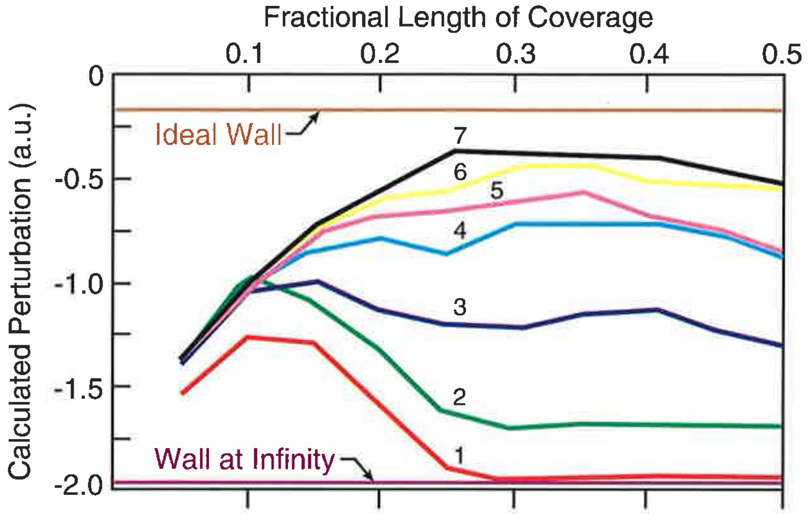


Figure 4. Computed perturbation at the DIII-D vacuum vessel wall versus fractional length of coverage by a set of feedback coils.

DIII-D vacuum vessel for feedback stabilization of resistive-wall modes.

Wave-plasma Interactions

As was the case in FY2000, PPPL played a significant role in FY2001 in the DIII-D program on electron-cyclotron heating and electron-cyclotron current drive (ECH/ECCD). Central to the program is the application of precisely controlled, powerful microwave beams for localized manipulation of the spatial profiles of plasma temperature and current density. The fully articulated ECH/ECCD launcher developed by PPPL and installed before the 2000 experimental run period enabled precise remote control of poloidal and toroidal injection angles of two of the four 1-MW, 110-GHz gyrotron sources available for the 2001 experimental campaign. The other microwave launchers used in the experiments, previously developed by GA, were adjustable in poloidal injection angle but were fixed in toroidal angle.

If powerful microwave beams are to be useful tools for localized manipulation of current density profiles, it is essential that the current generation process be reasonably efficient. Prior to the 2001 DIII-D experimental campaign, both low-power experiments and nonrelativistic theories showed a marked decrease in current-drive efficiency for off-axis microwave-beam injection. The availability of four powerful gyrotrons with controllable injection angles made it possible to test more recent relativistic calculations that predicted higher off-axis current-drive efficiency in plasmas with higher electron temperature and/or density. The measurements were in excellent agreement with the newer calculations and enhance predictive capability for future experiments.

Experiments in FY2000 achieved complete stabilization of m/n = 3/2 neoclassical tearing modes when the PPPL launcher was used to direct the beams of two gyrotrons (>1 MW total injected power) in the co-current direction and within a few centimeters of the radial location of the magnetic island. In FY2001, these experiments were extended to higher injected microwave power and used plasma-position feedback control to maintain coincidence of the magnetic-island position and the microwave resonance location. This allowed more neutral-beam-heating power to be applied and led to higher plasma pressure than was otherwise achievable.

Other experiments used perpendicularly injected microwave beams for localized electron-cyclotron heating in plasma transport studies. These included the use of local ECH to induce internal electron thermal transport barriers and the application of modulated ECH to study electron thermal transport.

Operational experience with the first steerable ECH/ECCD launcher was taken into account in the design and manufacture of a second, more robust, steerable ECH/ECCD launcher capable of supporting ten-second operation of two gyrotrons. A completely redesigned actuation mechanism will allow the new antenna to withstand the higher electromagnetic loads expected for the high heat capacity mirrors needed to prevent unacceptable temperature increases during ten-second pulses.

A photograph of the new launcher prior to final testing and shipment is shown in Figure 5. The new launcher, together with the antenna delivered in FY1999, will enable experiments with four fully steerable gyrotron beams in FY2002. A third dual launcher, identical to that shown in Figure 5, will be manufactured and delivered by the end of FY2002 in support of additional gyrotrons that will then be available.

Figure 5. The second electron-cyclotron current-drive steerable launcher designed and built by PPPL for DIII-D.

Heating experiments in the ion-cyclotron range of frequencies (ICRF) have not been conducted on DIII-D in the past few years. However, PPPL reported analysis of earlier observations of the chirping Alfvén instabilities that are sometimes observed during ICRF heating. The frequency spectrum and central electron temperature for a typical case are shown in Figure 6. By making use of detailed radial profiles of the safety factor q, taken from measurements with the Motional Stark Effect diagnostic on DIII-D, it has been possible to positively identify these instabilities as energetic-particle modes (EPM). When ICRF power is applied with a harmonic of the ion-cyclotron frequency near the center of the plasma, fast ions arising from neutral-beam injection can be accelerated to still higher energies and produce a strong population of very energetic ions. For cases with $q_0 < 1$, the resulting fast ion distribution inside the $q = 1$ surface can transiently delay the sawtooth crash, but it also generates Alfvén instabilities that transport fast ions radially outward, leading to a "monster" sawtooth crash. As was discussed above in the section on MHD stability, plasma toroidal rotation can be very effective in stabilizing global modes. Differential plasma rotation can also stabilize fine-scale modes. In neutral-beam-heated plasmas, the beams exert a torque that can drive toroidal rotation. Observations on Alcator C-Mod show that toroidal rotation can also arise in ICRF-heated plasmas, even though this heating process introduces negligible angular momentum.

To resolve this apparent conflict, PPPL has proposed and evaluated a mechanism for driving rotation in tokamak plasmas by minority ion-cyclotron heating. In the model, the slowing down of ion-cyclotron

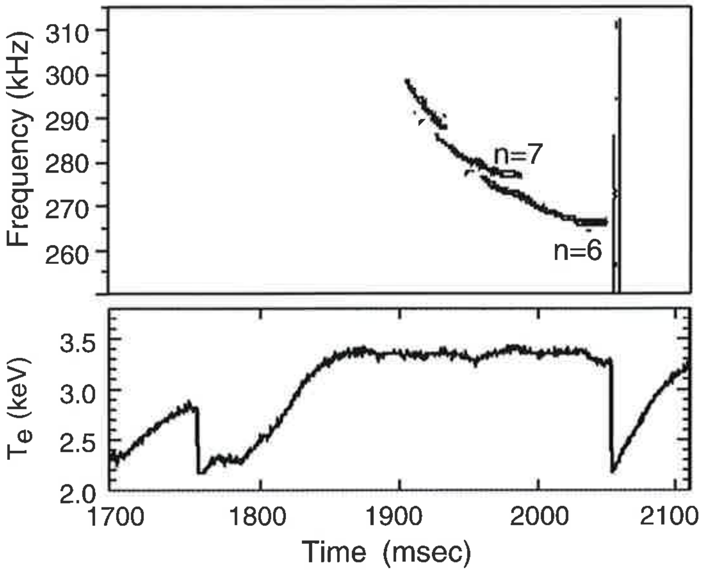


Figure 6. Alfvén frequency spectrum and "monster" sawtooth crash in DIII-D. The ICRF power was applied at 1.8 sec.

energized particles provides a torque density source that varies with minor radius. Calculations with the Monte-Carlo ORBIT code show that this mechanism can generate separated regions of positive and negative torque density, even though no net angular momentum is introduced. It is further assumed that angular momentum transport is governed by a diffusion equation, using the torque density source calculated with the ORBIT code together with an assumed boundary condition of zero toroidal velocity at the separatrix. The model predicts that the core of the plasma will rotate either in the same direction as the plasma current or the opposite direction, depending on the location of the ion-cyclotron resonance. For the assumed no-slip boundary condition, the sense of predicted axial rotation is co-current when the resonance lies on the low-field side of the magnetic axis, and overall agreement with experiment is good. When the resonance lies on the high-field side, the predicted rotation is in the opposite direction, and agreement with experiment is poorer. This may arise from uncertainty in the assumed surface boundary condition.

Confinement and Transport

PPPL continued its collaborative investigation aimed at increased understanding and control of internal transport barriers in DIII-D. Most of that activity during the past year was concentrated on expanding the operating space and improving the characterization and understanding of the recently discovered quiescent double barrier (QDB) operating regime. This mode of operation has attracted significant attention because it combines a core transport barrier with a high quality, edge-localized-mode-free high-confinement-mode edge barrier. It has demonstrated long-pulse, high-performance operation with control of plasma density and radiated power. Considerable progress was made during the past year in understanding details of QDB operation, and PPPL contributed to a number of important papers describing new experimental results and analysis.

PPPL is spearheading a new effort to perform similarity experiments on DIII-D and National Spherical Torus Experiment (NSTX). A preliminary outline of planned experiments has been prepared, and criteria for successful dimensionless and dimensional comparisons between the two devices have been developed.

Alcator C-Mod Collaborations

With its high magnetic field capability, high plasma density, and high heating power density, the Massachusetts Institute of Technology's (MIT) Alcator C-Mod tokamak offers a unique region of parameter space for fruitful scientific collaboration. Further improvements were made to the PPPL-supplied 4-strap ICRF antenna, and internal arcing and front surface plasma-radio-frequency interaction have been considerably reduced. Successful design reviews were held for the lower-hybrid launcher, and fabrication is in progress. The new gas-puff imaging diagnostic has revealed edge plasma turbulence information that is being compared to turbulence models. An upgrade to the microwave reflectometer diagnostic was designed that will allow the measurement of plasma fluctuations inward from the edge to the location of internal transport barriers. Transport model calculations have revealed that nonlinear simulations are needed to model the effect of drift-wave turbulence in high-confinement mode (H-mode) discharges, while gyrokinetic modeling to investigate microinstabilities in internal transport barrier experiments shows that the toroidal ion-temperature gradient mode is unstable outside the barrier, but stabilized at and within the barrier.

ICRF 4-strap Antenna Upgrades and Operational Support

The 4-strap ICRF antenna was designed and fabricated by PPPL, and due to machine port size constraints, was an attempt to achieve twice the power density of previous designs, as well as provide a directed wave launch for current drive in the plasma. Initial upgrades to reduce internal arcing to the Faraday shields, reduce possible radio-frequency (rf) leakage coupling to the plasma edge, reduce metallic impurity generation, and provide proper phasing were successful. Heating efficiency was now identical to that of the older Alcator C-Mod ICRF antennas up to the 2-MW power level, but plasma-rf interaction resulted in front surface arcing along magnetic field lines above this level. Internal high-voltage breakdown limited the maximum power to 2.8 MW, short of the 4-MW design goal. Inspection of the antenna's internal structure revealed repeated arcing in the striplines feeding the radio-frequency power to the antenna's radiating elements. These had been oriented with the radio-frequency electric field parallel to the tokamak's magnetic field to fit into the available space. The Alcator C-Mod discharges exhibit a high neutral edge pressure of 0.1-1 mTorr, which together with soft X-rays, hard ultraviolet light, and secondary particles, limited voltage holding in this region to about 15 kV/cm.

Joint MIT-PPPL work resulted in a reconfiguration of the striplines in a geometry that allowed the electric field to be oriented perpendicular to the magnetic field, along with further cleanup of the antenna structure. A boron-nitride septum was also added to the center of the Faraday shields to interrupt the plasma-facing-surface electric fields (Figure 7). These improvements eliminated the front surface arcing and internal stripline arcing, but arcing in one remaining location in the radiating element crossover, which also had the local electric field parallel to the magnetic field, limited the power to 3 MW. This is being corrected during the 2001-2002 machine opening.

The PPPL radio-frequency engineering group continued to work with Alcator

Figure 7. The 4-strap ion-cyclotron range of frequencies antenna with boron-nitride tiles and central septum.

C-Mod staff on transmitter maintenance and tuning through hands-on assistance at MIT.

ICRF Physics Results

The internal transport barrier (ITB) investigation was extended by using the two 2-strap ICRF antennas at 80 MHz to form the barrier through placement of the H-minority resonance off-axis, and then using the 4-strap antenna at a second frequency, 70 MHz, chosen to place its H-minority resonance inside the barrier for on-axis heating. The addition of the on-axis heating power arrests the usual ITB density rise, raises the plasma temperature, and reverses the central toroidal rotation. This result is shown in Figure 8.

Lower-hybrid Current-drive Project

Off-axis current drive in the Alcator C-Mod plasma through the launch of directed lower-hybrid waves is expected to modify the internal current density profile to allow exploration of the advanced tokamak regime of operation. This profile modification, together with high-power ICRF heating, has been modeled and should allow operation with a high (~70%) bootstrap current fraction, high plasma pressure (β_N ~ 3) and high con-

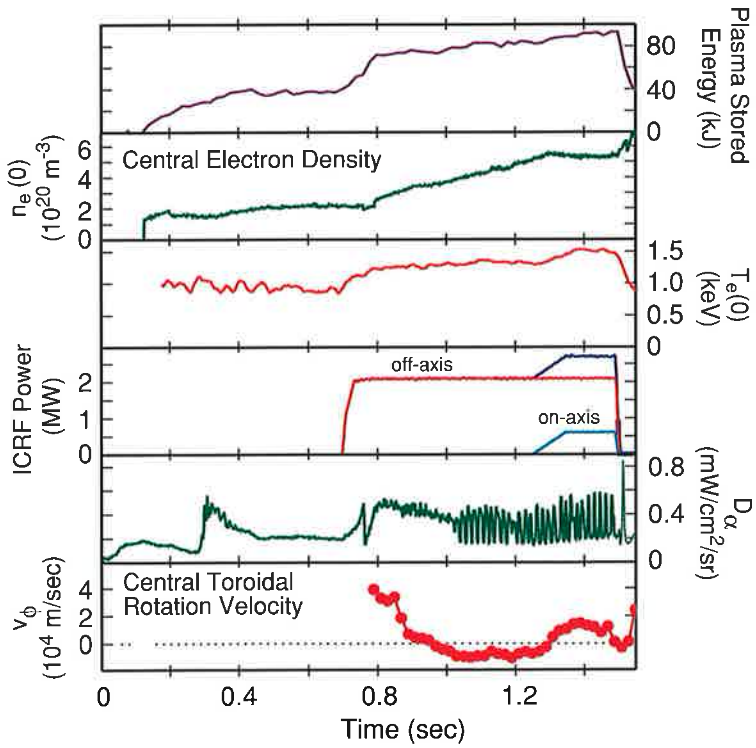


Figure 8. Internal transport barrier formation with second ICRF on-axis heating.

finement (H_H = 1-2) under pulse lengths approaching steady-state (T_{pulse} ~ 5 sec, L/R). Up to 4 MW of 4.6-GHz power will be launched from two antennas. PPPL is designing and fabricating the launchers, MIT is procuring and installing the power and control system. Successful Conceptual, Preliminary, and Final Design Reviews have been held, major procurements have been placed, and initial components are being received for prototype testing. The first launcher will be delivered to MIT in March, 2003, with the second launcher started immediately afterwards. The launcher, its support and drive mechanism, and its high-power phase shifters and splitters are shown in Figure 9.

Motional Stark Effect Diagnostic

Experiments to modify the current distribution inside the Alcator C-Mod plasma through the launch of directed ICRF or lower-hybrid waves depend crucially on the ability to measure the resulting current distribution. The Motional Stark Effect diagnostic relies on collisional excitation of fast neutral-beam atoms and a measurement of the polarization of the Stark split components. This gives the pitch of the local magnetic field, and extraction of the poloidal-field component leads to the current distribution. Optical component damage due to disruption shocks was initially repaired in 2000, further damage was repaired and a partial lens mount redesign was performed in 2001. Attempts to obtain good signals in 2001 were hampered by inadequate performance of the diagnostic neutral beam, which has since been discarded and is to be replaced by another beam. Optical component damage was observed once more, and a major redesign of lens and mirror mounting is in progress.

The limited measurements obtained so far were used to model the performance of this diagnostic with an improved beam, which then was compared with the measurements presently being performed on JET and planned for NSTX. This study indicates that the requirements for beam performance are more stringent than originally estimated in order to obtain sufficient magnetic field pitch-angle accuracy for an adequate determination of the inverted current density profiles expected from off-axis current drive. The 2002 experimental campaign with an improved beam is expected to provide more information on this issue.

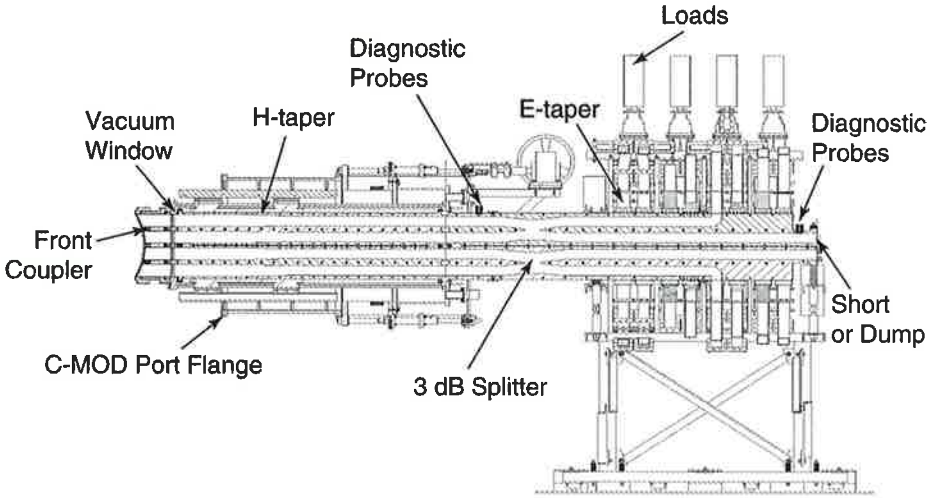


Figure 9. The lower-hybrid launcher under construction for Alcator C-Mod.

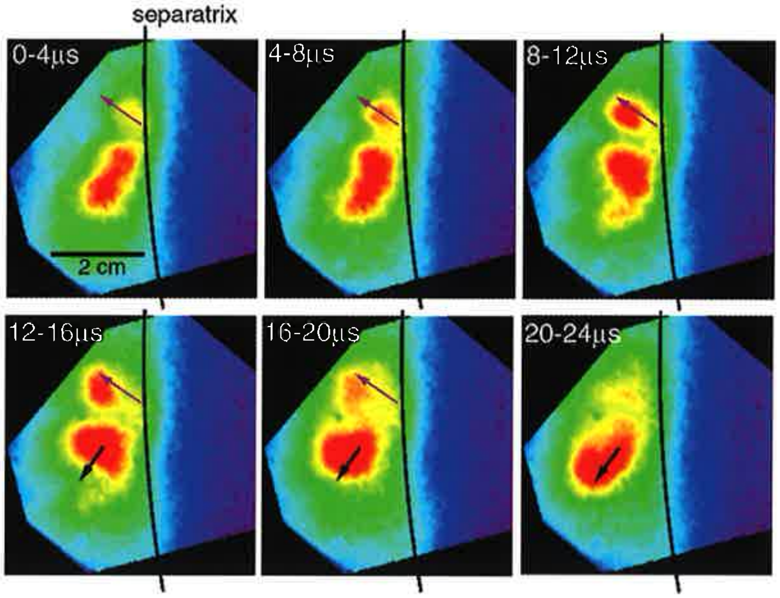


Figure 10. "Movie" of turbulence behavior in the Alcator C-Mod plasma edge.

Gas-Puff Imaging Diagnostic

The gas-puff imaging diagnostic has been improved this year with the addition of a fast-framing camera with high exposure rate capability on loan from Princeton Scientific Instruments. This diagnostic measures the spatial fluctuations in the visible light emission from a localized neutral gas puff near the outer wall, which are related to the local small-scale plasma density fluctuations. Two-dimensional images of this light emission are obtained over a 6 by 6 centimeters area centered around the magnetic separatrix near the outer limiter. Each frame has an exposure time of 4 µsec, with a repetition period of 4 µsec. A 6-frame "movie" of edge turbulence behavior for an edge-localized-mode-free H-mode discharge is shown in Figure 10.

These measurements are being compared to the nonlocal turbulence model of Hallatschek, Institut für Plasmaphysik (IPP), Garching, Germany, and the BOUT edge-turbulence model of Xu and Nevins, Lawrence Livermore National Laboratory. Comparison with the turbulence models is shown in Figure 11.

Microwave Reflectometer Diagnostic Upgrades

An upgrade to the Alcator C-Mod microwave reflectometer to higher frequency to allow density and fluctuation measurements further up the plasma-edge-density pedestal was delayed by vendor deliveries. The upgrade will be installed during the 2002 experimental campaign. A second upgrade was designed based on modeling of microwave propagation in Alcator C-Mod plasmas using a new one-dimensional full-wave code. Alcator C-Mod's high toroidal magnetic field and

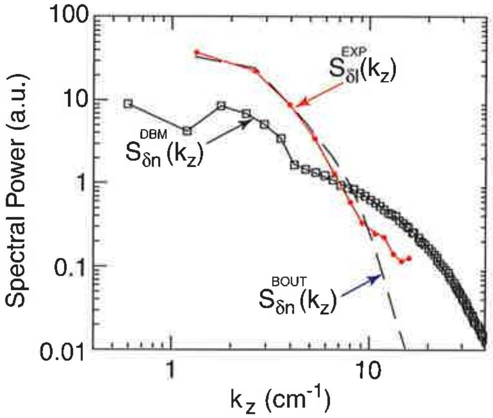


Figure 11. Comparison of edge-turbulence imaging with turbulence models.

operation in the over-dense regime (plasma frequency in core higher than electron-cyclotron frequency) places constraints on reflectometer core access. The addition of new channels operating at 150-180 GHz with Ordinary-mode polarization will allow the measurement of plasma fluctuations to the internal transport barrier, within which fluctuations are expected to be strongly reduced.

Wave-particle Modeling

Ion-cyclotron range of frequencies modeling code development continued. Results from the full-wave code TORIC (Brambilla, IPP, Garching) are compared with the results from the one-dimensional integral-wave code METS, the simpler dimensionality of which is thought to allow a more accurate description of the wave physics phenomena. ICRF experimental measurements are then analyzed using the ICRF codes in conjunction with the transport code TRANSP.

The one-dimensional integral-wave code METS has now been parallelized to run on a computer cluster. The resulting performance improvement allows an extension of this code to the lower-hybrid frequency domain, enabling numerical investigation of the physics of lower-hybrid wave propagation and absorption in Alcator C-Mod.

Transport Modeling

Alcator C-Mod's high magnetic field, high plasma density, high auxiliary heating power, and the upcoming ability to modify current and pressure profiles presents a unique area of parameter space in which to test plasma transport models. Suitable benchmarking of such models is necessary to establish their suitability for use in a predictive mode for future experiments.

Simulations of turbulent transport compare well with measurements in the core of typical H-mode plasmas in Alcator C-Mod. The PPPL two-species nonlinear gyrokinetic simulations of turbulent transport due to long wavelength ($k_{\perp}\rho_i < 1$) electrostatic drift-type instabilities employ a flux-tube domain based on a realistic noncircular magnetic geometry. These simulations with the GS2 code differ from previous work by including both trapped-electron effects and finite collisionality. While the Institute for Fusion Studies-Princeton Plasma Physics Laboratory (IFS-PPPL) model disagrees with measured temperatures in C-Mod, these new results can reconcile theory and experiment by means of a nonlinear upshift of the effective critical gradient. This upshift is not present in otherwise identical simulations with the collisionality lowered to a level that is typical of most other tokamaks. An upshift can be recovered at low collisionality if kinetic electron effects are ignored by using an adiabatic electron treatment — a simplification made in previous reports of such an upshift — but the transport in the region above the effective critical gradient is less stiff than with the more complete kinetic treatment at the actual C-Mod collisionality. These calculations indicate that it is important to include both collisions and nonadiabatic electron effects in simulations of turbulent transport in tokamaks.

Nonlinear simulation results are shown in Fig. 12 together with the conducted power predicted by the IFS-PPPL model, which predicts a power flow greatly exceeding the total heating power for values of the ratio of plasma radius to temperature scale length (R/L_T) near the measured range. In nonlinear simulations the heat transport rises slowly as the temperature gradient increases just above the linear stability threshold, but eventually it rises steeply — as in previous reports of a nonlinear upshift of the critical gradient.

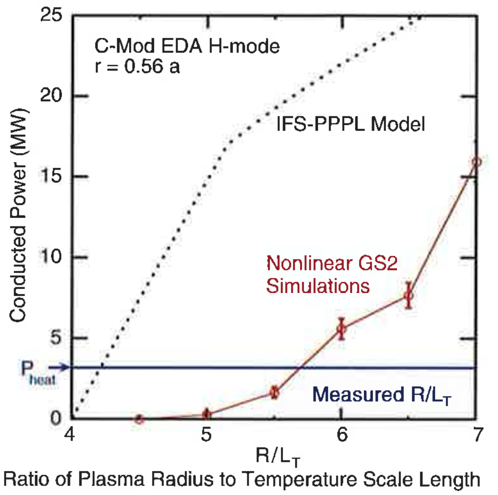


Figure 12. Simulations of turbulent energy transport using different models.

The upshift leads to consistency between the available heating power and the predicted transport for values of R/L$_T$ in the lower part of the measured range.

Gyrokinetic modeling has also been used to investigate the ion-temperature gradient, trapped-electron mode, and electron-temperature gradient microinstabilities in the initial phases of the Alcator C-Mod internal transport barrier experiments. The toroidal ion-temperature gradient mode was found to be unstable outside the barrier, but stabilized at and within the barrier. This is a complex situation and appears to be stabilized by the barrier's steep density profile and a relatively weak temperature gradient. The η_e parameter, which is the ratio of the scale lengths of the electron density and the electron temperatures, drops within the barrier and the trapped-electron mode is not strongly growing.

International Collaborations

JET Collaborations

The primary goal of the collaboration program on the Joint European Torus (JET) is to address burning plasma physics issues on a scale and in a parameter regime not accessible to domestic fusion facilities. In addition to its large size, JET is the only facility in the world capable of carrying out deuterium-tritium plasma physics experiments in the near term (1-5 years). Hence, continued involvement of U.S. scientists in the JET program is essential to maintain leadership in key topical areas of importance to a future burning plasma experiment. Highlights of the PPPL-JET collaboration during FY2001 are indicated below.

Transport Physics. The reliable prediction of the thermal transport in proposed next-step burning plasma experiments is one of the most critical tasks confronting the international scientific community. Because of its large size and its use of strong radio-frequency heating, JET provides an ideal opportunity for testing our predictive models against experiments. One of the significant achievements of the U.S.-JET collaboration this year was the detailed simulations of turbulence and anomalous transport in JET plasmas. In two important regimes, the edge-localized high-confinement mode and the optimized-shear mode of operation, local changes in the ion thermal transport correlate with the change in the ratio of the flow shear to the ion-temperature gradient mode linear growth rate. This work is expected to progress rapidly in FY2002 with the recent installation of a core reflectometer system designed to resolve turbulent activity in the core of the discharge.

Current Hole Regime. What happens when you drive sufficient off-axis current such that the central plasma current is driven towards negative values? This question was answered as part of the research performed with the new Motional Stark Effect (MSE) diagnostic on JET. The MSE system was developed as part of the PPPL-JET-UKAEA (United Kingdom Atomic Energy Agency) collaboration and is one of the most successful scientific activities shared with our European partners. The MSE diagnostic is a neutral-beam-based method for detecting the pitch of magnetic field lines in the plasma. From these measurements the plasma current can be derived. During plasma start-up in JET with strong lower-hybrid current drive (LHCD), it was noticed that the current in the core region of the discharge reached values as close to zero as the diagnostic could resolve. This initial observation was followed up by detailed analysis in which the absence of appreciable central current was confirmed despite predictions that a negative central current should have appeared. Figure 13 shows the radial profile of the plasma current in the plasma center computed using the MSE data. The dilemma was to resolve the apparent stability and high confinement of the discharge in the absence of appreciable central current. Current is essential both for macrostability and for plasma confinement, so understanding the physics of this regime is of great value to our research.

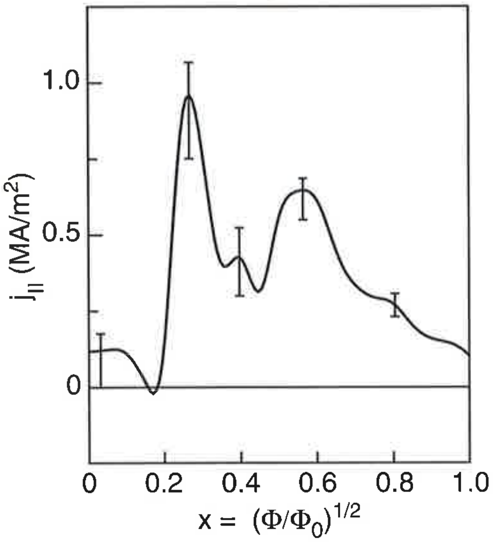


Figure 13. The radial profile of the parallel current density profile, $j_{||}(x)$*, showing near-zero core current density with a steep positive gradient to a narrow peak at* $x = 0.25$*.*

Simulation of the plasma current evolution in the JET device was performed using the M3D code developed at PPPL. The code is a state-of-the-art tool for understanding the nonlinear dynamics of the plasma induced by large-scale magnetic instabilities. The simulation indicates a mechanism for preventing the current from decreasing below zero near the central region of the plasma. Figure 14 illustrates the cyclic nature of the current evolution predicted by the M3D code simulation. The challenge for theory is to simulate the current evolution for the case of nonaxisymmetric modes. For experiment, detailed measurements are required to identify evidence for a cyclic oscillation of the current indicative of an MHD mechanism responsible for sustaining the current hole.

Fast-particle Research. A key element of the JET collaboration is the understanding of fast-ion behavior in the plasma. In a deuterium-tritium (D-T) power plant, highly energetic alpha particles will be produced and these will be the dominant heating source for the plasma. It is therefore essential to determine if the alpha particles produced by the D-T reactions will be confined for the time required to impart their energy to the plasma. JET has an highly flexible radio-frequency-heating system which allows for the generation of fast ions. These experiments can be used to assess fast-ion confinement before a D-T experiment is performed at some later date.

The neutral particle charge-exchange analyzer (NPA) is used in JET to measure the fluxes of fast particles generated by radio-frequency heating. From the flux of fast ions, the population of fast ions in the core of the discharge can be inferred. A key topic for investigation of fast ions in JET is the effect of central magnetic oscillations on their confinement. The NPA

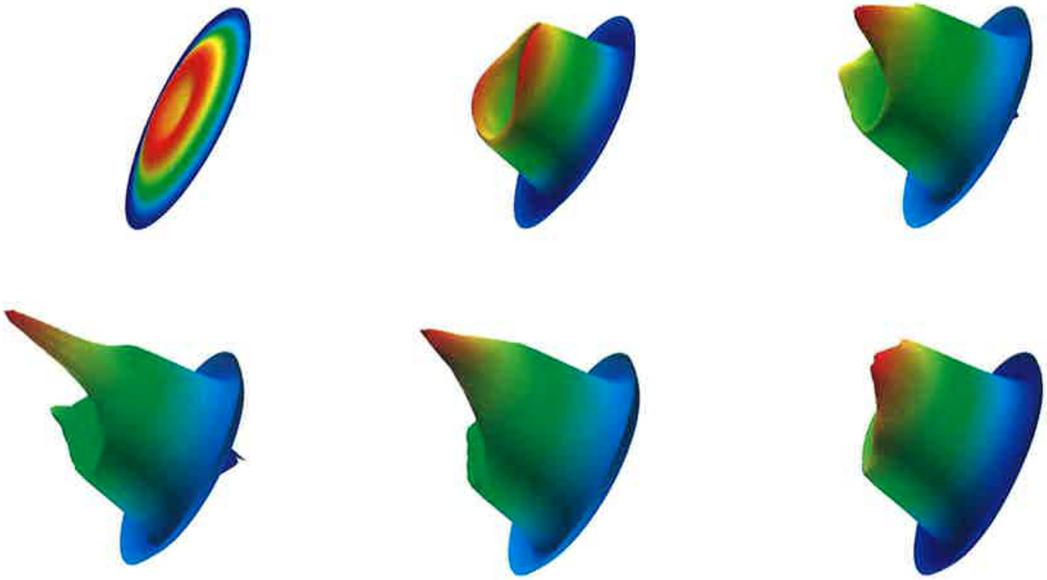


Figure 14. Cyclic evolution of the plasma current during the axisymmetric relaxation phenomenon predicted by the M3D code simulation.

was used to quantify the effect of an m = 2/n = 1 resonant magnetic oscillation on the confinement of fast ions. Figure 15 shows the observed flux of fast ions to the detector as a function of the central current density or magnetic safety factor of the plasma. This trend of increasing flux with decreasing central current in the presence of a global magnetic oscillation in the plasma was first predicted theoretically with a model of fast-ion resonant transport formulate at PPPL.

Tritium Retention on Carbon Tiles. A novel technique to detritiate plasma-facing components and to study high-heat flux issues on plasma-facing tiles was recently demonstrated at PPPL. The work was carried out in collaboration with international partners at the United Kingdom Atomic Energy Agency and the Tritium Laboratory Karlsruhe in Germany. The primary objective of the work is to develop methods to remove excess tritium trapped by the carbon in the tiles. This is an area of great importance in the investigation of the existing tiles extracted from JET after the first set of D-T experiments.

A method to extract tritium from the carbon deposits without removing the carbon from the tile was developed at PPPL. The method, based on a scanning neodymium laser, has successfully removed up

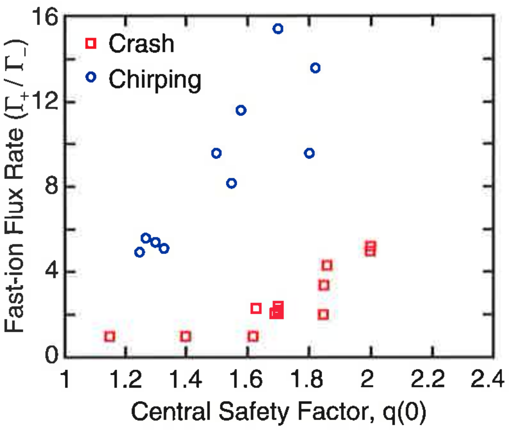


Figure 15. Neutral particle analyzer (NPA) data. Plotted is the ratio of fast-ion flux before and after the magnetic instability versus the central safety factor for a set of JET plasma discharges. The magnetic instability has a dominant m = 2, n = 1 component and resembles a sawtooth crash at high safety factor. Also shown is the ratio of the NPA-measured fast-ion flux before and after the onset of a long-lived frequency chirping magnetic island.

to 87% of tritium retained in the Tokamak Fusion Test Reactor and JET co-deposits, and the system is attractive for a next-step device. It also has provided an opportunity to study high-heat flux interactions, such as brittle destruction and dust generation, on a microscopic scale with tokamak-generated materials. Figure 16 displays a JET tile sample before and after laser treatment, where 87% of the tritium was removed using this technique. Plans are being made for the possible installation and testing of this tritium removal system in-situ on JET during the 2004 machine opening.

JT-60U Collaboration

The collaboration with the Japan Atomic Energy Research Agency (JAERI) on the JT-60U tokamak has produced significant new results this year with the continued analysis and interpretation of turbulence measurements in the internal transport barrier of reverse magnetic shear plasma and with the investigation of fast-ion phenomena. The key features of the JT-60U device for our collaboration program are the capability to simulate fast-ion regimes relevant to next-step burning plasmas and the capability to develop a range of confinement regimes with selective control over the rotation of the plasma. In addition, a strong technology development effort in negative-ion neutral beams continued with great success in improving the understanding and performance of these beams.

Negative Ion Beams. A very important component of the collaboration between PPPL and JAERI has been the improvement in performance of the ion sources of the negative-ion-based neutral beam on JT-60U. This year, some of the work concentrated on the task of improving the spatial uniformity of the plasma illuminating the plasma grid. Coupled with other improvements made in previous years, the best deuterium acceleration efficiency has increased from 55% to 77%. The reliability of the ion sources has increased as a result of less loss of beam in the accelerator. This has resulted in many more 1.5 to 2 second pulses at power levels sufficient for current-drive experiments and for beam-ion-driven toroidal Alfvén eigenmode experiments in the JT-60U tokamak.

A significant portion of this year's work involved innovations to improve the capabilities of the next generation of negative-ion sources. JAERI has fabricated new molybdenum plasma grid sections according to PPPL designs for test-stand evaluation. JAERI is also implementing control

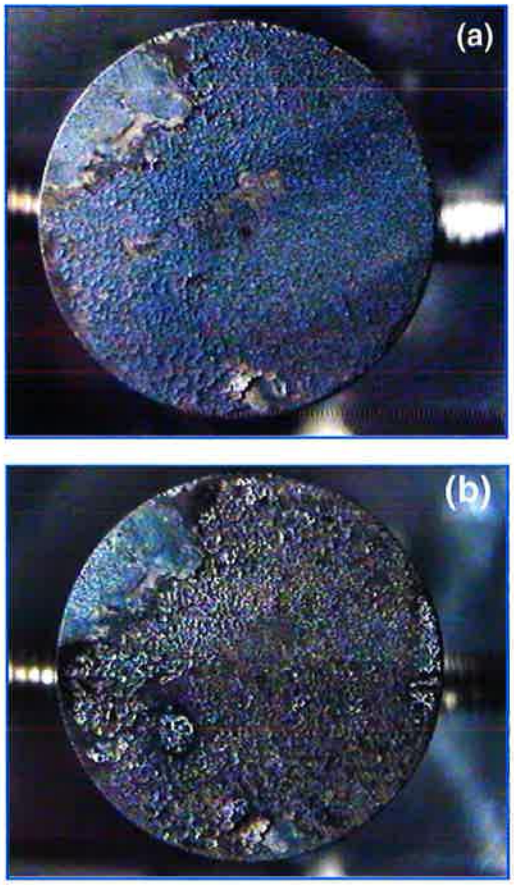


Figure 16. A JET tile sample from poloidal limiter 4B before (a) and after (b) 87% of the tritium was removed by laser scanning.

system changes suggested by PPPL to improve the response of the ion sources to high-voltage breakdowns. This should make it easier to condition the sources to higher power and to obtain beam pulses of extended length. This latter improvement will be available for the May-June 2002 experimental run of JT-60U.

Fast-ion Physics. A varied spectrum of energetic particle modes have been observed in JT-60U driven by intense negative-ion beams ($E_b \leq 400$ keV) which simulate passing alpha particles in a deuterium-tritium plasma. Reactor-relevant fast-ion parameters have been achieved, such as the ion velocity exceeding the Alfvén velocity and a fast-ion concentration of the order of 10% of the background plasma. Under conditions relevant to advanced confinement regimes where the central plasma current is significantly reduced, resulting in weak or reverse magnetic shear, very strong mode activity has been observed and loss of energetic particles seen. Theoretical developments at the Princeton Plasma Physics Laboratory are helping to explain the nature of these modes and to understand the mechanism for particle redistribution.

Transport Physics. Dramatic advances have taken place in the last year in the interpretation and modeling of reflectometer correlation measurements in the internal transport barrier of JT-60U plasmas. As part of PPPL's effort toward integrated modeling of diagnostics and turbulence, a highly efficient two-dimensional algorithm has been produced for the purpose of modeling and interpreting the complex reflection patterns observed in the experiment.

Figure 17 shows a computer simulation of microwaves injected into a plasma and reflecting from intense density fluctuations. The simulation was generated using the global gyrokinetic GTC code developed at PPPL. The effective integration of the turbulence and diagnostic simulation capability has the potential to revolutionize the way experiments are designed and data is interpreted.

Figure 18 illustrates the inferred density fluctuation profiles from microwave reflections before and after formation of

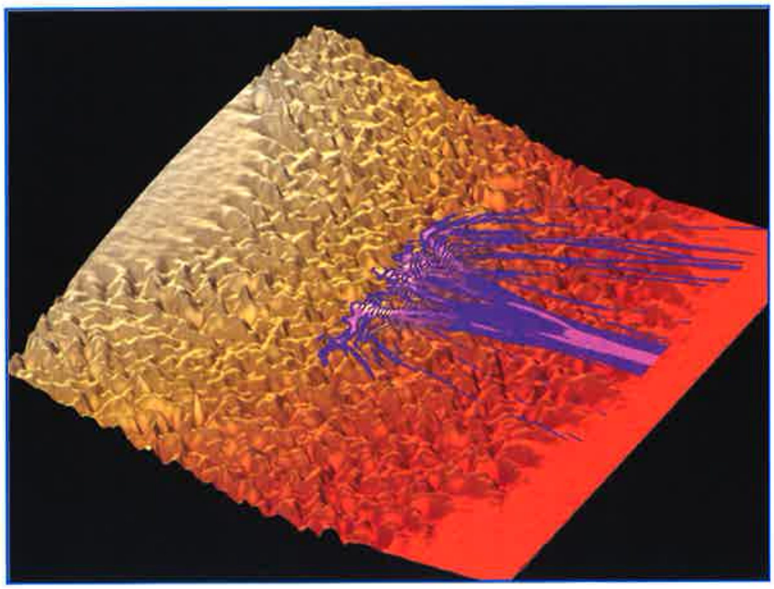


Figure 17. Simulation of the reflection of a microwave beam (purple) from intense density fluctuations generated using the GTC code.

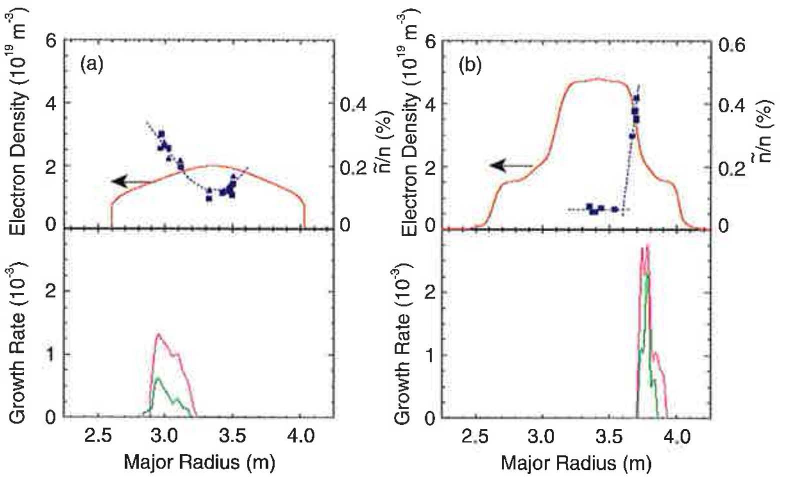


Figure 18. Profile of the inferred density fluctuation level in the target plasma (a) and in the internal transport barrier (b) compared to the profile of the maximum linear growth rate calculated using the FULL code. The linear growth rate is displayed without (blue) and with (red) the effect of the E × B flow shear. The rapid rise in the fluctuation level in the transport barrier is qualitatively consistent with the rapid rise of the linear growth rate.

the internal transport barrier in JT-60U. These profiles were obtained from the two-dimensional full-wave simulation of the data using randomly generated data. The fluctuation profiles are compared to the linear growth rate of microinstabilities calculated using the FULL code. Further work will focus on the simulation of the reflectometer data in JT-60U geometry using the GTC code.

KSTAR Collaboration

The Korea Superconducting Tokamak Advanced Research (KSTAR) tokamak in Korea will be the world's first tokamak to be fully superconducting. The proposal to establish KSTAR as an international user facility for the advancement of steady-state tokamak physics is a very exciting prospect for the world fusion program. The device will begin operation in late 2005, and active efforts are being made to involve the international community early in the KSTAR program to accelerate the development of the project and its attainment of peak performance parameters.

As part of the U.S. effort in steady-state fusion research, significant effort is being invested in collaboration with the KSTAR project team to resolve key technical and design issues required for long-pulse physics operation. In particular, strong effort is going into the design of radio-frequency heating and diagnostic cassettes.

The PPPL-KSTAR team carried out an engineering design of the diagnostic interface cassette for port-M and an advanced-concept design of the cassette for port-J in KSTAR. These two ports are primarily allocated to spectroscopic diagnostics. PPPL engineers and physicists worked with Korea Basic Science Institute scientists to jointly identify requirements for key spectroscopic diagnostics to be installed at bay-J and bay-M. Engineers at PPPL provided a concept for the integration of these diagnostic instruments into the cassette. Engineering drawings were completed at PPPL for two of the diagnostic cassettes, and many issues regarding the machine diagnostic interface were addressed.

Figure 19 shows a computer-aided design, three-dimensional drawing of one of the diagnostic cassettes (Bay-J). The drawing shows a number of spectroscopic diagnostics designed into the port. Fabrication should begin on these cassettes in the next year.

National Institute of Fusion Science

The most important accomplishment of the negative-ion source collaboration between the Princeton Plasma Physics Laboratory and the National Institute of Fusion Science in Japan this year was a preliminary measurement of the beam velocity spectrum. This preliminary data suggests a substantial spread in the beam energy due to premature neutralization of the negative ions during acceleration. If this can be improved, the amount of usable beam power should increase.

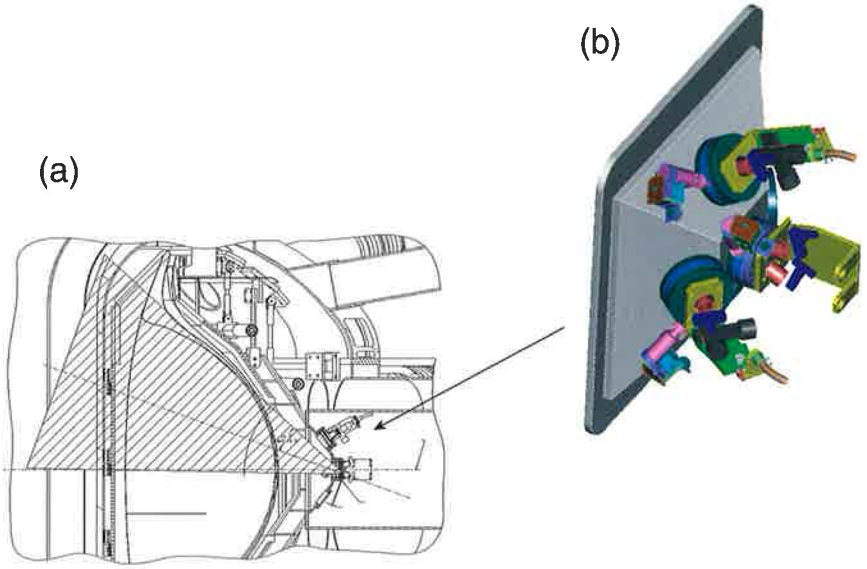


Figure 19. (a) Cross-sectional view of bay-J cassette with a view of the plasma and (b) a close-up view of the outside side of the bay-J port showing access for three spectroscopic diagnostics.

Space Plasma Physics

The Earth's magnetosphere and solar atmosphere have been the principal areas of research in space plasma physics at the Princeton Plasma Physics Laboratory. The goal of research in space physics is to understand solar activity and how the solar activity couples to the magnetosphere. This report focuses on recent progress in the areas of solar activity and solar wind and magnetosphere coupling.

3-D Force-free Fields in Multiple Flux Systems and Energetics of Coronal Mass Ejections

In typical observations of coronal mass ejections (CMEs), a magnetic structure of a helmet-shaped closed configuration bulges out and eventually opens up. This transition of field configuration is considered to occur spontaneously because the timescale of a CME (hours to a day) is much shorter than the timescale of CME energy buildup (days to a month). This observation requires that the pre-eruption closed magnetic field should have more energy than the post-eruption open field. In force-free fields, however, such a possibility is denied by the Aly-Sturrock theorem. The theorem states that the maximum energy state of force-free fields with a given boundary normal field distribution is the open field. Here it is noted that the proof of the theorem is based on the assumption that the maximum energy state, which must be a stationary state, exists in the set of closed force-free fields and the open field with the same boundary normal field distribution. Under this assumption, Aly and Sturrock proved that the maximum energy state is the open field because there are two sorts of stationary states, potential fields and the open field, and because the open field has higher energy than potential fields. However, the assumption cannot be taken for granted. The force-free state corresponding to the least upperbound of energy may not exist in the set of admissible force-free fields. In such cases, the Aly-Sturrock theorem is not valid.

To tackle this problem and resolve the CME field opening paradox, force-free fields containing tangential discontinuities in multiple flux systems were constructed and studied. These force-free fields can be generated from a potential field by footpoint motions. Some of these force-free fields are found to have more magnetic energy than the corresponding open fields with the same boundary normal field distribution.

The constructed force-free configurations share several interesting features with observations made in the pre-eruption stage. Satellite X-ray observations reveal the appearance of an S- or inverse-S-shaped bundle of coronal loops before solar eruption. This structure is called a sigmoid (Figure 1). The image of a flux surface of our force-free field solution projected on the solar surface takes an S shape and resembles the X-ray images of sigmoids (Figure 2). If the emission from a sigmoid is due to the heating by magnetic reconnection in the preeruption

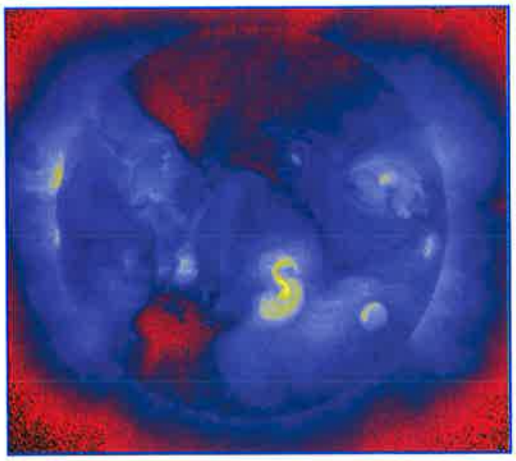


Figure 1. Soft X-ray observation of the sun by Satellite Yohkoh. The S-shaped emission structure near the center of the disk is a sigmoid. Sigmoids are good precursors of subsequent solar eruptions.

stage, the resulting change in field topology is regarded to play an important role in the subsequent solar eruption.

Ion Heating and Diffusion at the Magnetopause

Understanding the transfer of energy, mass, and momentum across the magnetopause boundary is one of the major issues in magnetospheric physics. Observations in the magnetosheath and magnetopause indicate that plasma that leaks across the boundary often have distinctive particle distributions indicative of acceleration processes. For example, electron distributions in the boundary layer are often found to be accelerated in the direction parallel to the magnetic field, while ions in the sheath transition layer and boundary layers often exhibit significant temperature anisotropy with the perpendicular temperature greater than the parallel temperature.

An unusual low-energy component of the ion distribution significantly heated in the perpendicular direction was recently observed by WIND/3DP in the low-latitude boundary layer and magnetosheath

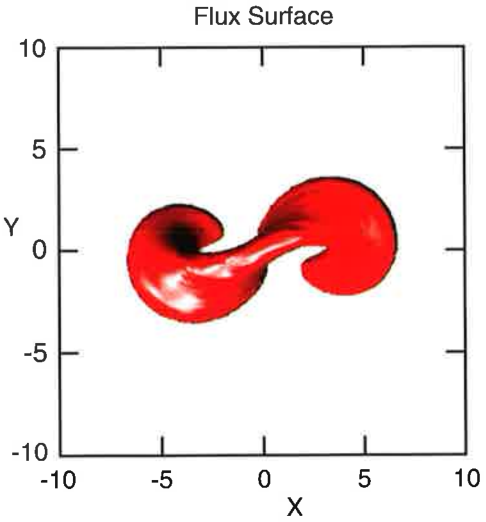


Figure 2. A flux surface in the interwinding force-free flux tube solution which has more energy than the open field. The projected image onto the solar surface very much resembles a sigmoid.

as shown in Figure 3. Similar ion distributions were also detected by the POLAR satellite in the magnetosheath near the high-latitude dayside magnetopause. These unusual ion features seem to be observed in the absence of the electron signatures typically associated with reconnection suggesting that they may result from wave-particle interaction.

In both observations, particles appeared to have undergone adiabatic streaming from a stronger magnetic field region with heating occurring near the magnetopause as deduced from the mirror ratios. The low-energy ions appear to have been heated perpendicular to the magnetic field and in some events the core of the distribution appears to be flattened as seen in Figure 3. Indeed, a flattening of the low-energy component of the ion distribution in the inner boundary layer as compared with the magnetosheath is typically observed during magnetopause crossings, suggesting that there is a source of heating close to the magnetopause boundary.

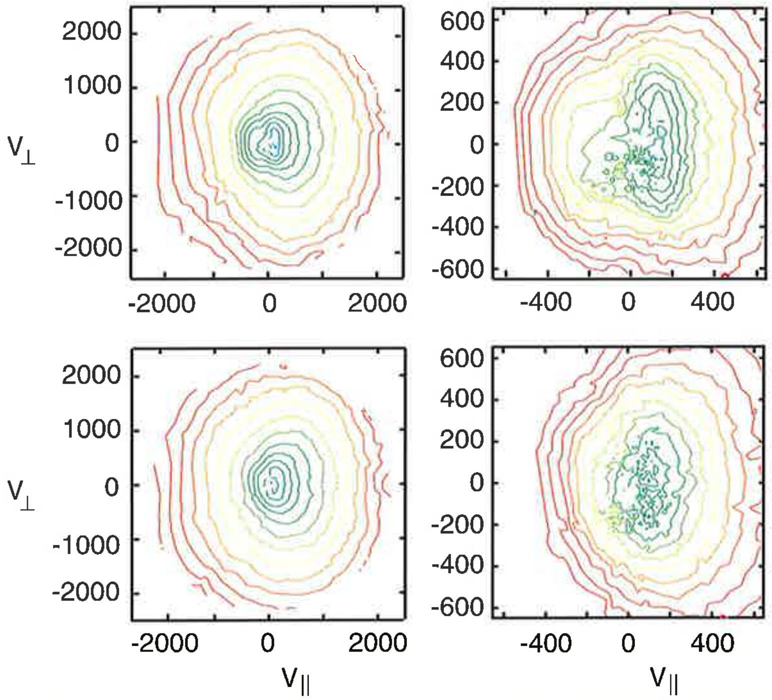


Figure 3. Ion distribution near the magnetopause measured by the WIND/3DP instrument (9/16/1995 at 14:14 universal time — courtesy M. Wilber, G. Park, and R. Lin). Contours represent the constant value of the distribution function at logarithmic increments. The distribution is a function of perpendicular and parallel velocity measured in kilometers per second. The upper left panel is the measured distribution for all ions detected by the plasma instrument at 14:14 universal time. The upper right panel shows the low-energy part of the distribution at that same time. Notice that the low-energy core of the distribution is heated predominately in the perpendicular direction. The low-energy distribution is flatter than the more energetic part of the distribution. The lower panels show the distribution function at a later time. The same features can also be seen at that time.

Recently, it has been shown that magnetic field fluctuations at the magnetopause are likely the result of a mode-conversion process which focuses wave energy at the magnetopause into large-amplitude kinetic Alfvén waves.

The observed waves are highly nonlinear with magnetic wave fluctuations, δB, as large as the global magnetic field at the magnetopause, B. Such waves not only are consistent with parallel electron heating, but they also can produce observed ion heating. To understand the process, particle motion was observed in a large amplitude kinetic Alfvén wave with wavelength characteristic of the mode-conversion process. The study consisted of a sequence of Poincaré sections taken at different wave amplitudes which demonstrate the onset of stochasticity. For sufficiently large wave amplitude, the particle orbits become stochastic, as shown in Figures 4 and 5.

Figure 4 shows the Poincaré section for $\delta B/B = 0.05$ with $\omega/\Omega_{ci} = 0.2$, where ω is the wave frequency and Ω_{ci} is the ion gyrofrequency. The magnetic moment μ (normalized to the magnetic moment obtained using the initial ion-thermal velocity) is plotted versus the wave phase, $\psi = k \cdot x - \omega t$.

The period-five island chain associated with a nonlinear wave and gyroperiod resonance is readily visible. Above

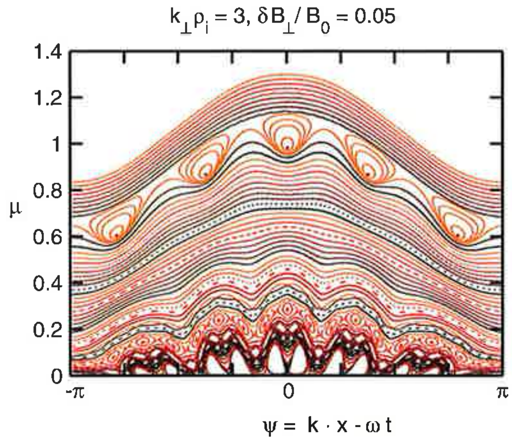


Figure 4. Phase-space plot of magnetic moment, μ, versus wave phase, ψ = k·x-ωt, in the presence of a kinetic Alfvén wave. The amplitude is just below the threshold condition for stochastic behavior.

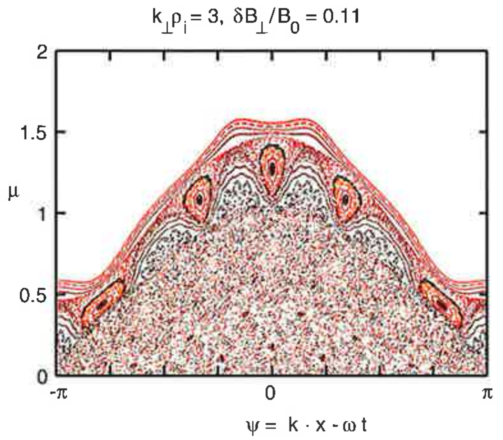


Figure 5. Phase-space plot when the amplitude is well above the threshold condition. For these conditions, a Maxwellian distribution develops core flattening in about 20 ion-cyclotron periods.

that chain, the high-energy particles do not show any structure related to gyromotion and simply float up and down in the wave. Other islands chains have also appeared at lower energies. The obvious island periods are in the sequence: 26, 21, 58, 16, 27, and so forth. Islands in the period 16 and 21 chains have just begun to overlap.

A slight increase in wave amplitude allows the phase-space islands to merge and regions of stochastic orbits to appear. Low-energy particles can wander to higher energies, leading to heating of the core of the distribution. For larger wave amplitude, δB/B = 0.11, the entire phase space, below a bounding energy, becomes globally stochastic as shown in Figure 5. The heating that occurs is anisotropic with perpendicular temperature greater than parallel temperature. Because low-frequency waves at the magnetopause often are observed with δB/B = 0.1 or larger, there would be sufficient nonlinearity to produce ion heating and stochastic particle behavior.

These results demonstrated: (1) stochastic ion heating can result through nonlinear coupling between low-frequency waves and cyclotron motion, (2) ions can be heated transverse to the magnetic field leading to temperature anisotropy, with perpendicular temperature greater than parallel temperature, as observed at the magnetopause, and (3) the stochastic process flattens the core of the distribution function as is observed near the magnetopause.

Basic and Applied Physics Experiments

The Princeton Plasma Physics Laboratory (PPPL) has an active program in Basic and Applied Plasma Physics which supports the Laboratory's mission to create new knowledge in plasma science and to use this knowledge to develop new plasma technologies. These projects generally consist of small experiments focused on a specific topic of interest. All of these projects have strong graduate and undergraduate participation, and many of them have ties to work being done in the PPPL Theory Department.

Some of these basic physics experiments lie at the frontiers of fusion research. For example, the novel Field-reversed Configuration experiment is designed to create a remarkably efficient magnetic confinement system which could eventually be used to burn advanced fusion fuels, while our heavy ion fusion research aims to create and focus extremely high intensity ion beams onto an inertial fusion target. These and all the other small experiments are strongly coupled to plasma physics research at other national laboratories and universities.

These experiments also have an important role in creating links between plasma physics and other areas of science and technology. For example, our work on high energy accelerators is directly applicable to future experiments in high energy physics, and our Hall Thruster Experiment may develop into a technology which could improve satellite communication systems.

Hall Thruster Experiment

A 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 twenty years, Russia has placed about 100 Hall Thrusters in orbit. However, the vast majority of satellites worldwide have relied on chemical thrusters and, to a lesser extent, ion thrusters.

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 has a medium-size Hall Thruster (Figures 1 and 2), which consumes several hundred watts of power, making it suitable for a satellite with a mass in the range of a few hundred kilograms.

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

Figure 1. The PPPL Hall Thruster team and collaborators standing inside the Hall Thruster vacuum vessel. The experiment was significantly upgraded in FY2001.

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 3). The ions, too heavy to be affected by the field, continue their journey through the virtual cathode. The azimuthal flow of negative electrical charges results in a net force on the thruster in a direction opposite that of the ion flow.

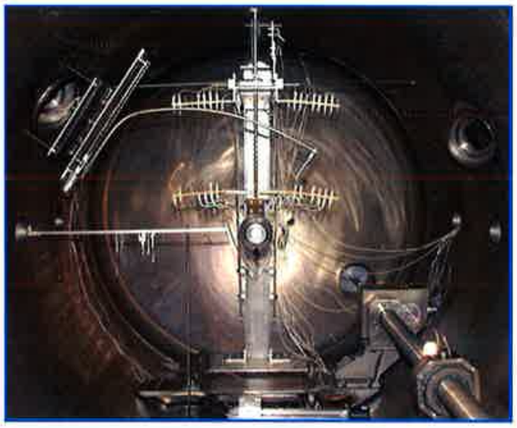


Figure 2. Interior view of PPPL Hall Thruster.

The PPPL Experiment

During FY1999, a Hall Thruster Experiment was established at PPPL, owing its intellectual origin to a collaborative theoretical research effort with the Center for Technological Innovation at Holon, Israel. The first theoretical studies, funded by the U.S. Air Force Office of Scientific Research, identified improvements that might make Hall Thrusters more attractive for commercial and military applications. The project acquired broader support after showing state-of-the-art thruster operation, including improvements such as decreased plasma plume. During FY2001, the Defense Advanced Research Projects Agency, the New Jersey Commis-

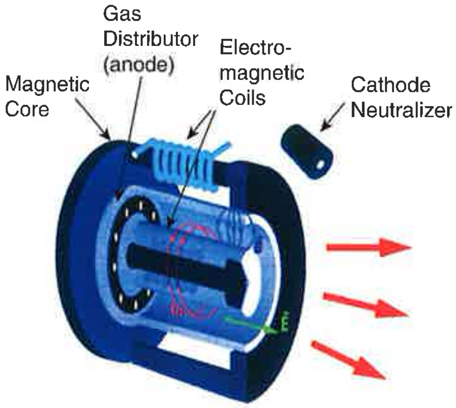


Figure 3. The Hall Thruster concept.

sion on Science and Technology, and the U.S. Department of Energy all funded scientific or technological projects on the PPPL Hall Thruster Facility.

Recent Results

Physicists at PPPL are developing improved plasma thrusters in both higher and lower power ranges as compared to the initial studies. Particularly interesting is a new cylindrical Hall Thruster, that operates as a microthruster with power outputs in the 100-watt range, useful for very small satellites with masses of 50 to 100 kilograms. One can envision a large satellite disbursing hundreds of smaller ones for the exploration of a planet or as a spaced-based radar array. Recent results at PPPL show efficiencies in the range of 30% for 100-watt operation, which surpasses present-day technology in this regime.

Previously, when the PPPL Hall Thruster operated at 900 watts it had an efficiency comparable to state-of-the-art thrusters. By segmenting the thruster and holding each segment at a specific electric potential, researchers were able to control exactly where the voltage drop occurred along the length of the thruster. Using these segmented electrodes in a specific way decreased the plume divergence. In FY2001, the Hall Thruster Facility was significantly upgraded by the addition of cyropanels that can maintain a suitable vacuum at powers greater than one kilowatt. Now, with the upgraded vacuum facility, PPPL researchers are poised to see if results using segmented electrodes can be extrapolated to high power.

Magnetic Nozzle Experiment

The Magnetic Nozzle Experiment (MNX) studies the properties 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. During FY2001 progress was made in two areas: (1) analyzing the spectrum of visible light emitted by helium plasmas formed by helicon waves and (2) measuring the transverse metastable argon ion temperature in a helicon argon plasma.

Analysis of the data produced in the first experiment was performed in collaboration with Dr. V. Sevastyanenko. The nonequilibrium plasma state was modeled using a multi-temperature approximation with quasi-Boltzmann distributions for the translational and excitation temperatures of each species. The system of equations was solved iteratively to find the population of excited states and the emitted lines. Several low-n spectral lines in both singlet and triplet series did not fit Boltzmann distributions, implying inverted populations.

Through a collaboration with Professor E. Scime and Dr. R. Boivin of West Virginia University, laser-induced-fluorescence measurements of metastable argon ion temperatures were made with a compact, tunable, 10-mW solid-state-diode laser system. Experiments were performed in the classic "blue core" helicon mode, as well as in a broader, more diffuse mode of comparable density. The transverse temperature of metastable argon ions ranged from 0.15 to 0.3 eV, increasing at higher powers and lower neutral pressures. Figure 4 shows the laser-induced-fluorescence spectrum obtained with a quarter-wave plate filter used to separate the π from the σ components. Figure 5 shows the dependence of ion temperature on input helicon power. The apparatus is now being reconfigured to allow measurements of parallel temperature and flow velocity as the ions exit the nozzle.

FRC/RMF Experiment

The Field-reversed Configuration (FRC) Rotating Magnetic Field (RMF) experiment is designed to study the effects of odd-parity rotating magnetic fields on magnetized plasmas. The first motivation for the experiment was the prediction that odd-parity RMFs would maintain the closed field lines of the field-reversed configuration and hence would improve energy confinement compared to conventional (even-parity) rotamaks. The second motivation was the theoretical prediction that RMF in the ion-cyclotron range of frequencies (ICRF) would heat ions to thermonuclear energies by a stochastic heating process.

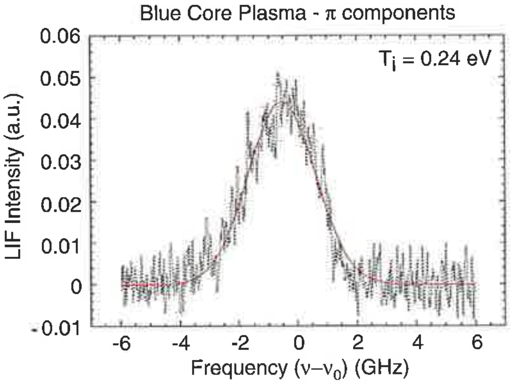


Figure 4. Laser-induced fluorescence (LIF) intensity versus frequency of the π component. The pump-laser's central wavelength was 668.61 nm.

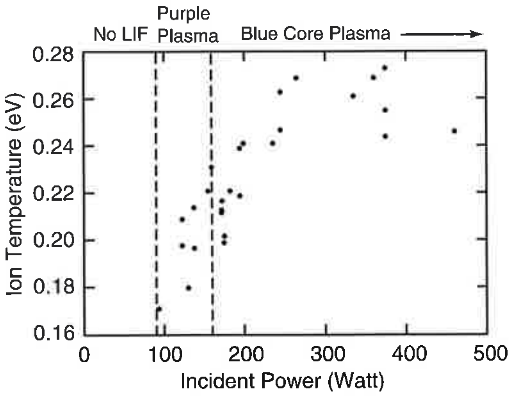


Figure 5. Transverse temperature of metastable argone ions versus helicon power.

In collaboration with A.H. Glasser (Los Alamos National Laboratory), theoretical studies continued on odd-parity RMF effects using Hamiltonian techniques with the surprising result that electrons, too, would be effectively heated by RMF in the ICRF. Again, the energy gain occurred stochastically, though punctuated by periodic spikes in energy as the electrons accelerated then decelerated in the azimuthal direction while very close to the O-point null line, see Figure 6. Even more surprising was the fact that the RMF caused an on-axis field-supporting current, independent of the direction of RMF rotation.

Calculation of Lyapunov exponents proved that simulating a single-particle trajectory for long time periods was equivalent to producing an ensemble average of many particle trajectories.

Liquid Metal Experiment

A small-scale experiment is underway at PPPL to study the fundamental physics of MHD effects on surface waves and turbulence in liquid metal. MHD turbulence has been regarded as an essential element of many intriguing phenomena observed in space and laboratory plasmas, and it has been a primary subject of basic

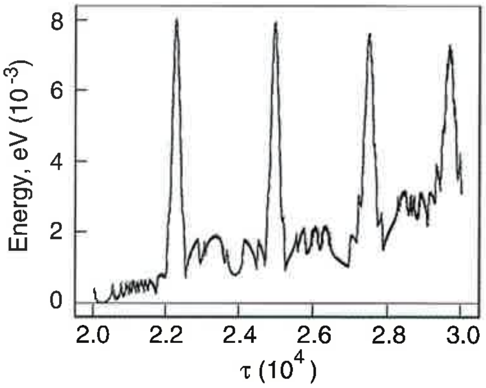


Figure 6. Electron energy as a function of time, in units of electron cyclotron period. Odd-parity rotating magnetic fields generate an azimuthal electric field which accelerates and decelerates electrons near the null line, producing energy spikes. Because of the stochastic nature of the trajectories. a secular heating also occurs, as evidenced by the rise in the baseline energy.

plasma physics research. Recent interests in the application of liquid metal in fusion devices also add new demands for a better understanding of MHD physics of electrically conducting fluids. The PPPL experiment focuses on MHD effects on fluid turbulence and surface waves using liquid gallium, which can be well approximated by MHD models. Three basic physics issues are being addressed: (1) when and how MHD effects modify surface stability, either in linear regimes or nonlinear regimes such as solitary waves; (2) when and how MHD effects modify a free-surface flow, such as by surface deformation; (3) when and how MHD effects modify thermal convection.

In neutral fluids such as water, depending on wavelength, gravity force and surface tension force are dominant restoring forces for a surface wave. When a liquid metal is subjected to a magnetic and/or electric field, the Lorentz force adds to the wave complexity, leading to possible new instabilities. In our experiment, an external wave driver with varying frequency and amplitude is used to excite surface waves in the liquid metal. Reference cases are established using water and gallium without magnetic and electric fields. MHD effects can be examined by imposing an external magnetic field and/or electric current with varying amplitudes and angles with respect to wave propagation direction. A laser reflection system combined with a gated ICCD camera is used to measure dispersion relation and wave amplitudes. It is found that the driven waves are not affected by a magnetic field applied perpendicular to the wave propagation, while the waves are damped with a parallel magnetic field. An example data is shown in Figure 7, where the wave amplitude is suppressed by parallel magnetic field. A linear theory, which takes into account MHD effects, predicts magnetic damping of surface waves, in good agreements with the experimental results.

Interfacial stability is also relevant to the mixing processes in many astrophysical phenomena. When a flowing layer of light material sits on top of a layer of heavy

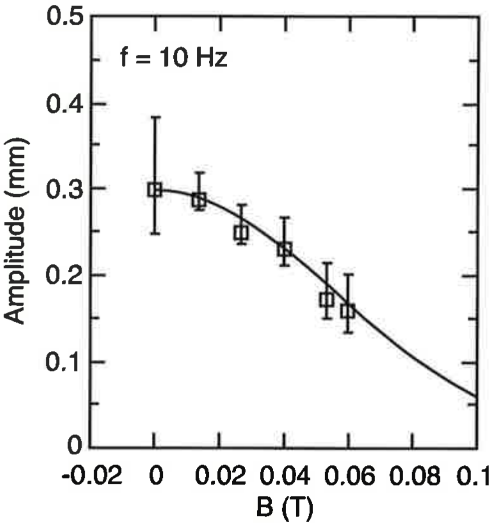


Figure 7. Measured wave amplitudes propagating along a magnetic field. When the magnetic field is increased, the wave amplitudes are suppresed — in good agreement with a linear theory (solid line).

material, the interface can be unstable due to resonance with the gravity waves to efficiently mix light and heavy materials. Collaborations are under way with Professor R. Rosner of the University of Chicago on this topic.

Nonneutral Plasmas and High Intensity Accelerators

A nonneutral plasma is a many-body collection of charged particles in which there isn't 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 of nonneutral plasmas:

- improved atomic clocks;
- positron and antiproton ion sources;
- antimatter plasmas, with application to antihydrogen production;
- coherent electromagnetic radiation generation, including free electron lasers, cyclotron masers, and magnetrons;
- advanced accelerator concepts with high acceleration gradients;
- investigation of nonlinear collective processes and chaotic particle dynamics in high-intensity charged particle beams;
- measurement of background neutral pressure and electron collision cross sections with neutral atoms and molecules.

Research on nonneutral plasmas and high-intensity accelerators at the Princeton Plasma Physics Laboratory focuses on three 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;
- basic experimental investigations of nonneutral plasmas confined in a Paul trap with oscillatory wall voltages, used to simulate intense beam propagation through a periodic quadrupole field configuration; and
- analytical and numerical studies of the nonlinear dynamics and collective processes in intense nonneutral beams propagating in periodic-focusing accelerators and transport systems, with particular emphasis on next-generation accelerators for heavy ion fusion and spallation neutron sources.

Electron Diffusion Gauge Experiment

Experimental research on nonneutral plasmas at the Laboratory is performed on a Malmberg-Penning trap called the Electron Diffusion Gauge Experiment. 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 (Figure 8). By varying the bias on the filament, the size and density of the plasma can be

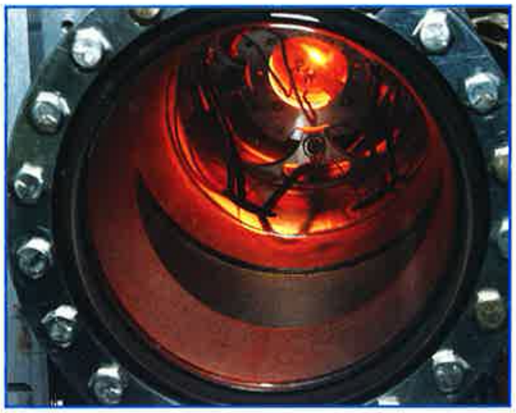


Figure 8. End-on view of electron emission from the tungsten filament in the Electron Diffusion Gauge Experiment.

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. The expansion rate of the plasma has been measured for background pressure variations by a factor of 100,000, 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. Extensive investigations of the nonlinear dynamics of the diocotron mode have also been carried out in circumstances where mode excitation is provided by a resistance in external circuitry.

Paul Trap Simulator Experiment

Construction of the Paul Trap Simulator Experiment (PTSX) was carried out at PPPL during fiscal year 2001. Figure 9 shows a view of the electrode configuration in the experiment. Axial confinement of trapped cesium ions is provided by applied dc voltages on end electrodes. Transverse confinement is provided by oscillatory voltages on the four quadrants of the segmented cylinder in the transverse plane.

This facility will be used to simulate, in the beam frame, collective processes and transverse dynamics of an intense charged-particle beam propagating through a periodic focusing quadrupole field configuration. Experimental studies will include investigations of beam mismatch and envelope instabilities, collective wave excitations, chaotic particle dynamics and production of halo particles, and mechanisms for emittance growth. Experiments on the Paul Trap Simulator Experiment are planned to begin in April, 2002.

High Intensity Accelerators

Theoretical advances in high-intensity accelerators and beam-transport systems have also been achieved in several areas. A kinetic (Vlasov-Maxwell) model for describing intense nonneutral beam propagation in periodic-focusing field configurations has been developed, including the

Figure 9. Electrode configuration in the Paul Trap Simulator Experiment.

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) electron component is present in the acceleration region or beam-transport lines.

In addition, a three-dimensional multispecies nonlinear perturbative 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 (Figure 10). Such collective interactions can play an important role in the next-generation accelerators, transport lines, and storage rings, envisioned for spallation neutron sources and heavy ion fusion. In the absence of a second charge component, the quiescent propagation of a high-intensity thermal equilibrium beam over thousands of equivalent lattice periods has been demonstrated.

Both kinetic and macroscopic (warm-fluid) models have been developed to describe collective processes in high-intensity beams, including detailed investigations of a collective Harris-like instability driven by large temperature 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. Simulations indicate that islands exist in the beam interior, allowing particles initially in the beam core to escape into the halo region due to collective mode excitations in the beam interior.

Charge Neutralization Experiments

Heavy ion fusion research has resulted in a reactor design requiring multiple heavy ion beams to be focused together in the target chamber at the emittance limit. The planned Neutralized Transport Experiment (NTX), and eventually the Integrated Beam Experiment (IBX), will investigate the most promising charge neutralization methods to achieve this level of focusing.

One approach utilizes large-volume plasma to charge neutralize multiple heavy ion beams. The charge neutralization has been modeled as a heavy ion beam propa-

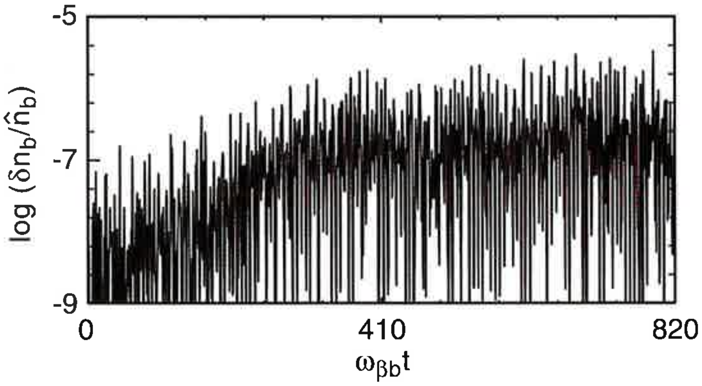


Figure 10. Numerical simulations using the BEST code showing the growth and saturation of the electron-proton two-stream instability in a high-intensity proton beam.

gating through a highly ionized cylindrical plasma column. The cold plasma ion motion is neglected and electrons from the plasma cylinder move into the beam channel, reducing the net positive beam charge over the larger volume of the plasma channel. Ion beam densities will be in the range of 10^{10} to 10^{11} cm^{-3}. Present calculations require the plasma to exceed one meter in length with an electron density comparable to 1 to 100 times the beam density.

PPPL researchers are developing plasma sources capable of producing large-volume plasmas to support neutralization studies on heavy ion beam experimental facilities at the Lawrence Berkeley National Laboratory. In some regimes of operation, the sources have previously been well characterized and applied to plasma processing of semiconductor devices.

Normally, plasmas of large dimension are not readily uniform. Plasmas made with electrodes are naturally heterogeneous in the vicinity of the electrodes. Alternatively, electromagnetic waves can be employed. Unmagnetized plasmas made with electromagnetic waves are naturally heterogeneous, because the skin depth determines the plasma scale length. For radio-frequency waves and microwaves, the skin depth is on the order of 1 cm and 1 mm, respectively. Consequently, it is difficult to make large-volume unmagnetized plasmas with electromagnetic waves. Increasing the power to these plasmas does not increase their volume. The problem of increasing electromagnetic wave penetration in partially ionized collisional plasmas has been studied theoretically. Large volume plasmas will be created with electron cyclotron resonant and helicon sources. The sources' plasma densities and temperatures will be characterized to determine their suitability to support charge neutralization experiments. Theory suggests that the plasma volume and density can be controlled with weak magnetic fields (10 to 50 gauss). An electron cyclotron resonant plasma source has been built and tested. The source is driven with 13-MHz wave power and operates in the 1 to 10 milliTorr range with magnetic fields of 20 to 40 gauss. Figure 11 shows a photo of the multipole magnet configuration used to provide transverse plasma confinement.

Multi-electron Loss Events

During FY2001, data was analyzed from experiments performed by PPPL researchers in collaboration with researchers at the Texas A&M University Cyclotron. As proposed by PPPL, multi-electron loss events were found to be a large contributor to the growth of the charge state in collisions of high-energy many-electron atoms with nitrogen gas. Nitrogen gas was chosen because it is a good surrogate for the FLIBE vapor which will be present in a heavy ion fusion target chamber. To maintain an acceptably small beam spot size at the target, it will be necessary to maintain a higher degree of space charge neutralization of the beam than had originally been anticipated. Theoretical calculations performed by PPPL researchers

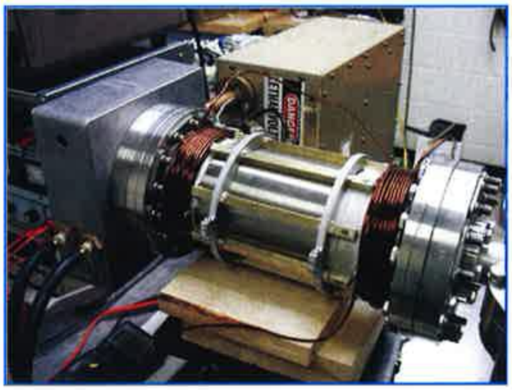


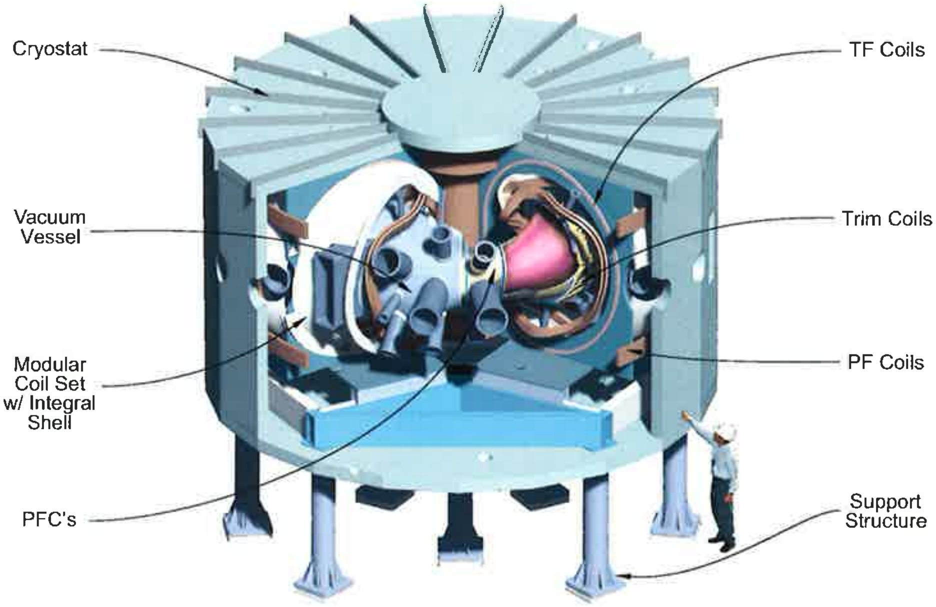
Figure 11. Multipole magnet configuration that provides transverse confinement of plasma in the radio-frequency source.

agreed well with the experiments. A paper reporting the experimental and theoretical results was published in *Physics of Plasmas* in May 2001. Additional experiments were performed using the cyclotron facility at the end of the fiscal year. These will be used to guide future experiments planned for the coming year.

Negative Ion Beams for Heavy Ion Fusion

A study of the feasibility of producing heavy neutral driver beams from photo-detachment of heavy negative ions was performed. This had been proposed as a way to avoid divergence growth by plasma instabilities in the target chamber. The study found that, because of the very high-energy density and low duty cycle of heavy ion fusion driver beams, krypton-fluoride lasers could be used to neutralize almost all of the beam with expenditure of negligible energy for the photo-detachment systems. Additionally, it was found that the accelerator vacuum constraints were not appreciably more restrictive than for positive ions, and that acceptable negative ion currents and current densities appeared obtainable, provided halogens, such as bromine, were used for the beam. The principal limiting factor, as expected, is the target chamber pressure, which needs to be a factor of 5 to 10 lower than the current baseline pressure for full advantage to be taken of the neutral beam. However, even without neutralizing the beam, there are some advantages to using negative ions, of which the most significant is that no electrons are drawn into the beam to change the focusing. A paper presenting these findings is being prepared for publication.

National Compact Stellarator Experiment



National Compact Stellarator Experiment

A key goal for fusion energy research is to develop physics solutions that improve the attractiveness of envisioned magnetic confinement concepts. The compact stellarator is aimed at a high-beta, low-aspect-ratio plasma configuration that can be sustained in steady-state without disruptions and without the need for conducting structures close to the plasma, feedback control of instabilities, or current drive. Such a configuration is potentially attractive for fusion power plants, based on present physics understanding, but a true assessment of the attractiveness requires further development of the physics via experimental tests. That will make it possible to quantify the benefits and costs relative to other concepts and to design an optimum compact stellarator power plant configuration for evaluation.

In FY2000, the U.S. Fusion Energy Sciences Program adopted a ten-year goal to: "determine the attractiveness of a compact stellarator by assessing resistance to disruption at high beta without instability feedback control or significant current drive, assessing confinement at high temperature, and investigating three-dimensional divertor operation." The key element of the national stellarator proof-of-principle program established to achieve this goal is a new research facility, the National Compact Stellarator Experiment (NCSX), to be located at the Princeton Plasma Physics Laboratory (PPPL). The NCSX project team is led by PPPL, in partnership with the Oak Ridge National Laboratory. In FY2001, the project completed its preconceptual design, had a successful physics validation peer review, and was approved for proof-of-principle status by the Fusion Energy Sciences Advisory Committee (FESAC). The FESAC cited the compact stellarator's potential to resolve significant issues for fusion energy (steady-state operation and disruption avoidance), to complement existing tokamak and stellarator research, and to advance the science of three-dimensional magnetized plasmas. The FESAC said that the potential gains "earn for the compact stellarator an important place in the portfolio of confinement concepts being pursued by the U.S. Fusion Energy Sciences Program." Following Department of Energy approval of mission need for NCSX, the project moved into conceptual design.

NCSX Design

The NCSX design is based on the quasi-axisymmetric stellarator (QAS) concept, in which the plasma has a three-dimensional shape, but approximate toroidal symmetry in the magnetic field magnitude in magnetic coordinates. The QAS provides good fast-ion confinement and low neoclassical transport losses, allows undamped flows to stabilize turbulence, and uses the self-generated bootstrap currents to generate some of the rotational transform. It is best suited for merging tokamak and stellarator physics at aspect ratios ≤4.4, approaching those of tokamaks rather than those of typical stellarators, which are in the 6-12 range.

The reference QAS plasma configuration for NCSX has three periods, an aspect ratio R/<a> = 4.4, and strong axisymmetric and three-dimensional components of shaping. Through the use of advanced theoretical and computational design tools, it is optimized to provide good physics properties: low effective helical ripple (Figure 1), good magnetic surfaces, and marginal stability to ballooning, external kink, vertical, and Mercier modes at $\beta = 4\%$. Its rotational transform, which rises from 0.4 at the center to 0.65 at the edge, is generated by a combination of external coils (75%) and bootstrap current (25%). The plasma is designed to have good magnetic surfaces all the way to the edge.

The NCSX magnet set consists of the eighteen modular coils (of three different shapes) shown in Figure 2, eighteen toroidal-field coils (not shown), six pairs of poloidal-field coils (not shown), and helical-field trim coils (Figure 3). The coils produce equilibria with the physics properties of the reference plasma, drive ohmic current, and provide flexibility, for ex-

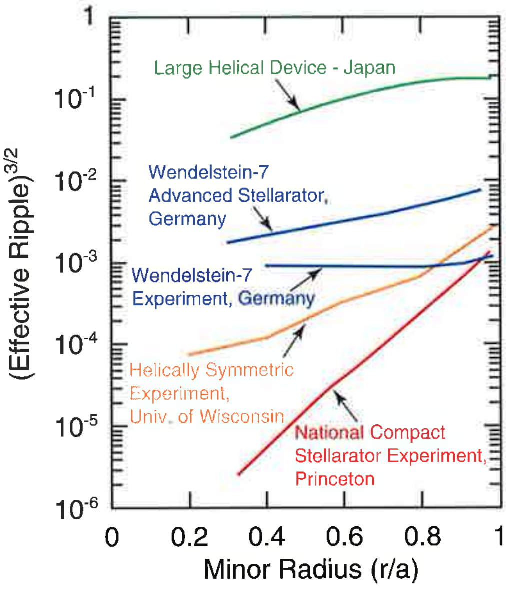


Figure 1. Plot of (effective ripple)$^{3/2}$ in NCSX reference plasma compared to other stellarators. The low value corresponds to negligible helical ripple contributions to neoclassical transport, good energetic particle confinement, and low flow damping.

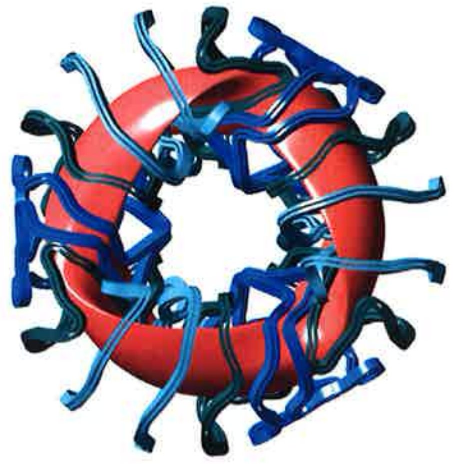


Figure 2. The NCSX modular coils and plasma.

ample the ability to vary the rotational transform, the shear, and the stability beta limit, while maintaining good quasi-symmetry. Good physics properties are available over wide variations in beta, plasma current, and profile shapes. The design provides a stable evolution path from an initial vacuum state to the high-beta target state. The trim coils provide a capability for controlling island widths in experiments. As a further measure, the configuration is designed with "reversed shear" so that neoclassical effects should reduce the widths of any islands.

The NCSX will have a major radius of 1.4 m and a magnetic field (B) range of 1.2-1.7 T with a flattop time of ≥0.2 sec in the nominal configuration and 2 T at reduced rotational transform. Transport predictions based on these machine parameters indicate that plasmas with β = 4%, ion collisionality $\nu_i^* = 0.25$, B = 1.2 T, and average density 6×10^{19} m^{-3} can be realized with 6 MW of neutral-beam injected power. This requires a global confinement time 2.9 times the International Stellarator Scaling (ISS-95), somewhat higher than the best achieved on Japan's Large Helical Device (LHD) and Germany's Wendelstein-7 Advanced Stellarator (W7-AS), or 0.9 times the International Thermonuclear Experimental Reactor (ITER-97P) low-confinement mode tokamak scaling.

The machine will accommodate up to 12 MW of auxiliary heating, 6 MW of tangential neutral-beam injection and 6 MW of radio-frequency heating. The neutral-beam injection will be provided by the four existing Princeton Beta Experiment-Modification (PBX-M) neutral beamlines, and high-field-side wave launchers can be installed for mode conversion radio-frequency heating. Initially, the machine will be equipped with 3 MW of 0.3-sec pulse-length neutral-beam-injection heating. The power and pulse length (up to 1 sec) can be increased later, depending on the needs of the program. About 80 ports of various sizes provide good diagnostic access, including good views of the plasma's six symmetry planes, where measurement interpretation is easiest.

The plasma will be surrounded by an Inconel vacuum vessel with an internal structure that can support molded carbon fiber composite (CFC) panels that are bakeable to 350 °C. The plasma-facing components will be configured to control neutral sources for good plasma performance, to absorb plasma energy losses, and to protect the vacuum vessel walls. Space

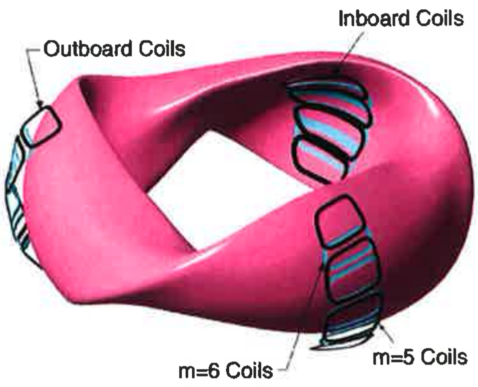
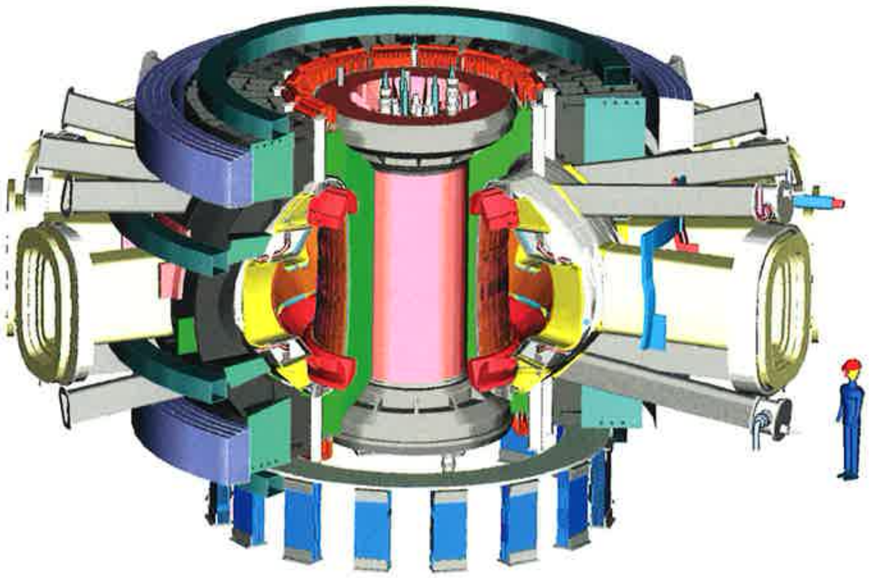


Figure 3. The NCSX helical-field trim coils for island correction.

is provided to permit a later upgrade to a pumped divertor configuration. Surrounding the vessel are the magnets, which will be made of flexible copper conductor wound on structural winding forms. A cryostat will enclose the stellarator core to allow the magnets to be precooled to cryogenic temperatures. The NCSX will be installed in the former Princeton Beta Experiment/Princeton Large Torus (PBX/PLT) Test Cell at the Princeton Plasma Physics Laboratory. Some key systems, such as the neutral beams, power supplies, and vacuum pumping system, are available from previous projects and will be reused. The fabrication project is expected to be carried out from fiscal year 2003 to 2007 at a cost of about $70 M.

Fusion Ignition Research Experiment



Fusion Ignition Research Experiment

The next major frontier in magnetic fusion physics is to explore and understand the strong nonlinear coupling among confinement, magnetohydrodynamic (MHD) stability, self-heating, edge physics, and wave-particle interactions that is fundamental to fusion plasma behavior. The international fusion community is actively pursuing a fusion physics and technology experiment, called the International Tokamak Experimental Reactor (ITER), which would address these physics issues as well as major developments in fusion technology. It is possible that it will not prove feasible, however, to construct such a device, even based on international collaboration. A U.S.-based study has been undertaken to define low-cost options. The Fusion Ignition Research Experiment (FIRE) Design Study is a national collaboration with participants from more than 15 U.S. institutions; it is managed through the Virtual Laboratory for Technology. The Next Step Option Program Advisory Committee has guided the technical work on FIRE. It includes members from 12 U.S. fusion institutions, as well as participants from Europe and Japan.

An Advanced Burning Plasma Physics Experiment

The physics objectives of a next-step burning plasma physics experiment include:

- Determine the confinement physics, operational limits, and alpha dynamics of self-heated plasmas with alpha heating exceeding auxiliary heating.

- Demonstrate heating, current drive, fueling, and plasma-handling techniques to control and optimize the performance of reactor-level power density, self-heated plasmas.
- Determine the behavior of self-heated plasmas in advanced tokamak configurations with significant self-driven current.

FIRE activities have focused on the physics and engineering assessment of a compact, high-field tokamak with the capability of achieving $Q \approx 10$ in the edge-localized high-confinement mode for a duration of about two plasma current redistribution times during an initial burning plasma science phase, and the flexibility to add additional hardware (e.g., lower-hybrid current-drive system) later to produce and study advanced tokamak modes in the presence of strong self-heating. The configuration chosen for FIRE is similar to that of ARIES-RS (one of a series of Advance Reactor Innovation Evaluation Studies), the U.S. fusion power plant study utilizing an advanced tokamak reactor. The key "advanced tokamak" features are: strong plasma shaping, double-null pumping divertors, low toroidal-field ripple (less than 3%), internal control coils, and space for wall-stabilization capabilities.

Optimized Burning Plasma Physics Experiment

A systems study was undertaken to find the minimum-size burning plasma to achieve the physics requirements discussed above. This study was specialized for inductively driven tokamaks with toroidal-field (TF) and poloidal-field (PF) coils that are precooled to liquid-nitrogen temperature and then heated adiabatically during the pulse. The systems code includes constraints for stress, resistive and nuclear heating of the coils, and volt-second requirements. The geometry can be chosen to have TF and PF coils unlinked as in FIRE, or linked as in low-aspect-ratio tokamaks (for example, spherical tori). The code optimizes the allocation of the space in the inner coil stack between the freestanding ohmic solenoid and the wedged TF coil. Confinement is taken to be the high-confinement mode (H-mode) with ITER98(y,2) scaling. For these studies, the plasma density had a small peaking of $n(0)/\langle n \rangle = 1.2$, $n/n_{GW} \leq 0.75$ with 3% beryllium impurities. The systems code varied the major radius, R, and aspect ratio, A, with $H(y,2) = 1.1$, $\kappa_{95} = 1.8$, $q_{cyl} = 3.1$ and $P_{fusion} = 150$ MW to obtain plasmas with $Q \sim 10$ and 20-sec burn time.

For these constraints, the smallest-size device to achieve the burning plasma requirements for a cryogenically cooled, inductively driven tokamak with unlinked TF and PF coils has a shallow minimum around $A \approx 3.6$, magnetic field $B \approx 10$ T, and $R \approx 2.1$ m (see Figure 1). The normalized burn time $\tau_J = \tau_{burn}/\tau_{CR}$ (where τ_{burn} is the duration of the fusion burn and τ_{CR} is the plasma current redistribution time) is measured in plasma-current redistribution times and increases significantly as the aspect ratio is increased. The minimum aspect ratio that satisfies the physics requirement of $2\tau_J$ is $A \geq 3.4$. The advanced tokamak feature of significant bootstrap current are also enhanced at higher aspect ratios. Indeed, the fusion power plant design studies based on advanced tokamak scenarios have all chosen $A = 4$ and relatively high magnetic field such as ARIES-RS (8.2 T) and ASSTR (11 T). These objectives have lead to the

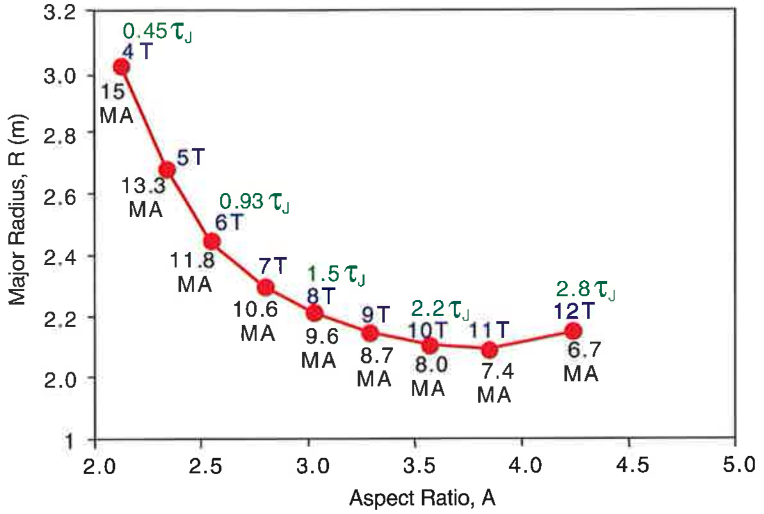


Figure 1. Optimization of an inductively driven copper coil burning plasma experiment.

choice of A = 3.6 for FIRE, which is higher than the aspect ratios chosen for other burning plasma experiments (ITER-FEAT: A = 3.1 and IGNITOR: A = 2.8).

Optimized Design Point

The reference design points for FIRE are: major radius R_0 = 2.14 m, minor radius a = 0.595 m, toroidal magnetic field $B_t(R_0)$ = 10 T, and plasma current I_p = 7.7 MA with a flattop time of 20 sec $(\sim 2\tau_{CR})$ for 150 MW of fusion power. The magnetic fields and pulse lengths would be provided by wedged, beryllium-copper, oxygen-free, high-conductivity TF coils and copper-chromium-zirconium alloy, oxygen-free, high-conductivity PF coils that are precooled to 80 °K prior to the pulse and allowed to warm up to 373 °K at the end of the pulse. FIRE will utilize only metal plasma-facing components, beryllium-coated tiles for the first wall and tungsten brush divertors to reduce tritium retention as required for fusion reactors. A longer-term goal of FIRE is to explore advanced tokamak regimes with bootstrap fractions (f_{BS}) approximately 70% at beta-normalized approximately 3.5 at high fusion gain (Q > 5) for a duration of 1 to 3 plasma current redistribution times. This will require the addition of about 20 MW of lower-hybrid current drive at 5.6 GHz and a feedback system to stabilize the n = 1 kink.

The operating modes, physics issues, and physics design guidelines for projecting burning plasma performance in FIRE are based on those used for ITER. Parameters for a Q = 10, edge-localized high-confinement mode plasma in FIRE are shown in Table 1. Recent analyses of the H-mode confinement database suggest that the H-mode confinement in FIRE will be enhanced, H98(y,2) ≈ 1.1, due to modest density relative to Greenwald and high cross-section triangularity. The TSC (Tokamak Simulation Code) modeling of the reference edge-localized H-mode attains Q ≈ 10 sustained for approximately 20 sec $(\sim 2\tau_{CR})$. Physics-based modeling of FIRE using the GLF23 code suggests that the temperature pedestal required to achieve Q ≈ 10 regimes is in the 2.5 to 3.1 keV range. The experimental databases of pedestal temperatures from existing tokamak experiments suggests that the high plasma triangularity and lower operating density relative to the Greenwald density will enhance the capability of FIRE to produce the required pedestal temperatures.

Table 1. FIRE Parameters at Q ~ 10.

Plasma Parameter	Values
Major Radius, R	2.14 m
Minor Radius, a	0.595 m
Elongation, κ_x, κ_{95}	2.0, 1.77
Triangularity, δ_x, δ_{95}	0.7, 0.4–0.55
q_{95}	≥3
Magnetic Field on Axis, $B_t(R_0)$	10 T
Plasma Current, I_p	7.7 MA
$Q = P_{fusion}/(P_{aux} + P_{OH})$	10
H98(y,2)	1.1
Normalized Beta, β_N	1.81
P_{Loss}/P_{LH}	1.3
Z_{eff} (3% Be + He)	1.4
$R\nabla\beta_\alpha$	3.8%

Advanced Tokamak Operating Mode

Equilibrium and ideal-MHD stability analysis, combined with lower-hybrid current drive (LHCD) calculations, have identified attractive targets for advanced tokamak operation. The most attractive has a minimum q (q_{min}) just above 2.0 and $r/a(q_{min}) = 0.8$. The low-order neoclassical tearing modes could be avoided, although the (5,2) and (3,1) surfaces would be present. The location of q_{min} is determined by the penetration of the lower-hybrid (LH) waves for expected FIRE parameters. On-axis current-drive requirements from ion-cyclotron range of frequency (ICRF) fast wave (FW) are typically less than 0.4 MA. The design of FIRE includes a close fitting copper-clad stainless-steel passive stabilizer for n = 0 and n = 1 mode control. The maximum β_N, determined for n = ∞ ballooning and n = 1 external kink modes, with no wall stabilization, is 2.5.

The three-dimensional finite-element feedback-control code VALEN was used to model and optimize the performance of a feedback-control coil and passive-stabilizer configuration for FIRE. Using a set of four n = 1 pairs of control coils in each of the eight open midplane ports, an active feedback system was found to stabilize the n = 1 resistive wall mode (RWM) up to β_N of 4.16 with reasonable amplifier gain. The TSC is used to simulate the advanced-tokamak discharge, with the LSC (Lower-Hybrid Simulation Code) ray-tracing package connected for the lower-hybrid current-drive calculations.

The primary goal is to establish quasi-stationary burning plasmas, where the current and safety factor profiles do not significantly change. Although inductive and noninductive current drive are used to ramp the plasma current up, the flattop plasma has 100% noninductive current provided by the combination of bootstrap, lower-hybrid, and fast-wave current as shown in Figure 2. The parameters achieved in this simulation are $B_t = 8.5$ T, $I_p = 5.4$ MA, $\beta_N = 3.5$, $\beta = 4.5\%$, bootstrap current $I_{BS} = 3.6$ MA, lower-hybrid current drive $I_{LH} = 1.5$ MA, fast-wave current drive $I_{FW} = 0.35$ MA, and $Q = 5.7$ with H98(y,2) = 1.6. Quasi-stationary conditions were sustained for 32 sec. The density relative to Greenwald density reaches 0.5, with the peak density reaching 4.7×10^{20} m^{-3}, and with a peak-to-average density of 1.6. The bootstrap current fraction is 66%, with lower-hybrid current providing 28% and fast wave the remaining 6%. The attainment of H98(y,2) would require an internal transport barrier. Physics-based calculations using the GLF23 code showed that an internal transport barrier could be formed with reversed shear and modestly peaked density profile.

Engineering Peer Reviews

Engineering peer reviews of the major FIRE systems were held in June 2001. The most critical elements of the project were addressed, including the TF and PF coils, vacuum systems, plasma-facing components, structures, heating and fueling systems, nuclear effects and activation, the cryoplant, facilities, and siting. Input from the review team has been used to form the basis of an engineering work plan. Several recommendations have already been incorporated, such as focusing on a single engineering design option to achieve project goals. A wedged TF coil design with toroidal magnetic field of 10 T and plasma current of 7.7 MA was chosen. The peer review committee recommendation to have an additional margin of 30% relative to the usual design allowable during the preconceptual design phase was adopted.

Reactor-relevant Power-handling

The burn time in FIRE is limited primarily by the power-handling capability of the divertor and first wall. The development of high-power-density divertors and first walls in FIRE will provide valuable information for future tokamak power plants, where power densities will be higher. The divertor geometry has been shown to survive incident heat fluxes of 25 MWm^{-3} for 1,000 cycles in testing, using several different joining procedures.

The UEDGE code was used to calculate the expected edge conditions in FIRE. For all cases considered, the power into

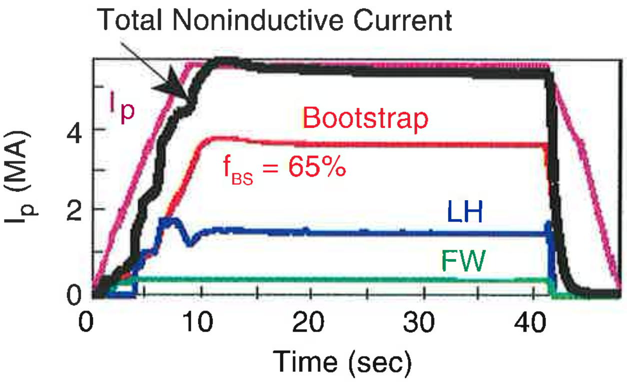


Figure 2. Advanced tokamak mode in FIRE.

the scrape-off layer was 28 MW and the separatrix density was 1.5×10^{20} m^{-3}, with a wall recycling coefficient of 1.0. Without a radiative divertor, the heat loads are high (~25 MWm^{-2}). The intrinsic impurity content of the plasma (2% helium and 3% beryllium) is sufficient to reduce the outer divertor heat loads to about 20 MWm^{-2}. Addition of small amounts of neon can cause complete detachment of the outer divertor with maximum heat loads of about 6 MWm^{-2}. Smaller amounts of neon cause increased radiation and can reduce the heat load to 10-15 MWm^{-2}. Heat flux in this range is needed to accommodate edge-localized mode activity. The inner divertor is relatively open, but easily detaches due to the low power load in the double-null conditions in FIRE.

Simulations of plasma disruptions using the TSC and the three-dimensional OPERA codes (Sandia National Laboratories) have provided improved analyses of the mechanical stresses in the divertor and vacuum vessel components that are a factor of three lower than simple estimates.

R&D for Diagnostics

The plasma measurement needs for both the physics understanding of FIRE performance and for providing control of the plasma in advanced tokamak modes were evaluated. Draft specifications for the measurement quality in terms of resolution and accuracy have been proposed, and the diagnostic techniques to meet these goals have been selected.

Full use of the generous port access has been made in laying out a possible arrangement of the diagnostics. Conceptual designs of individual systems are now necessary to integrate the systems with other diagnostics, and with the thick shielding plugs, to determine the quality of measurements that will in fact be achievable. A Research and Development (R&D) program, particularly emphasizing studies of radiation effects, a diagnostic neutral-beam to support key measurements, and alpha-particle diagnostics has been defined.

The design of the diagnostic configurations within the ports will move forward in parallel with device hardware design. The tight coupling of the diagnostics with the shielding, the need for sight lines through and between the divertor modules and the passive plates, the very tight space provided for magnetic diagnostics within copper plating for cooling the vacuum vessel, are all significant facility integration issues. In-vessel coils to provide stabilization will also be considered in the design of diagnostics within the ports.

Engineering & Technical Infrastructure

The Engineering and Technical Infrastructure Department is responsible for managing the Princeton Plasma Physics Laboratory's (PPPL) engineering resources. This includes a staff of more than 200 engineers and technicians organized functionally (Mechanical; Electrical; Computer; and Fabrication, Maintenance, and Operations Divisions) to support the Laboratory's research endeavors. The Department is responsible for the technological infrastructure supporting the experiments, as well as managing the caretaking of D-Site and the Decontamination and Decommissioning of the Tokamak Fusion Test Reactor (TFTR).

NSTX Engineering

Engineering Operations

Coaxial helicity injection operations on the National Spherical Torus Experiment (NSTX) were improved with the conversion of the NSTX's PF1A magnet system from unipolar to bipolar operation. Current ripple in the PF1A circuit was reduced with the addition of series inductors.

The new NSTX neutral-beam injection system operated reliably at the design specification of 80 keV and 5 MW this past year. The beam pulse modulation capability under development was tested and is now being used to support beam-notching experiments. NSTX ion sources were conditioned to above the rated 80 keV operating level at the end of the last experimental run period to support upcoming experiments. In addition to the three operating neutral-beam ion sources, two additional TFTR ion sources have been dismantled, refurbished, and tested for use on NSTX.

Coil Repairs

After nearly two years of successful operation, several water leaks were discovered in the upper section of the inner toroidal-field coil bundle of the NSTX center stack. It appeared that these leaks were a result of damage to the copper cooling tubes that occurred during manufacturing and assembly. Repairs required the partial disassembly of the upper toroidal-field hub assembly (Figure 1) while the center stack remained in position.

Resoldering or replacement of damaged coolant lines easily repaired several of the leaks, but two were in inaccessible areas, requiring the use of the epoxy sealing process developed and used successfully on TFTR.

An electrical short through the ohmic-heating (OH) ground wall was also discovered. This presented more of a challenge, requiring the partial disassembly of the inner center-stack components, plus the removal of the OH coil from the inner vacuum vessel wall (Figure 2). The OH coil was successfully removed, repaired, and reinstalled while maintaining a good vacuum in the vessel. Maintaining a good

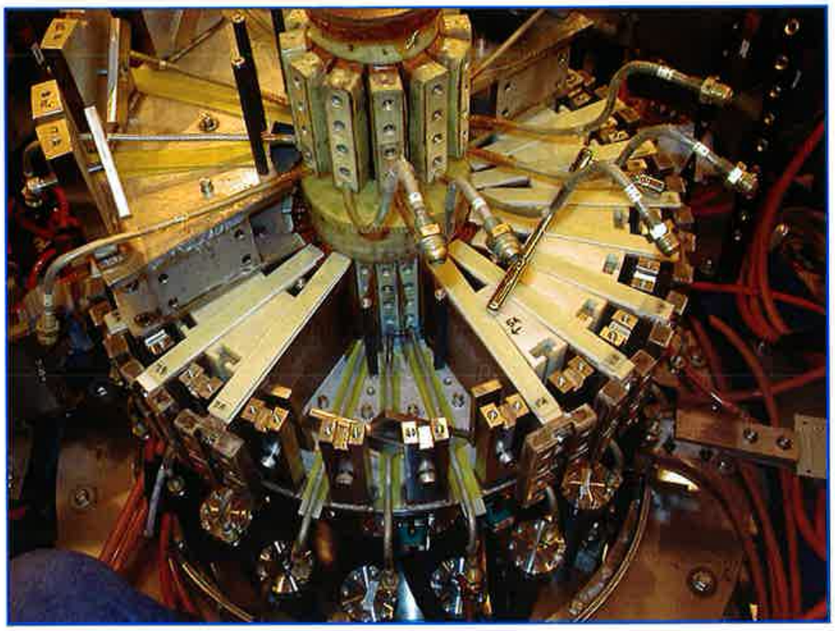


Figure 1. The partially disassembled National Spherical Torus Experiment hub assembly.

vacuum avoided a lengthy reconditioning period for the vessel and in-vessel components, thus minimizing the start-up time following the repairs.

Although each of these repairs was unique, they were successfully completed on the originally planned schedule and allowed NSTX to resume normal operations, thus demonstrating the ease of maintenance of spherical tori.

Summer Outage

During summer 2001, NSTX was taken off-line for system maintenance and upgrades. The outage started in August with the venting of the vacuum vessel for interior work.

More than 300 tasks were completed, including the installation of a center-stack gas-injection system, upgrade of the in-vessel flux loops and Mirnov coils, and installation of a scanning motion diagnostic, a helium high-temperature bakeout system, and a toroidal-field array cooling system.

The center-stack gas-injection system was added based on highly successful results achieved on another spherical tokamak. The system consists of a plenum and piezoelectric-valve gas injector and a 1/8-inch stainless-steel injector tube routed beneath the carbon-fiber-reinforced

Figure 2. The ohmic-heating coil being removed from the center stack of the National Spherical Torus Experiment.

graphite tiles on the center stack. The gas enters the plasma midplane from between the tiles.

Inspections of the in-vessel diagnostic flux loops revealed kinks and cracks in the stainless-steel shielding tubes. The damage was attributed to differential thermal expansion between the passive plate arrays and the vacuum vessel during bakeout. The design was improved using a flexible braided shield, which allows the loops to flex with thermal motion.

A scanning neutral-particle diagnostic was installed during the outage, requiring extensive reinforcement of the Test Cell platform to reduce deflections from the additional weight of the Neutral Particle Analyzer and to provide a stable foundation for the drive rails. The system provides both horizontal and vertical scanning motions.

Helium Bakeout System

In FY2001, a high-temperature helium-filled bakeout system was fabricated, installed, and commissioned on NSTX (Figure 3). After the evaluation of several approaches, including the use of heat transfer oils and steam, a compressed helium system was determined optimal. The system is designed to heat internal plasma facing components to 350 °C during "bakeout" conditioning of the vacuum vessel. The helium system utilizes a blower operating inside of a pressure vessel installed on a skid in the D-site pump room. This arrangement allows the base pressure to be raised to 23 atmospheres. With the system pressure elevated, the helium blower need only provide the motive force for overcoming 28 psi of friction losses and is not encumbered with compressing the gas. At 23 atmospheres, the density of the helium is high enough to provide the heat capacity necessary to meet the NSTX requirements of 66 kW for heating and 82 kW for cooling.

Fluorinert Cooling System

PPPL engineers designed and installed a toroidal-field coil cooling system which uses the 3M Company's PF-5070 perfluoroheptane liquid (commonly called "Fluorinert") as an alternative coolant to

Figure 3. The National Spherical Torus Experiment bakeout skid.

the deionized water previously used. Deionized water may fail to be an acceptable insulating magnet coolant when a coolant channel flaw allows the water to leak onto atmospheric surfaces or into stagnant internal fissures. The leaked water may become conductive and able to support destructive electrical faults. The new coil cooling system shares many of the design features of the deionized cooling water system, including interlocked flow monitoring to prevent overheating damage, protection against loss of dew point control, and protection against high system pressures. The major system elements include a preexisting TFTR 2,500-gallon storage tank in the pump room, a pump and filter skid on the mechanical equipment room mezzanine, a plate and frame heat exchanger on the mezzanine which rejects heat locally to the deionized water system, a supply and return manifold skid in the NSTX Test Cell; and an elevated suction-head tank skid on top of the south shield wall.

NCSX Engineering

The conceptual design configuration for the National Compact Stellarator Experiment (NCSX) was developed in FY2001 (Figure 4). Numerous improvements were incorporated in this configuration. The number of modular coils was reduced from twenty-one to eighteen, permitting larger diagnostics ports with more advantageous locations. The minimum bend radius of the modular coil turns was increased, as was the coil-to-coil spacing. These changes will ease their manufacture. The peak field capability was increased to 2 T and the plasma current capability was doubled to 350 kA to permit a broader range of experimental operation. Two pairs of poloidal-field coils were added which improve the distribution of the ohmic field and allow the generation of higher order multipole fields, up to the octupole. The vacuum vessel was expanded to provide room for a pumped divertor. The expanded vacuum vessel has a smoother geometry, which will ease the forming of the

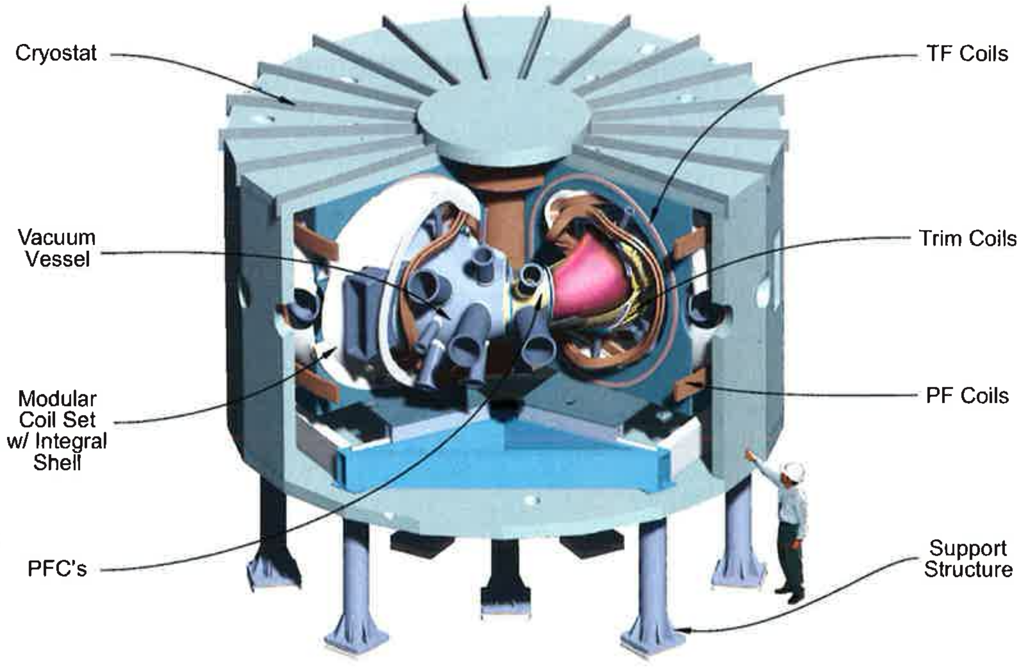


Figure 4. The National Compact Stellarator Experiment.

Inconel plates from which it will be manufactured. The first-wall boundary was expanded to permit a broader range of plasma shapes. This new modular coil design will serve as the basis for the Conceptual Design Review (CDR) scheduled for April 2002.

In preparation for the CDR, manufacturing studies were initiated. Several industrial companies, both domestic and foreign, are reviewing the NCSX modular coil and vacuum vessel designs. The goal of these studies is to gain early industrial input on their engineering design details, materials choices, and specification details. These inputs will be evaluated in the final design process and will assist in planning for research and development and prototype activities. These activities will help to improve component manufacturability and reliability and should also help to reduce costs.

FIRE Engineering

In June, 2001, engineering peer reviews were held for the Fusion Ignition Research Experiment (FIRE). The reviews included the most critical elements of the project, including the toroidal-field and poloidal-field coils, vacuum systems, plasma facing components, structures, heating and fueling systems, nuclear effects and activation, the cryoplant, facilities, and siting. The review team made a number of very useful comments and recommendations that are presently being addressed. In addition, very favorable comments were received regarding the depth of analyses, considering that the project is only in the preconceptual design phase.

One recommendation particularly emphasized was for FIRE to select and focus on a single set of machine and operating parameters. Prior to the engineering peer review, FIRE was considering a range of operating parameters in response to recommendations of the FIRE/Next Step Option (NSO) Program Advisory Committee (PAC). In addition a bucked and wedged toroidal-field design option was being considered. In response to engineering peer review recommendations, FIRE adopted a focused set of parameters and selected a wedged toroidal-field configuration over the bucked and wedged configuration. This will permit the project to proceed much more efficiently toward the Conceptual Design Phase in FY2003.

During this selection process, the machine size parameters were adjusted to permit the plasma current to be increased from 6.5 to 7.7 MA to improve FIRE's margin with respect to the global energy confinement scaling provided by International Thermonuclear Experimental Reactor (ITER) $H_{98}(y,2)$ confinement scaling. This physics decision has been endorsed by the FIRE/NSO-PAC. The wedged configuration was chosen over the bucked and wedged configuration after considerable discussion on the advantages and disadvantages of the two concepts Key elements in this decision were the considerable worldwide experience with wedged machines and the avoidance of a complex interface between the center solenoid and the toroidal-field coils. During the review of machine parameters, it was also decided that a maximum toroidal-field of 10 T is adequate and will meet the design objectives with an additional 30% margin. Previously, a 12 T/7.7-MA capability was considered because it provided a margin should the advanced tokamak performance or the achieved Q prove to be disappointing at 10 T/6.44 MA. Now the desired physics capability is provided by the slightly larger size and lower aspect ratio at 10 T. A cross-sectional view of FIRE in its thermal shield is shown in Figure 5.

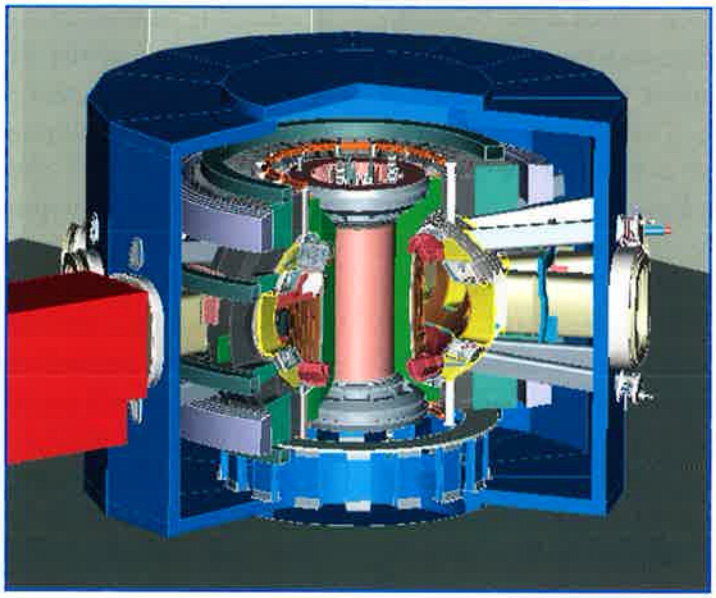


Figure 5. Cross-sectional view of the Fusion Ignition Research Experiment in its thermal shield enclosure.

During this year, Research and Development (R&D) plans were developed for FIRE engineering systems. FIRE has relatively modest R&D requirements, since it will utilize cryogenically cooled copper coils and therefore can draw upon a wealth of data from the Compact Ignition Experiment (CIT), the Burning Plasma Experiment (BPX), the ALCATOR C-Mod, and the IGNITOR designs. Consequently, FIRE R&D will concentrate on filling the gaps in available data, reducing manufacturing and operational risks, and improving performance and reliability.

There were 52 presentations on FIRE at various technical meetings, workshops, and colloquia around the world in FY2001. Fourteen papers were published on FIRE physics and engineering activities. The FIRE web site was expanded as a repository for FIRE and fusion information. The site was accessed approximately 15,000 times during FY2001.

TFTR D&D

The decontamination and decommissioning (D&D) of the TFTR was started in October 1999 and is scheduled to be completed in September 2002. The primary objective of the TFTR D&D Project is to clear the TFTR Test Cell and remove activated and/or contaminated components from the TFTR Test Cell basement. This is being done so the facility will be ready for another fusion device.

Technology from the nuclear fission industry is being utilized as appropriate to safely dismantle activated and contaminated systems. In some areas, most notably the dismantling of the vacuum vessel, new technologies have been developed to permit the work to proceed more safely and effectively. Disassembled components are being packaged for disposal in compliance with Department of Energy, Department of Transportation, and waste receiver requirements. The TFTR D&D Project differs from a typical D&D project in that the facility will not be returned to "greenfield" conditions, nor will it be released for unrestricted use. PPPL will retain ownership and reuse of the facility.

During FY2001, the TFTR D&D Project made impressive progress in the removal of significant components from the Test Cell and the Test Cell basement. The D&D Engineering Group prepared all but a handful of the remaining procedures required to render the equipment safe and for the removal of the components from the TFTR Test Cell and the Test Cell basement.

More than 225 procedures are required for the entire D&D Project. The underlying principles for these procedures are those of Integrated Safety Management. Another important feature is the use of digital photos of the equipment, with labels indicating key disconnection points. Once approved, these procedures are incorporated into Engineering Work Packages which include a Job Hazards Analysis, necessary permits, and any drawings needed to complete the field activities. The Engineering Work Packages are reviewed for completeness by the Work Control Center, which schedules the work and acts as a liaison between the field crews and the D&D Engineering Group, ensuring work efficiency.

During the first quarter of FY2001, the primary focus was the removal of the TFTR umbrella structure, which provided support for the upper poloidal-field coils and counteracted the overturning moment of the toroidal-field coils. In November 2000, it was removed in one piece. At 92 tons, this was the heaviest and largest single lift of the TFTR D&D Project. The structure was then cut into pieces using reciprocating guillotine saws to reduce its size for shipment and burial at the U.S. Department of Energy's (DOE) Hanford site.

During the second quarter of FY2001, the lintels and columns which had supported the umbrella structure were removed, as well as the appendages to the vacuum vessel. Significant improvements to the technology for cutting up the vacuum vessel using diamond wire rope were developed. This included cooling and cleaning techniques for the diamond wire rope using CO_2 pellets (instead of water), as well as the monitoring of the rope temperature, tool pressure, and feed rates. These technology developments led to reduced radiation exposure for workers, reduced releases to the environment, reduced radwaste generation, and reduced costs, compared to the standard plasma arc cutting. Also during this period, the training of personnel to conduct the diamond wire cutting of the vacuum vessel went into its final phase on specially constructed mock-ups.

During the third quarter of FY2001, the training of technicians to perform the diamond wire cutting of the TFTR vacuum vessel was completed. The vacuum vessel was then filled with lightweight concrete to trap the tritium contamination and provide a void space filler for the eventual burial of the vacuum vessel segments. The diamond wire cutting equipment was then installed in the TFTR Test Cell.

During the fourth quarter of FY2001, the diamond wire cutting system setup in the TFTR Test Cell was completed. In mid-August 2001 the first diamond wire cut of the TFTR vacuum vessel was initiated, and on September 11, 2001 the first cut was successfully completed (Figure 6).

Overall, the TFTR D&D Project continues to do very well. DOE Cost and Schedule Reviews of the Project in December 2000 and again in July 2001 were very successful. By the end of the second of three years, the Project continued under budget and on schedule for completion in September 2002.

D-Site Caretaking

The safety and radiological cleanliness of the D-Site facility was successfully maintained during extensive TFTR D&D

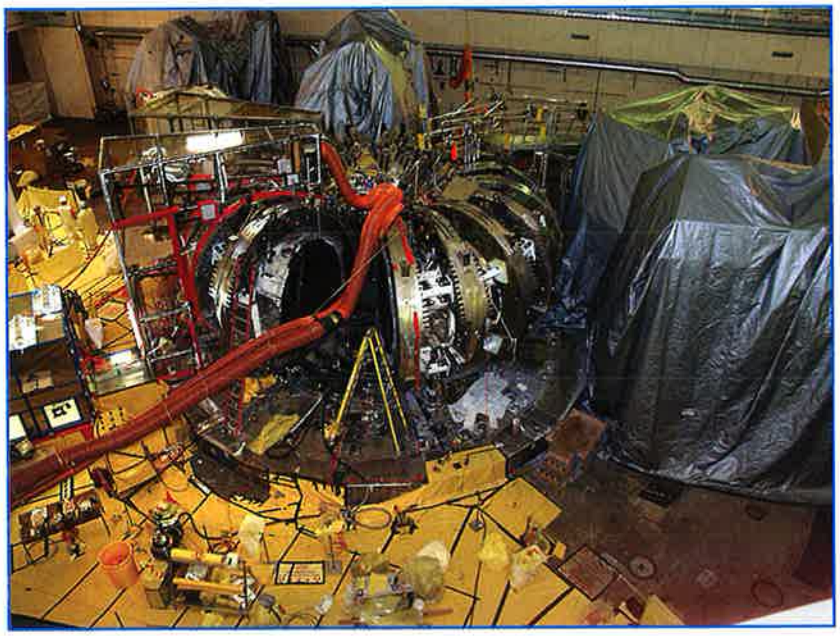


Figure 6. The Tokamak Fusion Test Reactor with the first sector removed.

activities and a highly successful year of experiments on NSTX. The TFTR neutral-beam lines and ion sources were decontaminated to the point where the bubbler systems were removed and sources and beamlines now vent directly to the D-site stack.

Considerable work was performed to correct drawings and complete maintenance on mothballed equipment.

Computing Systems

Scientific Computing

In late FY2001 an Intel-Beowulf Linux cluster was built at PPPL, pooling hardware purchased by the Theory and Off-Site Research Departments and the Computational Plasma Physics Group. Initially comprising 68 processors, this prototype system has increased PPPL's overall UNIX CPU capacity by more than 300% and is providing PPPL researchers with a local facility for code development and parallel computing resources. If successful, this cluster could be increased up to 2000 nodes.

In FY2002, various tools for building, maintaining, and operating the cluster will be evaluated. These will include batch queuing systems, schedulers for deciding where tasks run and their priority, and imaging tools which would help bring systems on-line, keep them updated, and manage software requirements for individual computational needs. Networking, file serving, and physical (e.g., space, power) requirements will also be reviewed in preparation for larger needs.

Network Systems

The PPLnet infrastructure is presently a hybrid of 10-Mbps shared Ethernet and 10/100-Mbps switched Ethernet to the desktops and computer centers at PPPL. The optical fiber network backbone comprises one legacy 100-Mbps FDDI link and an infrastructure of switched 100 and 200-Mbps uplinks to remote switching hubs. A CISCO 7513 router provides services to 19 Class C network segments and connectivity to the local ESnet router via full duplex 200-Mbps switched Ethernet.

A PPPL site firewall is on the input port of the CISCO 7513 router.

The migration of critical data servers and desktops to 100-Mbps ports continued, with more than 550, 100-Mbps ports in use at the end of FY2001. An upgrade to the PPPL Theory Department infrastructure was put in place during the year. Six wireless Ethernet segments were deployed in the NSTX Test Cell and to conference rooms throughout the Laboratory. A 200 optical cable infrastructure was completed as an upgrade to the NSTX diagnostic infrastructure and for general TCP/IP networking at D-Site. This provides a computer-networking base at D-Site for immediate needs and future initiatives.

A 100 megabytes per second microwave link from PPPL to the main campus became operational which allows high-speed connectivity to Princeton University collaborators, business systems, and provides DOE-affiliated projects connectivity to ESnet. The aging remote access system was upgraded to a digital, T1-based system with 56-kbps dial-up and 128-kbps ISDN capability. The new remote access system is integrated with PPPL's user authentication system offering improved security.

Cyber Security

Computer security at PPPL continues to be an important issue. The number of viruses and known machines worldwide that have been infected by both worms and viruses has grown into the hundreds of thousands. Every minute of every day, the PPPL firewall drops attempted connections numbering in the hundreds. The automated firewall virus protection is also very busy, picking off nearly 100 e-mail attached viruses daily. Much of the effort in the cyber security area has been targeted at addressing computer security alerts, installing the latest patches, and ensuring that all users have the latest virus protection. A focus has also been to increase the number of individuals who use SecurID to authenticate at the firewall. There have been no known successful break-ins and a substantial decrease in virus infections since the equipment was deployed in its current configuration. In FY2001, a program to further bolster internal security was begun. This effort included more complete vulnerability scanning of both internal servers and desktop machines.

Business and Financial

Princeton Plasma Physics Laboratory Business Computing operates on an IBM 9121-210 mainframe. The current application software was, for the most part, developed in the late 1970s and early 1980s using database products developed in the early 1970s. In FY2001, an analysis was performed to determine how the Laboratory would meet its financial and administrative computing needs in the future. As a result of the analysis, a proposal was written and approved to replace the business application systems and mainframe with a mid-level enterprise resource planning (ERP) business computing system from Microsoft's Great Plains Software.

Business Management International, a consulting firm and reseller of Great Plains Software, was contracted to implement the new system which utilizes client-server technology running on a Microsoft's Windows 2000 Server and a SQL Server 2000 as the database management system. Four Dell 6400 quad-processor servers were purchased to support the new system.

Implementation of the Great Plains ERP system will commence in October 2001, with a "Go-Live" scheduled for FY2003. Successful deployment will allow the IBM mainframe to be shut down, reducing costs.

HRMIS

In FY2001, Princeton University completed the implementation of PeopleSoft as an enterprise-wide HRMIS (Human Resources Management Information System), moving from mainframe to client-server architecture and replacing TESSERACT and the existing mainframe system. PPPL participated as a collaborative partner in the PeopleSoft HRMIS implementation and the associated University time collection system. In June of FY2001 these systems became operational, providing PPPL administrators with significantly increased functionality through desktop access to relevant databases, reports, and reporting tools.

Technology Transfer

The transfer of technology to private industry, academic institutions, and other federal laboratories is one of the missions of the Princeton Plasma Physics Laboratory (PPPL). The Laboratory is presently working with a number of partners in scientific research and technology development. These collaborations, are Cooperative Research and Development Agreements (CRADAs) or Work For Others (WFOs) projects, and primarily involve applications of science and technology developed for PPPL's fusion program. In addition to CRADAs and WFOs the Laboratory also uses Personnel Exchanges and Technology Maturation projects to promote the transfer of PPPL technology.

A CRADA, which is a contractual agreement between a Federal Laboratory and one or more industrial partners, enables industry and PPPL researchers to work on programs of mutual interest. Costs and project results are generally shared between the PPPL and the partner. WFOs arrangements may involve either federal or non-federal partners. The partners pay for the work performed at PPPL. In the Personnel Exchange Program, researchers from industry assume a work assignment at the Laboratory, or PPPL staff may visit the industrial setting. In a Technology Maturation Project, a Laboratory researcher may work on technologies of interest to industry, but further development is required before a formal collaboration can begin. In addition to the above technology transfer mechanisms, the PPPL Technology Transfer Office encourages the development of technologies that are potentially relevant to commercial interests. These projects are funded by PPPL as Laboratory Program Development Activities (LPDAs).

The PPPL Technology Transfer Office works closely with the Laboratory's Budget Office and with the Princeton University Office of Research and Project Administration (ORPA). PPPL technology is licensed through ORPA, and PPPL inventions are processed through OPRA. The Laboratory works closely with the University for the patenting and protection of PPPL intellectual property.

The American Textile Partnership

Work continued on The American Textile Partnership (AMTEX), 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 and Wellman Incorporated through the Princeton Textile Research Institute to develop a non-contact diagnostic instrument that can be used by U.S. synthetic fiber manufacturers to assure that fibers conform to specifications. Measurements will be made optically on the production line in real time.

PPPL has developed computer modeling to predict the relationship between fiber birefringence and the resultant pattern of laser light scattered from the fibers

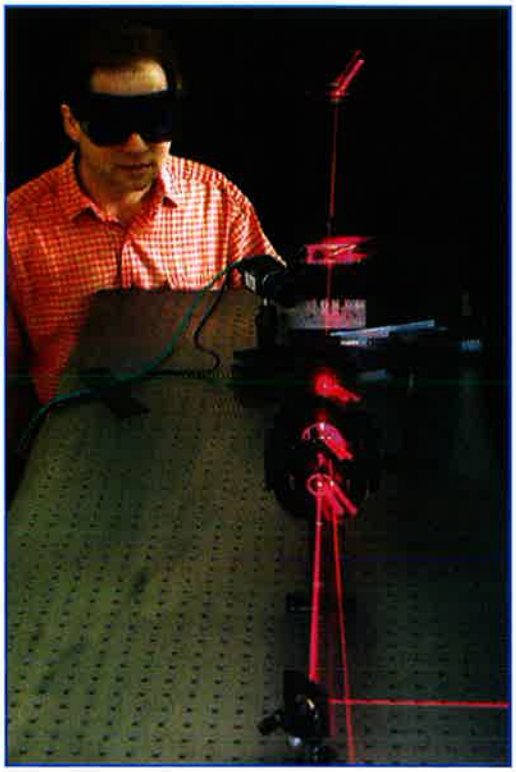


Figure 1. Analysis of helium-neon laser light scattered from a textile fiber is being investigated as a possible means of measuring important properties of these fibers, such as the birefringence and diameter. The goal is to develop a nearly real-time measurement that can be used by the textile industry. This photo shows a laboratory experiment in which scattered light is observed with a TV camera and processed by a computer.

(Figure 1). Birefringence is the difference between the refractive index of a fiber measured parallel to the fiber axis and that measured perpendicular to the axis. This provides information on the orientation of the molecules in the fiber. In comparing the measured results with accepted industry measurements, it was found that the refractive index measurement for the perpendicular direction was inconsistent with the industry measurements and had variations in readings that were too wide to be useful for the fiber industry. It was determined that the main cause of the errors was the nonround cross-sections of the fibers during manufacture. Computer modeling was continued on nonround fibers and on fiber bundles during FY2001 and fiber data was taken from a two-dimensional measurement system that uses a laser and a CCD camera to detect the pattern. The results were compared with fiber birefringence data supplied by the Princeton Textile Research Institute. These measurements confirmed that the technique is accurate in the parallel direction, but work is still needed to resolve the inconsistencies in the perpendicular direction.

Work for Others

Title: Experimental and Theoretical Studies of Nonneutral Plasmas

Sponsor: Office of Naval Research

Scope: This program includes theoretical and experimental work in critical problem areas related to the equilibrium, stability, and nonlinear properties of nonneutral plasmas. (See Nonneutral Plasmas and High Intensity Accelerators, page 70.)

Start Date: April 1, 1996

Completion Date: March 31, 2002

Title: Sterilization of Liquid Foods

Sponsor: U.S. Department of Agriculture (USDA)

Scope: The purpose of this effort is to develop new pasteurization methods that use radio-frequency waves and microwave heating. These techniques, also used to heat plasma in a fusion device, are being tested for pasteurizing raw liquid foods such as eggs, fruit juices, and milk. 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 radio-frequency waves of the appropriate wavelength may allow pasteurization without heating liquid foods to temperatures that cause food deterioration.

During FY2001, new radio-frequency equipment was assembled and operated at the USDA facility with the help of PPPL engineers and technicians. The equipment has the capability of operating at lower frequencies and higher field strengths than the radio-frequency equipment originally used. The fields are being applied across a gap of 0.20 cm between two rounded electrodes, between which the liquid flows. The new equipment is also capable of generating various waveforms that include sine wave, square wave, and triangular wave. Due to power limitations of the energy supply, only low conductivity liquids can be treated at present. The population of Saccharomyces cerevisiae in water at 45 °C was reduced by 99%. Such nonthermal inactivation could preserve unique functional properties and flavor of liquid foods such as beer, juices, and cider.

Start Date: October 1, 1997

Completion Date: September 30, 2001

Title: Low-frequency MHD Waves in the Magnetosheath

Sponsor: National Science Foundation

Scope: This program involves a systematic study of the generation, propagation, and structure of low-frequency magnetohydromagnetic waves and their effects on plasma transport in the magnetosheath-magnetopause region for quasi-perpendicular bow shocks.

Start Date: February 1, 1998

Completion Date: September 30, 2001

Title: Hall Current Microthruster

Sponsor: Air Force Office of Scientific Research

Scope: This project involves the design, fabrication, and testing of a family of microthrusters that are based on the Hall-Current thruster principle, but exhibit novel features that make the scaling to the micro-propulsion regime attractive. (See Hall Thruster, page 65.)

Start Date: February 1, 1999

Completion Date: September 30, 2001

Title: Equilibrium Magnetic Field and Current of the Earth's Magnetosphere

Sponsor: National Aeronautics and Space Administration (NASA)

Scope: The objective of this project is to perform studies of realistic three-dimensional magnetospheric equilibrium structures of magnetic field, plasma currents, and plasma pressure by solving the force balance equation. The studies will be based on satellite measurements of anisotropic plasma pressure and magnetic fields.

Start Date: February 9, 1999

Completion Date: February 28, 2002

Title: Magnetic Reconnection Experiment

Sponsors: National Aeronautics and Space Administration (NASA), National Science Foundation (NSF)

Scope: A basic plasma physics research facility, the Magnetic Reconnection Experiment, is studying the physics of magnetic reconnection — the topological breaking and reconnection of magnetic field lines in plasmas. Scientists hope to understand the governing principles of this important plasma physics process and gain a basic understanding of how it affects plasma characteristics such as confinement and heating. The results of these experiments will have relevance to solar physics, astrophysics, magnetospheric physics, and fusion energy research. (See Magnetic Reconnection Experiment, page 23.)

Start Date: October 1, 1995

Completion Date: January 31, 2003

Title: DOE/JAERI Annex IV

Sponsor: Japan Atomic Energy Research Institute (JAERI)

Scope: The Tokamak Fusion Test Reactor (TFTR) completed experimental operations at PPPL in 1997, following three years of experiments with deuterium-tritium plasmas. This effort involves: (1) measurements and analysis of tritium distribution in the TFTR vacuum vessel; (2) basic research for the different radioactive liquid waste treatment techniques at TFTR; (3) experiments on the removal of tritium from plasma-facing graphite tile surfaces using UV and Nd:Yag lasers; (4) experiments on different technologies for the decontamination and decommissioning of TFTR components, including graphite tiles and vacuum vessel components; and (5) the characterization of materials, such as tile and concrete, which were exposed to tritium for long periods of time (Figure 2).

Start Date: July 1, 1998

Completion Date: June 30, 2001

Title: Spherical Torus Propulsion by Means of Coaxial Helicity Ejection

Sponsor: National Aeronautics and Space Administration (NASA)

Scope: Direct extraction of nuclear fusion energy for propulsion has the potential for enabling relatively fast outer solar system travel. Coaxial Helicity Ejection (CHE) offers the possibility of extracting plasma kinetic energy for propulsion directly from a spherical torus, a compact plasma confinement system expected to deliver high fusion performance. PPPL has developed the overall goals and requirements for testing the scientific feasibility of CHE propulsion utilizing the National Spherical Torus Experiment magnetic fusion research facility.

Figure 2. Nd:YAG lasers are used at PPPL for the removal of tritium from first-wall materials. This technique has proven to be quite effective in the removal of co-deposited layers from the Tokamak Fusion Test Reactor and the Joint European Torus tiles and surfaces. Up to 87% of tritium has successfully been removed using this technique.

Start Date: March 1, 2000

Completion Date: March 31, 2001

Title: Electromagnetic Launcher

Sponsor: U.S. Army

Scope: Engineering analyses were performed on electromagnetic launcher coils for the Army Research Laboratory (ARL) in Aberdeen, Maryland. These coils are part of a system being studied by ARL which would electromagnetically launch plates to provide active protection of a tank against incoming projectiles. PPPL-developed electromagnetic analysis codes were used in conjunction with commercial finite element codes to gain an understanding of the behavior of the coils during operation and to identify potential design improvements.

Start Date: October 1, 1999

Completion Date: December 31, 2000

Title: Korea Superconducting Tokamak Advanced Research, Phase II

Sponsor: Korean Basic Science Institute

Scope: PPPL is coordinating a U.S. team to support the design of the Korean Superconducting Tokamak Advance Research (KSTAR) device. KSTAR is the flagship project of the Korean National Fusion Program that was launched officially in January, 1996. The KSTAR device will be built at the National Fusion R&D Center at the Korean Basic Science Institute in Taejeon, Republic of Korea (Figure 3).

Start Date: October 1, 1999

Completion Date: March 31, 2002

Figure 3. The Korean Superconducting Tokamak Advance Research facility under construction in Taejeon, South Korea.

Title: Lithium Fluoride Bolometer

Sponsor: Princeton Electronic Systems, Inc.

Scope: PPPL collaborated on the design of a lithium fluoride bolometer and provided facilities and expertise for its calibration for a minority small business.

Start Date: October 1, 1999

Completion Date: December 31, 2000

Title: Ion-Bernstein Wave Antenna Windows for Frascati Tokamak

Sponsor: Ente per le Nuove Tecnologie, L'Energia e L'Ambiente

Scope: PPPL fabricated and tested three ceramic windows for the Ion-Bernstein Wave system on the Frascati Tokamak in Frascati, Italy.

Start Date: October 1, 1999

Completion Date: February 7, 2001

Title: Development of Innovative Micro-air Vehicles

Sponsor: Naval Research Laboratory

Scope: This effort is directed to the development of innovative Micro-air Vehicles that feature unique methods of mobility, propulsion, and control in support of the Naval Research Laboratory's Micro-air Vehicle Program. Micro-air Vehicles are aircraft that generally have a wing span of less than 12 inches, weigh less than one pound, and have a payload of less than one ounce. This program involves fundamental research into unconventional aerodynamics of miniature air vehicles and exploratory development involving feasibility demonstrations of useful Micro-air Vehicles.

Start Date: October 1, 2000

Completion Date: October 30, 2001

Title: Novel Materials for Electra's "Hibachi" Electron Beam Windows

Sponsor: Naval Research Laboratory

Scope: The goals of this project are to study, design, and produce thin "hibachi" windows fabricated from silicon or other novel materials for the Electra KrF laser system and perform a system engineering study for Electra (Figure 4).

Start Date: October 1, 2000

Completion Date: March 1, 2002

Title: Concept Exploration of Novel Hall Thruster

Sponsor: Defense Advanced Research Projects Agency (DARPA)

Scope: A critical component of satellite technology is the propulsion system that

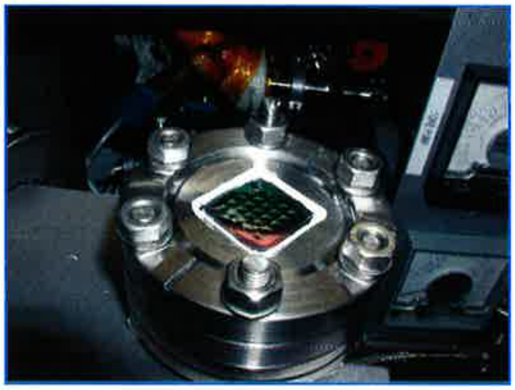


Figure 4. PPPL in collaboration with the Naval Research Laboratory is developing an electron-beam transmission window for use in KrF lasers for Inertial Fusion Energy. Novel components such as single-crystal silicon wafers shown in this photo are being investigated for this purpose.

maintains the position of orbiting satellites or transfers the satellite between orbits. A promising propulsion system is the Hall plasma thruster which employs magnetized electrons in crossed electric and magnetic fields, where the magnetic surfaces are also equi-potential surfaces, acting as virtual grids for electrostatic acceleration of unmagnetized ions. PPPL researchers seek to extend the scientific understanding of Hall thrusters or, more generally, the insulating properties of magnetized plasma, thereby developing novel and superior Hall thruster technology. (See Hall Thruster, page 65.)

Start Date: October 1, 2000

Completion Date: September 30, 2001

Title: Raman Pulse Compression of Intense Lasers

Sponsor: Defense Advanced Research Projects Agency (DARPA)

Scope: A moderately intense, but long, laser pulse can be scattered into short, very intense counter-propagating pulses in plasma through a variety of related mechanisms. The simplest and most efficient method is the well-studied stimulated Raman backscatter effect. In principle, fluences tens of thousands of times higher can be handled in plasma, making feasible significantly more intense lasers. In a collaboration involving the University of California, Berkeley, and Princeton University, scientists at PPPL are assessing the practical realization of the plasma-based pulse compression schemes. Preliminary experimental results show apparent amplification of the counter-propagating wave.

Start Date: October 1, 2000

Completion Date: September 30, 2002

Title: Energy Transport and Dissipation of Electromagnetic Ion Cyclotron Waves in the Magnetosphere/Ionosphere

Sponsor: National Aeronautics and Space Administration (NASA)

Scope: Electromagnetic ion cyclotron waves in plasmas are generated by electron-beam-driven instabilities. These waves play an important role in magnetosphere-ionosphere coupling. They are thought to be responsible for heating ionospheric ions, modulating auroral electron precipitation, populating the magnetosphere with energetic heavy ions during substorms, as well as producing parallel electric fields and electrostatic shock signatures. This program involves the development of solutions to full-wave equations for electromagnetic ion-cyclotron waves using a nonlocal theory that includes kinetic effects and ionospheric collisions. The solutions can provide specific predictions of global electromagnetic ion-cyclotron wave structure, wave polarization, and Poynting fluxes that are observable parameters that can be compared directly with spacecraft measurements.

Start Date: March 2, 2001

Completion Date: April 30, 2004

Title: UV Reactor Vessel

Sponsor: Rutgers University

Scope: The Princeton Plasma Physics Laboratory provided detailed design and fabrication support for the development of a stainless steel vacuum vessel for a photochemical remediation reactor system under development at Rutgers University. This technology has the potential to provide an efficient process for the destruction of organic contaminants.

Start Date: December 1, 2000

Completion Date: March 31, 2001

Patents and Invention Disclosures

Patent Issued

X-ray Imaging Crystal Spectrometers for Extended X-ray Sources
— Manfred L. Bitter, Ben Fraenkel, James L. Gorman, Kenneth W. Hill,
A. Lane Roquemore, Wolfgang Stodiek, and Schweickhard E. von Goeler

Patent Application

Energetic Ions for Sterilization
— John A. Schmidt

Invention Disclosures

Particle Bunch Compressor Based on Counter-propagating Laser Beams
— Gennady Shvets and Nathaniel J. Fisch

Low Power RF Sterilization Experiment
— Christopher D. Brunkhorst

Window for Transmission of Electron Beam
— Richard J. Hawryluk and H.M. Fan

Methods of Directing Plasma Flow along Magnetic Discontinuities
— Ilya Dodin and Nathaniel J. Fisch

A Method to Drive On-axis Current in the Field-reversed Configuration (FRC)
— Samual A. Cohen and Alan H. Glasser

Resonant Heating Below the Cyclotron Frequency
— Liu Chen, Zhihong Lin, and Roscoe White

Electrostatic Cleaning of Dielectric Surfaces
— Lewis Meixler

Method for Combining Pulsed-laser Beams into a Single Laser Beam with One Polarization
— Benoit Paul LeBlanc

Oxidative Tritium Decontamination System
— Charles Gentile, Gregory Guttadora, and John Parker

Method for Producing Toroidal Current in a Spherical Torus by Outboard Biasing
— Stephen C. Jardin

Pin Diode Tritium Detector
— Charles Gentile, Steve Langish, and Andy Carpe

Renewable Variable Resistor/Circuit Breaker for High Electric Currents
— Leonid E. Zakharov, Charles L. Neumeyer, and Neil Morley

CO_2 Blast Cleaning and Cooling and New Processes for Diamond Wire Saw Cutting of Complex Metal Structures
— Robert F. Parsells, Geoff Gettelfinger, Erik Perry, and Keith Rule

A System to Mitigate JxB Forces on Liquid Metal Plasma-facing Components
— Richard Majeski

Toroidal Closed Magnetic Field Plasma Thruster
— Nikolai Gorelenkov and Leonid Zakharov

Laser Backscatter Measurement of Optical Indices
— Brentley Stratton, Hideo Okuda, Dennis Mansfield, and Phil Efthimion

Self-ionizing, Plasma-based Backward Raman Laser Amplifier
— Daniel S. Clark and Nathaniel J. Fisch

Hydrostat/Pump Cart
— J. Desandro, Mike Kalish, and Bob Herskowitz

Collaborators

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
Brookhaven National Laboratory, Upton, NY
Budker Institute of Nuclear Physics, Novosibirsk, Russia
Centro De Fusão Nuclear, Instituto Superior Técnico, Lisbon, Portugal
Consorzio RFX, Padua, Italy
Ecole Royal Militaire, Brussels, Belgium
EFDA-Garching, Garching, Germany
EFDA-JET Close Support Unit, Abingdon, Oxfordshire, United Kingdom
Environmental Measurements Lab, U.S. Department of Energy, New York, NY
Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID
Institute of Applied Physics, Nizhny Novgorod, Russia
Institute for Nuclear Research, Kyiv, Ukraine
Institute for Plasma Research, Ghandinagar, India
Forschungszentrum, Jülich GmbH, Germany
Forschungszentrum Karlsruhe Technik und Umwelt, Eggenstein-Leopoldshafen, Germany
ITER Joint Work Site, Garching, Germany
Japan Atomic Energy Research Institute, Naka Fusion Research Establishment, Ibaraki, Japan
Japan Atomic Energy Research Institute, Tokai Research Establishment, Ibaraki, Japan
Korea Atomic Energy Research Institute, Taejon, Korea
Korea Basic Science Institute, Taejeon, Korea
Lawrence Berkeley National Laboratory, Berkeley, CA
Lawrence Livermore National Laboratory, Livermore, CA
Los Alamos National Laboratory, Los Alamos, NM
Lovelace Respiratory Research Institute, Albuquerque, NM
Max Planck Institüt für Plasmaphysik, Garching, Germany
Max Planck Institüt für Plasmaphysik, Greifswald, Germany
Max Planck Institüt für Quantenoptik, Garching, Germany
Mound Large Scale DDP, Miamisburg, OH
National Energy Technology Laboratory, Morgantown, WV
National Institute for Fusion Science, Toki, Japan
Oak Ridge National Laboratory, Oak Ridge, TN
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
The 2001 DOE Pollution Prevention Conference Committee, Albuquerque, NM
Troitsk Institute of Innovative and Thermonuclear Research, Troitsk, Russian Federation
UKAEA, Government Division, Fusion, Culham, United Kingdom
US Department of Agriculture, Eastern Regional Research Center, Philadelphia, PA
Virtual Laboratory for Technology, San Diego, CA

Industries

Active Environmental Technologies, Mount Holly, NJ
Advanced Energy Systems, Medford, NY
Badger Meter, Inc., Tulsa, OK
BASF, Charlotte, NC
Boeing Company, St. Louis, MO
Charged Injection Corporation, Monmouth Jct., NJ
ChemTreat, Inc., Richmond, VA
CompX, Inc., Del Mar, CA
DuPont Chemical Corporation, Wilmington, DE
Ecopulse, Washington, DC
Framatone Connector, Inc., Manchester, NH
Freehold Soil Conservation District, Freehold, NJ
General Atomics, San Diego, CA
HDR Engineering, Omaha, NE
Lodestar, Boulder, CO
Lucent Technologies, Murray Hill, NJ
Mission Research Corporation, Newington, VA
Nova Photonics, Inc., Princeton, NJ
Princeton Electronic Systems, Princeton Junction, NJ
Princeton Satellite Systems, Princeton, NJ
Princeton Scientific Instruments, Inc., Princeton, NJ
QC, Inc., Southampton, PA
Radiation Science, Belmont, MA
Schlumberger EMR Photoelectric, Princeton Junction, NJ
Stony Brook Regional Sewage Authority, Princeton, NJ
U.S. Filter-Stranco Products, Bradley, IL
Wellman, Charlotte, NC

Universities and Educational Organizations

Allentown High School, Allentown, NJ
American Association of Engineering Societies, Washington, DC
American Physical Society, College Park, MD
Antheil Elementary School, Ewing, NJ
Auburn University, Auburn, AL
Augsburg University, Augsburg, Germany
The Australian National University, Canberra, Australia
A+ for Kids, Plainsboro, NJ

Bridges To The Future,
Lawrenceville, NJ
Burlington City Schools, Burlington, NJ
Caltech, Pasadena, CA
Carl Getz Middle School, Jackson, NJ
Center for Technological Education
Holon, Holon, Israel
Chesterfield Elementary,
Bordentown, NJ
Christopher Columbus School,
Trenton, NJ
The College of New Jersey, Trenton, NJ
Colorado School of Mines, Golden, CO
Columbia University, New York, NY
The Contemporary Physics Education
Project, Palo Alto, CA
Corpus Christi School, Willingboro, NJ
Drexel University, Philadelphia, PA
Ecole Polytechnique, Palaiseau, France
The Education Fund of Trenton,
Trenton, NJ
The Foxcroft School, Arlington, VA
Florence Public Schools, Florence, NJ
Foundation for Research & Technology-
HEKLAS, Heraklion, Greece
Georgia Institute of Technology,
Atlanta, GA
Grace N. Rogers School, East Windsor
Regional District, NJ
Harvard-Smithsonian Center for
Astrophysics, Cambridge, MA
Himeji Institute of Technology, Himeji
Hyogo, Japan
Hiroshima University, Hiroshima, Japan
Hope College, Holland, MI
IASA Advisory Council
Idaho State University, Pocatello, ID
Institute of Electrical and Electronics
Engineers, Washington, DC
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, Korea
Korea Astronomical Observatory,
Taejeon, Korea
Kyoto University, Kyoto, Japan
Kyushu Tokai University,
Kumamoto, Japan
Lehigh University, Bethlehem, PA
Martin Luther King Middle School,
Trenton, NJ
Massachusetts Institute of Technology,
Cambridge, MA
Mid-Atlantic Eisenhower Consortium,
U.S. Department of Education,
Philadelphia, PA
Mount St. Mary's High School,
North Plainfield, NJ
The National Science Foundation,
Washington, DC
National Urban League-Executive
Exchange Program, New York, NY
New Jersey Department of Education,
Trenton, NJ
New Jersey Institute of Technology,
Newark, NJ
New York University, New York, NY
Oak Ridge Institute for Science and
Engineering, Oak Ridge, TN
Parkway Elementary, Trenton, NJ
Peddie School, Hightstown, NJ
Philadelphia Alliance for Minority
Participation, Philadelphia, PA
Plainsboro Public Library,
Plainsboro, NJ
Pohang University of Science and
Technology, Pohang, Korea
Prairie View A&M University,
Prairie View, TX
Princeton University, Princeton, NJ
Racah Institute, Hebrew University,
Jerusalem, Israel
Ruhr-Universität, Bochum, Germany
Rutgers University, New Brunswick, NJ
Seoul National University, Seoul, Korea
Shady Side Academy, Pittsburgh, PA
Sigma Xi, the Scientific Research
Society, Princeton, NJ

Steinert High School, Hamilton, NJ
Sullivan County Community College, Liberty, NY
Swarthmore College, Swarthmore, PA
Swiss Federal Polytechnic Institute, Lausanne, Switzerland
Technische Universitat Graz, Graz, Austria
Terrill Middle School, Scotch Plains, NJ
Texas A&M University, College Station, TX
Timberlane Middle School, Hopewell, NJ
Toll Gate Grammar School, Pennington, NJ
Trenton Public Schools, Trenton, NJ
Université-Paris XI, Orsay, France
University of Alaska, Fairbanks, AK
University of California, Berkeley, CA
University of California, Davis, CA
University of California, Irvine, CA
University of California, Los Angeles, CA
University of California, San Diego, CA
University of Chicago, Chicago, IL
University of Houston, Houston, TX
University of Illinois, Urbana, IL
University of Maryland, College Park, MD
University of Michigan, Ann Arbor, MI
University of Montana, Missoula, MT
University of Pittsburgh at Greensburg, Greensburg, PA
University of Sussex, Falmer, United Kingdom
University of Texas, Austin, TX
University of Tokyo, Tokyo, Japan
University of Washington, Seattle, WA
University of Wisconsin, Madison, WI
WEPAN (Women Engineering Program Advocates Network), Fairfax, VA
Westminster College, New Wilmington, PA
Yale University, New Haven, CT

Graduate Education

Program in Plasma Physics graduate students for academic year 2000-2001. On the floor is Jef Spaleta. Seated (from left): Barbara Sarfaty (Graduate School Administrator), Prateek Sharma, Weihua Zhou, Moses Chung, Vyacheslav (Slava) Lukin, Fei Chen, Tim Gray, Seunghyeon Son, and David Smith. Standing middle row (from left): Pavel (Paul) Kolchin, Alexandra (Sasha) Landsman, Yang Ren, Brent Jones, Elizabeth (Jill) Foley, and Adam Rosenberg. Standing top row (from left): Nikolai Yampolsky, Soren Zaharia, Kyle Morrison, Mark Boaz, Tom Kornack, and Tom Jenkins.

The Princeton Plasma Physics Laboratory (PPPL) supports graduate education through the Program in Plasma Physics in the Department of Astrophysical Sciences and the Program in Plasma Science and Technology which is interdisciplinary, including the departments of Astrophysical Sciences, Chemical Engineering, Chemistry, Civil Engineering, Computer Science, Electrical Engineering, Mechanical and Aerospace Engineering, and Physics.

Program in Plasma Physics

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

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

In FY2001, there were 36 graduate students in residence in the Program in Plasma Physics, holding between them four U.S. Department of Energy Magnetic Fusion Science Fellowships, one Hertz Fellowship, one National Science Foundation Graduate Fellowship, and one Princeton University Charlotte Proctor Honorific Fellowship.

Nine new students were admitted in FY2001, one from Russia, two from China, one from Korea, one from India, and four from the United States (Table 1). Five students graduated in FY2001, two receiving postdoctoral positions, one at the Naval Research Laboratory and one at the Princeton Plasma Physics Laboratory. Two students won U.S. Department of Energy Fusion Energy Postdoctoral Fellowships and are working at the University of California, Los Angeles, and PPPL. One graduate took a position in private industry (Table 2).

Program in Plasma Science and Technology

Applications of plasma science and technology meld several traditional scientific and engineering specialties. The Program in Plasma Science and Technology (PPST) provides 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 PPST. 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 mi-

Table 1. Students Admitted to the Plasma Physics Program in FY2001.

Student	Undergraduate Institution	Major Field
David Auerbach	Swarthmore College	Physics
Fei Chen	Peking University	Plasma Physics
Moses Chung	Seoul National University	Plasma Physics
Timothy Gray	Swarthmore College	Physics
Vyacheslav Lukin	Swarthmore College	Physics
Prateek Sharma	India Institute of Technology	Physics
David R. Smith	Northwestern University	Physics
Nikolai Yampolsky	Nizhny Novgorod University	Plasma Physics
Weihua Zhou	Peking University	Plasma Physics

Table 2. Recipients of Doctoral Degrees in FY2000.

Breslau, Joshua
Thesis: Numerical Study of Magnetic Reconnection in Merging Flux Tubes
Advisor: Stephen C. Jardin
Employer: Princeton Plasma Physics Laboratory

Li, Xiaohu
Thesis: Laser-plasma Interaction in Plasma Channel and Relativistic Dynamics
Advisor: Gennady Shvets
Employer: Lehman Brothers

Munsat, Tobin
Thesis: Transient Transport Experiments in the CDX-U Spherical Torus
Advisor: Richard P. Majeski and Masayuki Ono
Employer: Princeton Plasma Physics Laboratory

Schekochihin, Alexander
Thesis: Statistical Theory of Small-scale Turbulent Astrophysical Dynamo
Advisor: Russell M. Kulsrud
Employer: University of California, Los Angeles

Strasburg, Sean
Thesis: Dynamics of Intense Charged-particle Beams
Advisor: Ronald C. Davidson
Employer: Naval Research Laboratory

croelectronic and micro-optical components and the deposition of tribological, magnetic, optical, conducting, insulating, polymeric, and catalytic thin-films. Plasmas are also important for illumination, microwave generation, destruction of toxic wastes, chemical synthesis, space propulsion, control system theory and experiment, and advanced-design particle accelerators.

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. In FY2001, 15 graduate students received support from the Program in Plasma Science and Technology during the academic year and/or summer. They coauthored more than a dozen refereed publications. Four PPST-supported students received Ph.D. degrees from their respective departments.

Dr. R. Siemon (Los Alamos National Laboratory) was the distinguished speaker at the Program in Plasma Science and Technology public lecture series, inaugurated last year to inform the Princeton community of contributions made by plasma science and technology to our society. In a talk entitled, "Fusion in a Beer Can," Dr. Siemon described an innovative concept for a compact fusion reactor.

To maintain this strong graduate program, increased efforts were made to develop appreciation for plasma physics in Princeton undergraduates. Through a summer internship program, three Princeton undergraduates worked on plasma-related projects. The Physics Department awarded Emma Torbert, an alumnus of our internship program, with the Kusaka prize, given for the best senior thesis, a study of “Discrete Modes in the Ion Acoustic Range of Frequencies in a Glow Discharge Plasma Column.”

Science Education

The goals of the Princeton Plasma Physics Laboratory (PPPL) Science Education Program are to provide a comprehensive portfolio of initiatives that leverages the creativity and enthusiasm of teachers to enhance the science learning and understanding of America's children in grades K through 12, to integrate research and education to improve teaching, to contribute to the training of the next generation of American scientists and engineers, and to improve the scientific literacy of the community at large. These initiatives allow PPPL staff to participate in science education and outreach through informal educational activities with K through 12 teachers and students and undergraduate college students.

Expand Your Horizons

Fiscal Year 2001 marked the inaugural year of the "Expand Your Horizons" Mini-conference for Young Women in Science, Mathematics, and Technology. More than 160 seventh through twelfth grade female students from schools throughout New Jersey participated. The goals were to increase interest in science and mathematics, to provide students an opportunity to meet women working in scientific fields, and to foster an awareness of varied career opportunities for women.

The daylong event included talks by female scientists, an interactive panel discussion with female graduate students in physics, and hands-on exhibits. Guest speakers and panelists were from the NASA/Goddard Space Flight Center,

Participants of the 2001 "Expand Your Horizons" Mini-conference for Young Women in Science, Mathematics, and Technology.

Table 1. Schools that participated in the 2001 "Expand Your Horizons" Mini-conference for Young Women in Science, Mathematics, and Technology.

Colleges

The College of New Jersey College Bound Program, Ewing, NJ

High Schools

High Technology High School, Lincroft, NJ
Northern Burlington High School, Columbus, NJ
Trenton Central High School, Trenton, NJ
Vineland High School-South, Vineland, NJ
West Windsor-Plainsboro High School-North, Plainsboro, NJ
Woodbridge High School, Woodbridge, NJ

Middle Schools

Arthur Holland Middle School, Trenton, NJ
Grace A. Dunn Middle School, Trenton NJ
Helen A. Fort Middle School, Pemberton, NJ

Elementary Schools

Columbus Elementary School, Trenton, NJ
Granville Charter School, Trenton, NJ
Joyce Kilmer Elementary School, Trenton, NJ

Princeton University, the Princeton Plasma Physics Laboratory, the Fashion Institute of Technology, Massachusetts Institute of Technology, the New Jersey Institute of Technology, the University of California-Los Angeles, and the University of Pennsylvania. Exhibitors included Bristol-Meyers Squibb, FMC Corporation, Lucent Technologies, Communications Workers of America, Princeton Environmental Institute, and the PPPL Science Education Program.

The conference was effective in introducing young women to careers open to them in science. One participant, a tenth grader stated, "It made me realize that there are a lot of opportunities for women to advance in science and math. It was very interesting and provided us with a lot of information. It also motivated me to pursue a career in science and math." Another said, "This conference opened my eyes to tons of career possibilities, broadened my horizons, and also stimulated my mind. I loved it."

The event was co-sponsored by the PPPL Science Education Program, the PPPL Director's Advisory Committee on Women, and the Director's Minority Advisory Committee.

Plasma Camp

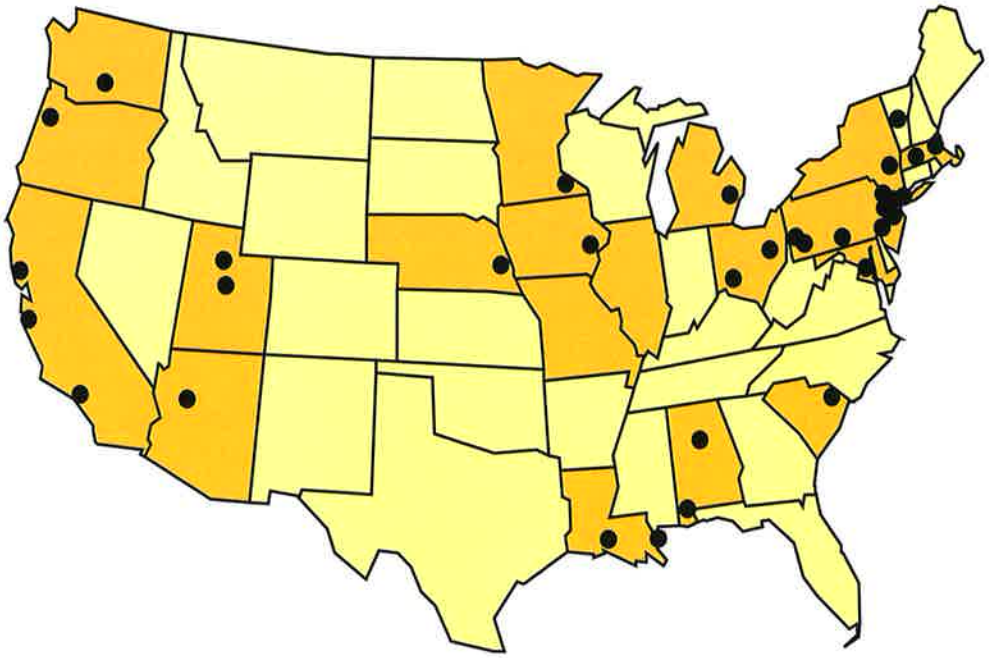
For the fourth time since FY98, the Plasma Physics and Fusion Energy Institute for High School Physics Teachers (Plasma Camp) brought together at PPPL the best physics teachers in the country for a two-week intensive workshop of lectures, lab work, and curriculum design (see map below).

Plasmas are ideal to illustrate many concepts in physics curricula including waves, atoms, nuclear reactions, relativity, electricity and magnetism. The goal of Plasma Camp is to weave plasmas into existing introductory physics curricula at a variety of levels. A student of a Plasma Camp participant wrote, "Besides plasma's obvious merits, it looks cool and is fun to play with, it teaches a type of thinking I think is more important to learn than any single physical concept."

In FY2001, participants included new teachers and veterans of past workshops. Lecture topics included plasma theory, fusion basics, tokamaks, atmospheric plasmas (ionosphere, whistler waves), and energy and the environment. New teachers performed experiments on plasma breakdown, plasma spectroscopy, and microwave interferometry. Veteran teachers ran a "piggy-back" experiment on the National Spherical Torus Experiment (NSTX) and built a dc glow discharge tube for their classroom. All participants wrote new curricula based upon their theoretical and experimental work. A participant of this year's workshop wrote, "Helping students discover the beauty and complexity of the physical world is a great endeavor... . Working with scientists doing research on fusion and bringing part of this knowledge to students is an experience all physics teachers should have."

Doing Research at NSTX

Five of the veteran teachers spent a day in the NSTX control room, participating in group meetings before and after experimental runs, as well as collecting and analyzing data from their "piggy back" experiment. This is the first time that NSTX was used for science education purposes. Plasma Camp teachers looked at basic plasma parameters (density, temperature, confinement time) in ohmic- and neutral-beam-heated plasmas with different toroidal fields. The results and analysis were presented to the entire group using PPPL's high-resolution display wall. As one par-



Home Locations of Plasma Camp Participants 1998-2001

Plasma Camp attendees (l-r) Michael Liebl (Elkhorn, NE), Paulette Struckman (Monterey, CA), and Mark Brooks Hedstrom (Dayton, OH) in the National Spherical Torus Experiment Control Room analyzing data during an experimental run.

ticipant wrote, "I hope to be able to share with my students what an incredible experience it is to sit in the control room and share the excitement of the researchers."

Building Equipment

In a new activity in FY2001, Plasma Camp veteran teachers built a dc glow discharge tube for classroom demonstrations and for advanced student projects. Participants were trained in the physics and engineering of the plasma source and designed curricula that utilized the source. Student experiments planned with the tube included plasma breakdown and plasma spectroscopy.

Plasma Academy

In FY2001, a new PPPL science education program began that reaches out to under-represented high school students from the surrounding area called "Plasma Academy." Fifteen students from grades nine to twelve spent two weeks during the summer at PPPL working on a variety of topics centered upon energy (mechanical, solar, fusion) and astronomy. Students visited a coal-fired power plant, the Hayden Planetarium in New York City, and the planetarium at The Peddie School in Hightstown, NJ. At PPPL, students worked on solar energy projects and performed investigations of plasmas using plasma globes and half-coated fluorescent light bulbs. School-year follow-up workshops are planned during FY2002.

High School Mentoring

During FY2001, the PPPL Science Education Program continued mentoring outstanding high school students who engage in independent plasma physics research at their schools. Non-local students communicate predominately via e-mail and telephone, with an occasional visit to the Lab. Past projects have won national and international awards at student competitions and this trend continued in FY2001. Frank Provenzano, a student at New Rochelle High School, New Rochelle, NY, was a semifinalist in the 2001 Intel Science Talent Search, based on his research entitled "Analysis of Striations in a DC Glow Discharge Plasma." Erik Kaiser, a student at the Marine Academy of Science and Technology in Sandy Hook, NJ, continued his research on the Interactive Plasma Display.

Scientist-in-Residence Program

In FY2001, as part of its partnerships with surrounding school districts, PPPL began a Scientist-in-Residence Program targeting elementary schools. A PPPL scientist works with an entire grade of students over an extended period of time to increase their scientific literacy and teach scientific methodology using topics that complement the school's existing curriculum. Students work in small collaborative groups on a research topic, supported by their teacher and the PPPL scientist. During the residency, a variety of activities to support student projects are used to foster critical thinking skills, as well as increase understanding of the current topic.

Plasma Academy student testing his solar-powered car.

The first residency program involved the fifth grade of the Woodrow Wilson Elementary School in Westfield, NJ. The FY2001 project was entitled "The Sun, the Solar System, and Solar Energy." Each group designed and built a solar powered device of its choice using solar panels, motors, gears and Legos™. It is expected that the program will continue at Woodrow Wilson Elementary School and will expand into other districts.

Awards and Honors

Individual Honors

Ronald Bell

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

Will Fox

Allen G. Shenstone Prize in Physics
Princeton University, Department of Physics

Robert Goldston

Leadership Award for 2001
Fusion Power Associates

Zhihong Lin

Presidential Early Career Award for Scientists and Engineers
President Bill Clinton

and

Early Career Award in Science and Engineering
U.S. Department of Energy, Office of Science

Charles Neumeyer

PPPL Distinguished Engineering Fellow
Princeton Plasma Physics Laboratory

and

Engineer of the Year
New Jersey Society of Professional Engineers

Francis "Rip" Perkins

PPPL Distinguished Research Fellow
Princeton Plasma Physics Laboratory

Edmund Synakowski
Kaul Foundation Prize for Excellence
in Plasma Physics and Technology Development
Princeton University
and
Fellow
American Physical Society

Michael Williams
Outstanding Achievement Award
American Nuclear Society, Fusion Energy Division

Kenneth Young
Distinguished Associate Award
U.S. Department of Energy

Sorin Zaharia
Ray Grimm Memorial Prize in Computational Physics
Princeton University

2000 PPPL Employee Recognition Award Recipients

Honored by their co-workers for their "personal qualities and professional achievements, fifteen PPPL employees received Employee Recognition Awards in 2000. The recipients are, from left, Greg Rewoldt, Colin McFarlane, Tom Holoman, Neil Pomphrey, Ceil O'Brien, Joellyn Lumberger, Wilbert Barlow, Marie Robbins, Steve Green, Antonio Morgado, Tom Egebo, Verne Clift, Don Perez, and James Nah. Not pictured is Steve Kemp.

Laboratory Awards

Outstanding Contribution to the Advancement of a Business Education Partnership

Princeton Area Chamber of Commerce

Recognition Award

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

Citation of Merit Award

New Jersey Governor's Occupational Safety and Health Awards Program
for the Environment, Safety & Health and Infrastructure Support Department
for Working throughout Calendar Year 2000 without Lost Time
from a Work-related Injury or Illness

Special Emphasis Award

U.S. Department of Energy
for PPPL's "Outstanding Achievement"
in Technology Transfer with Small Businesses

PPPL's Arlene White (middle) holds the Special Emphasis Award that PPPL received from the U.S. Department of Energy. William A. Lewis, Acting Director of Economic Impact and Diversity (left) and Stephen Mournighan, Acting Executive Director, DOE Office of Small and Disadvantaged Business Utilization, presented the award to White during the 2nd Annual DOE Small Business Conference in Las Vegas.

The Year in Pictures

U.S. Energy Secretary Bill Richardson brought welcome news to PPPL during an October 2000 visit, announcing a five-year extension of the contract between Princeton University and the U.S. Department of Energy. Richardson made the announcement to a large assembly of PPPL personnel, media, and visitors at the Laboratory.

On November 2, PPPL Director Rob Goldston delivered his annual "State-of-the-Lab" address to staff. Goldston lauded the Lab's research accomplishments, as well as the goals and successes of its external relations efforts and operations, stressing that PPPL's programs were "off and flying."

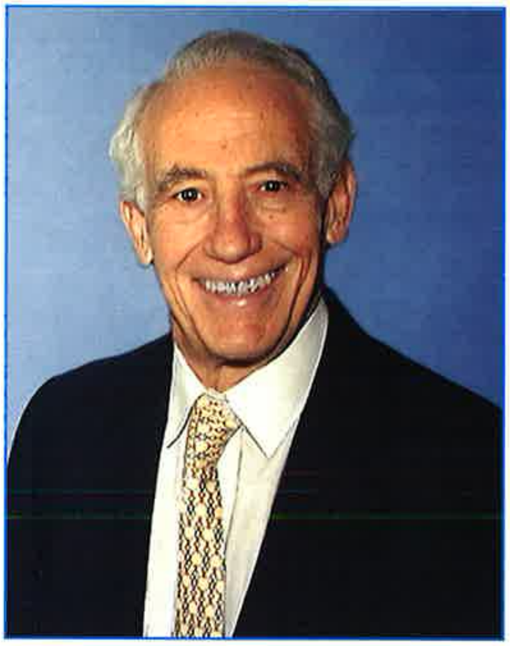
The disassembly of the Tokamak Fusion Test Reactor (TFTR) at PPPL progressed. On November 8, the umbrella structure and upper magnetic poloidal-field coils were lifted off the top of TFTR. Workers used the 110-ton capacity overhead bridge crane to make this 92-ton lift. The structure and coils were removed as part of the machine's disassembly, which is expected to be completed by September, 2002.

Former PPPL Director Melvin B. Gottlieb, an international leader in the field of research on fusion energy, died on December 1. Gottlieb, Director of PPPL from 1961-1980, was known for his tireless dedication to the fusion concept and for his constant inspiration to the fusion program worldwide, as well as for his leadership and for being the consummate "people person."

Experiments continued on the National Spherical Torus Experiment (NSTX), yielding positive results. The use of neutral-beam injection heating on NSTX, coupled with good confinement, allowed the NSTX National Research Team to produce a plasma toroidal beta of up to 22.5 percent. High betas could lead to the development of smaller, more economical fusion reactors.

The PPPL Scientific Speakers' Program kicked off in 2001. Researchers from the Lab delivered scientific talks at 11 sites, including colleges, universities, and research institutions. Those who participated in the program during 2001 are (from left) Raffi Nazikian, Janardhan Manickam, Ed Synakowski, Cynthia Phillips, John Schmidt, and Daren Stotler. Not pictured is Ned Sauthoff. As PPPL Director Rob Goldston noted during his State-of-the-Lab talk, "This is an important component of outreach to the broader scientific community."

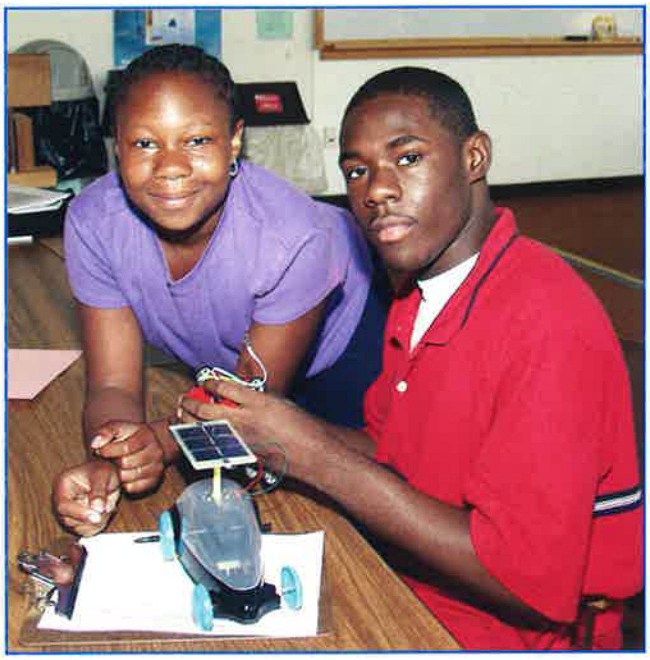
Twenty local government officials from surrounding communities, including county freeholders, mayors, elected committee members, school officials, and emergency services personnel, came to PPPL for a "Breakfast Briefing" on March 1, 2001. PPPL Director Rob Goldston gave a presentation, "Fusion for the New Century," discussing the present state of the fusion program and the Lab's major research activities. Following the breakfast and the presentation, many of the visitors toured the National Spherical Torus Experiment (NSTX) and the Tokamak Fusion Test Reactor (TFTR).



Thomas Stix, one of the most original thinkers and leading developers of the field of plasma physics, died April 16. Stix was a former Associate Director for Academic Affairs at PPPL and a former Director of the Program in Plasma Physics at Princeton University.

In June, the Laboratory honored 21 inventors for Fiscal Year 2000 during the annual Patent Awareness Program Recognition Dinner at Princeton University's Prospect House. Those attending the dinner and receiving awards were, from left, Tobin Munsat, Gail Eaton, John Desandro, Martha Redi, Nathaniel Fisch, Richard Majeski, Samuel Cohen, Charles Gentile, John Schmidt, Gennady Shvets, Robert Woolley, and John Parker.

In a quest for knowledge about energy and solar power, 16 high school students from the Trenton area came to PPPL in August to build solar-powered devices and shoot toy rockets. These hands-on activities were part of Plasma Academy (officially called the Energy, Space, and the Environment Institute). Topics covered were solar energy; clouds, weather, and storms; and the Sun, stars, planets, and plasmas. The Institute was part of a Mercer County Community College Upward Bound program. The participants test their solar-powered model car.



PPPL Financial Summary by Fiscal Year
(Thousands of Dollars)

	FY97	FY98	FY99	FY00	FY01
Operating Costs					
Fusion Energy Sciences					
TFTR Physics/Data Analysis	$13,607	$4,955	$317	$ –	$ –
TFTR Operations	13,497	–	–	–	–
TFTR Shutdown/Caretaking	12,368	3,292	2,952	3,125	3,800
TFTR D&D	–	–	371	8,976	13,602
Subtotal TFTR	$39,472	$8,247	$3,640	$12,101	17,402
NSTX	$1,441	$3,241	$13,737	$18,248	20,538
NCSX	702	2,524	2,840	3,644	3,156
Theory and Computation	2,929	4,003	5,161	5,823	5,757
Off-site Collaborations	4,028	9,241	9,281	8,342	7,722
Off-site University Research Support	–	985	697	719	871
CDX-U	479	802	680	876	771
MRX	39	165	221	600	513
Heavy Ion Fusion	210	238	415	513	1,078
Next-step Options	–	–	1,365	900	771
Science Education Programs	440	691	652	515	593
Waste Management*	–	–	–	–	3,086
ITER	3,546	3,677	488	–	–
TPX	(1,062)	(224)	(116)	–	(102)
Other Fusion	1,220	1,982	935	1,073	1,512
Change in Inventories**	(35)	(50)	(35)	4	(41)
Total Fusion Energy Sciences	$53,409	$35,522	$39,961	$53,358	$63,627
Environmental Restoration and Waste Mgt	$4,066	$3,735	$3,564	$3,036	95
Computational and Technology Research	157	101	92	21	72
Basic Energy Sciences	–	302	534	608	391
High Energy Physics	–	73	80	98	316
Safeguards and Security***	–	–	–	–	1,670
Other DOE	105	3	58	34	120
Total DOE Operating	$57,737	$39,736	$44,289	$57,155	$66,291
Work for Others					
Korea Basic Science Institute	$1,837	$2,039	$871	$81	(6)
All Other	1,199	2,218	1,755	1,180	2,138
TOTAL OPERATING COSTS	$60,773	$43,993	$46,915	$58,416	$68,423
Capital Equipment Costs					
TFTR	$241	$ –	$ –	$1,273	870
NSTX	3,412	12,268	8,503	5,532	2,393
Off-site Collaborations	–	–	544	655	1,714
All Other Fusion	32	–	426	242	917
Environmental Restoration and Waste Mgt	75	(1)	58	1	177
TOTAL CAPITAL EQUIPMENT COSTS	$3,760	$12,267	$9,531	$7,703	$6,071
Construction Costs					
General Plant Projects - Fusion	$473	$454	$798	$2,070	$1,533
Energy Management Projects	255	45	15	110	77
Other DOE Construction	35	–	(2)	7	–
TOTAL CONSTRUCTION COSTS	$763	$499	$811	$2,187	$1,610
TOTAL PPPL	$65,296	$56,759	$57,257	$68,306	$76,104

*Waste Management transferred to the Fusion Energy Sciences Program from Environmental Restoration/Waste Management in FY2001.

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

***Safeguards and Security became a direct funded activity in FY2001; funded through overhead prior to FY2001.

PPPL Organization

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Deputy Director

William M. Tang
Chief Scientist

Nathaniel J. Fisch
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Off-Site Research
  Ned R. Sauthoff

Plasma Science and Technology
  Philip C. Efthimion

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

Theory
  William M. Tang, Head
  Ronald C. Davidson, 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

	FY97	FY98	FY99	FY00	FY01
Faculty	6	6	3	3	3
Physicists	88	87	89	91	97
Engineers	76	74	74	85	82
Technicians	137	136	139	197	210
Administrative	66	68	69	77	73
Office and Clerical Support	19	18	19	21	20
Total	392	389	393	474	485

PPPL Advisory Council

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

Dr. Norman R. Augustine
Lockheed Martin Corporation

Dr. David E. Baldwin
General Atomics

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Yale University

Dr. Jonathan M. Dorfan
Stanford Linear Accelerator Center

Dr. Andrea Dupree
Harvard University

Professor Edward A. Frieman
Scripps Institution of Oceanography

Mr. Robert I. Hanfling
Putnam Hayes & Bartlett

Dr. William L. Kruer
Lawrence Livermore National Laboratory

Dr. Jerry D. Mahlman
Geophysical Fluid Dynamics Laboratory

Dr. Barrett Ripin
Research Applied

Professor Marshall N. Rosenbluth
University of California, San Diego

Publications

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*First author is from another institution. PPPL co-authors are underlined.
†Paper presented at a conference in fiscal year 2001; proceedings to be published.
§Submitted for publication in fiscal year 2001.

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Abbreviations, Acronyms, and Symbols

2-D	Two-dimensional
3-D	Three-dimensional
AS	Advanced Stellarator
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)
ARL	Army Research Laboratory
ARIES	Advanced Reactor Innovation Evaluation Studies
ASDEX	Axially Symmetric Divertor Experiment (at the Max-Planck-Institut für Plasmaphysik, Garching, Germany)
AT	Advanced Tokamak
B_t	Toroidal Magnetic Field
BEST	Beam Equilibrium Stability and Transport Code
BPX	Burning Plasma Experiment
CAD	Computer-aided Design
CADD	Computer-aided Design and Drafting
CAE	Compressional Alfvén Eigenmodes
CCD	Charge-coupled Device
CDR	Conceptual Design Review
CDX-U	Current Drive Experiment-Upgrade at the Princeton Plasma Physics Laboratory
CFC	Carbon Fiber Composite
CHE	Coaxial Helicity Ejection
CHERS	Charge-exchange Recombination Spectrometer

CHI	Coaxial Helicity Injection
CIC	Charge Injection Corporation
CIT	Compact Ignition Tokamak
cm	Centimeter
CME	Coronal Mass Ejection
C-Mod	A tokamak in the "Alcator" family at the Plasma Science and Fusion Center at the Massachusetts Institute of Technology
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 the DIII-D National Fusion Facility 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
ECRH	Electron Cyclotron Resonance Heating
EDA	Enhanced D_α Mode
EFDA	European Fusion Development Agreement
EFIT	An equilibrium code
E-LHDI	Electrostatic Lower-hybrid Drift Instability
ELMy	Edge Localized Modes
EPM	Energetic Particle Mode
ER/WM	Environmental Restoration and Waste Management
ERP	Enterprise Resource Planning
ET	Experimental Task
eV	Electron Volt

FAC	Field-aligned Current
FEAT	Fusion Energy Advanced Tokamak
FESAC	Fusion Energy Sciences Advisory Committee
FIRE	Fusion Ignition Research Experiment (a national design study collaboration)
FIReTIP	Far-infrared Tangential Interferometer and Polarimeter
FPT	Fusion Physics and Technology, Inc.
FRC	Field-reversed Configuration
FTP	File Transfer Protocol
FW	Fast Wave
FY	Fiscal Year
GA	General Atomics in San Diego, California
GDC	Glow Discharge Cleaning
GTC	Gyrokinetic Toroidal Code
HCX	High Current Experiment at the Princeton Plasma Physics Laboratory
H-mode	High Confinement Mode
HHFW	High Harmonic Fast Waves
HRMIS	Human Resources Management Information System
HYM	Hybrid and MHD Code
I_p	Plasma Current
IBX	Integrated Beam Experiment
ICF	Inertial Confinement Fusion
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
IGNITOR	Ignited Torus
IMF	Interplanetary Magnetic Field
IPP	Institut für Plasmaphysik, Garching, Germany
IRE	Integrated Research Experiment at the Princeton Plasma Physics Laboratory
IRE	Internal Reconnection Event

ISS	International Stellarator Scaling
ITB	Internal Transport Barrier
ITER	International Thermonuclear Experimental Reactor
ITG	Ion-temperature Gradient
JAERI	Japan Atomic Energy Research Institute
JET	Joint European Torus (JET Joint Undertaking) in the United Kingdom
JFT-2M	A small Japanese tokamak
JHU	Johns Hopkins University
JT-60U	Japanese Tokamak at the Japan Atomic Energy Research Institute
kA	Kiloampere
KAWs	Kinetic Alfvén Waves
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
LHCD	Lower-hybrid Current Drive
LHD	Large Helical Device; a stellarator operating in Japan
LHDI	Lower-hybrid Drift Instability
LIF	Laser-induced Fluorescence
L-mode	Low-confinement Mode
LPDA	Laboratory Program Development Activities at the Princeton Plasma Physics Laboratory
MA	Megampere
MAST	Mega Amp Spherical Torus at the Culham Laboratory, United Kingdom
MAV	Micro Air Vehicle
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
MPP	Massively Parallel Processor
MPTS	Multi-point Thomson Scattering
MRX	Magnetic Reconnection Experiment at the Princeton Plasma Physics Laboratory
ms, msec	Millisecond
MSE	Motional Stark Effect (Diagnostic)
MW	Megawatt
NASA	National Aeronautics and Space Administration
NBI	Neutral Beam Injection (Heating)
NCSX	National Compact Stellarator Experiment (a national design study collaboration)
NERSC	National Energy Research Supercomputer Center
NNBI	Negative-ion-based Neutral-beam Injection
NPA	Neutral Particle Analyzer
NRL	Naval Research Laboratory
NSF	National Science Foundation
NSO	Next Step Option
NSTX	National Spherical Torus Experiment at the Princeton Plasma Physics Laboratory
NTM	Neoclassical Tearing Mode
NTX	Neutralized Transport Experiment
OFES	Office of Fusion Energy Sciences (at the U.S. Department of Energy)
OH	Ohmic Heating
ORNL	Oak Ridge National Laboratory, Oak Ridge, Tennessee
ORPA	Office of Research and Project Administration at Princeton University
OS	Optimized Shear
PAC	Program Advisory Committee

PBX-M	Princeton Beta Experiment-Modification at the Princeton Plasma Physics Laboratory (no longer operating)
PF	Poloidal Field
PFC	Plasma Facing Component
PLT	Princeton Large Torus at the Princeton Plasma Physics Laboratory (no longer operating)
PPPL	Princeton Plasma Physics Laboratory in Princeton, New Jersey
PPST	Program in Plasma Science and Technology
PSACI	Plasma Science Advanced Scientific Computing Initiative
PTSX	Paul Trap Simulator Experiment
Q	The ratio of the fusion power produced to the power used to heat a plasma
QA	Quality Assurance
QA	Quasi-axisymmetry
QAS	Quasi-axisymmetry Stellarator
QDB	Quiescent Double Barrier
REs	Reconnection Event(s)
rf	Radio-frequency (Heating)
R&D	Research and Development
RI	Radiative-improved Confinement Mode
RMF	Rotating Magnetic Field
RTAE	Resonant TAE
RWM	Resistive Wall Modes
SOL	Scrape-off Layer
ST	Spherical Torus
START	Small Tight Aspect Ratio Tokamak at Culham, United Kingdom
T	Temperature
TAE	Toroidicity-induced Alfvén Eigenmode or Toroidal Alfvén Eigenmode
TEM	Trapped-electron Mode
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
UCSD	University of California at San Diego
ULF	Ultra-low Frequency
USDA	United States Department of Agriculture
USDOE	United States Department of Energy
UV	Ultraviolet
W7-AS	Wendelstein-7 Advanced Stellarator, an operating stellarator in Germany
W7-X	A stellarator being built in Germany
WFOs	Work For Others
XP	Experimental Proposal
Y2K	Year 2000

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