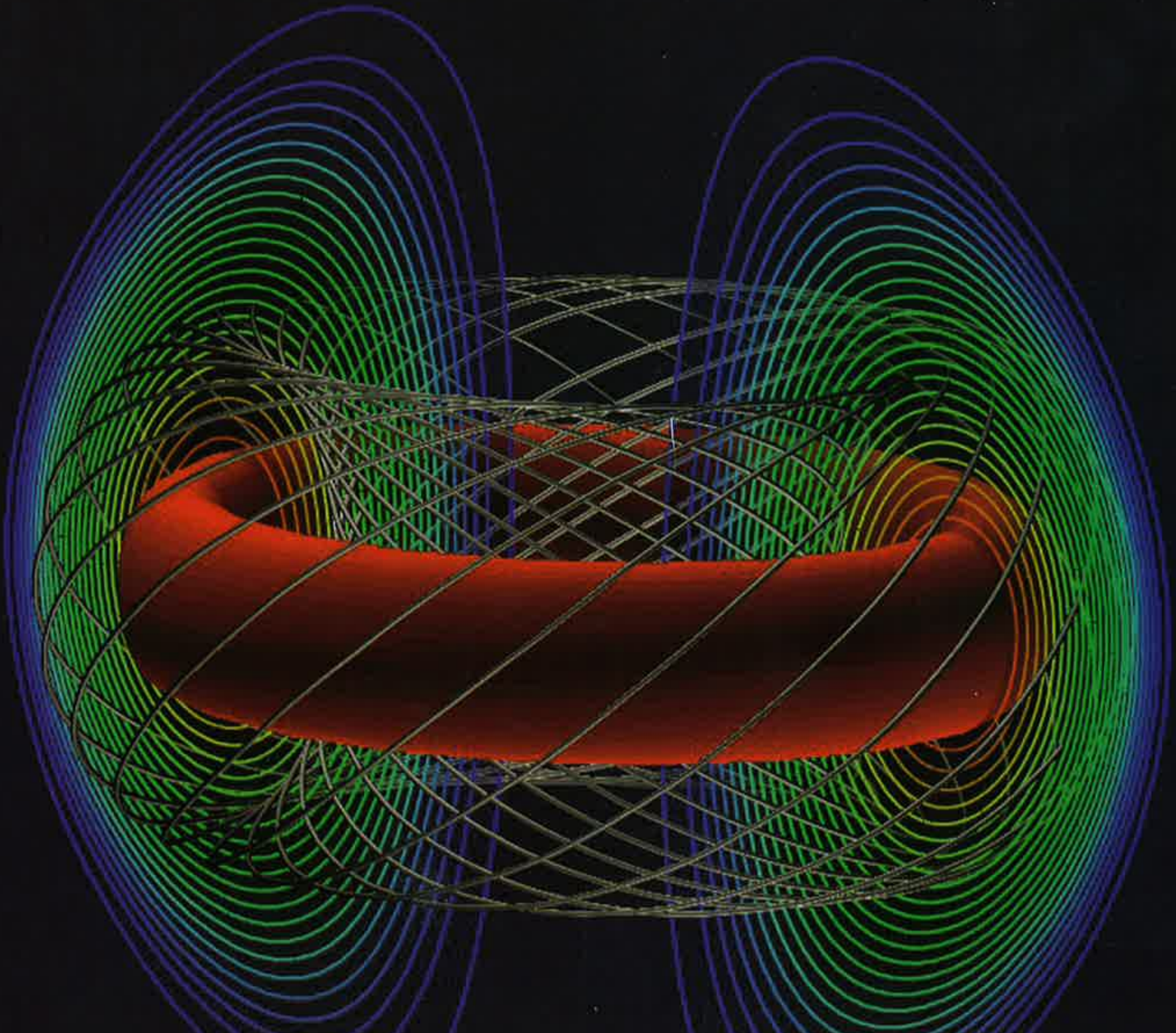


FY2000 Annual Highlights

PPPL
PRINCETON PLASMA
PHYSICS LABORATORY

About PPPL

Established in 1951, the Princeton Plasma Physics Laboratory (PPPL) is dedicated to developing the scientific and technological knowledge base for magnetic fusion energy as a safe, economical, and environmentally attractive energy source for the world's long-term energy requirements. It has been the site of the Tokamak Fusion Test Reactor which completed a historic series of experiments using deuterium-tritium fuel in April 1997. A new innovative facility, the National Spherical Torus Experiment, began operation in 1999 ahead of schedule and on budget and began high-power heating experiments this year.

Princeton University manages PPPL under contract with the U.S. Department of Energy. The FY2000 budget was approximately $68 million. The number of full-time regular employees at the end of the fiscal year was 389, not including 85 limited-duration employees and approximately 80 subcontractors, graduate students, and visiting research staff. The Laboratory is sited on 72 acres of Princeton University's James Forrestal Campus, about four miles from the main campus.

Through its efforts to build and operate magnetic fusion devices, PPPL has gained extensive capabilities in a host of disciplines including advanced computational simulations, vacuum technology, mechanics, materials science, electronics, computer technology, and high-voltage power systems. In addition, PPPL scientists and engineers are applying knowledge gained in fusion research to other theoretical and experimental areas including the development of 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

Shown is a representative visualization of a mathematical model of the magnetic-field lines and pressure distribution in the National Spherical Torus Experiment (NSTX).

The white "rope like" structures represent typical individual magnetic-field lines. Tracing these lines many times around the torus forms a set of thin shells, or "magnetic surfaces." The intersections of the surfaces with an imaginary plane are shown here as contours ranging from purple (outside) through green, yellow, and red (inside). The annular red region is a full three-dimensional iso-surface. The plasma pressure and temperature are uniform within these surfaces, with the inner (red) surface corresponding to the highest plasma temperature, in this case approximately 1,000,000 degrees Kelvin.

Mathematical models are used to study the confinement and stability properties of plasmas. The PPPL theory and computational plasma physics groups solve the resulting mathematical equations on some of the world's most powerful supercomputers. Visualizations can be rendered on the researchers' desktop computers, or on the new PPPL high-resolution display wall.

This publication highlights activities at the Princeton Plasma Physics Laboratory for fiscal year 2000 — 1 October 1999 through 30 September 2000.

Mission Statement

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

Creating 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.

Table of Contents

From the Director vii

Research
- National Spherical Torus Experiment 1
- Current Drive Experiment-Upgrade 11
- Magnetic Reconnection Experiment 17
- Fusion Theory and Computational Plasma Physics 25
- Off-Site Research 35
- Space Plasma Physics 59
- Basic and Applied Physics Experiments 63
  - Hall Thruster Experiment 63
  - Magnetic Nozzle Experiment 65
  - Nonneutral Plasmas and High-Intensity Accelerators 66
  - Multi-electron Loss Events 69
  - Field-reversed Configuration Heating 70
  - Charge Neutralization Experiments 70
  - Liquid Metal Experiment 71

Advanced Fusion Devices and Studies
- National Compact Stellarator Experiment 73
- Fusion Ignition Research Experiment 77

Engineering and Technical Infrastructure 83

Technology Transfer 93

Collaborations 101

Patents and Invention Disclosures 105

Education
- Graduate Education 107
- Science Education 111

Awards and Honors 115

The Year in Pictures 117

Financial Summary 121

Organization and Staffing 123

PPPL Advisory Council 125

Publications 127

Abbreviations, Acronyms, and Symbols 151

From the Director

Fiscal Year 2000 was an exciting time both for the Princeton Plasma Physics Laboratory (PPPL) and for the wider fusion energy sciences community. At PPPL the National Spherical Torus Experiment (NSTX) continued to yield important results using strongly shaped, very low-aspect-ratio plasmas. A major milestone of one million amperes of current in the plasma was accomplished nine months ahead of schedule. This has positioned the NSTX experimental team very well to begin experimentation with auxiliary heating and current drive, in order to exploit the potential of the spherical torus concept, both for scientific discovery and for the development of fusion energy.

PPPL's research program extends significantly beyond NSTX, and we scored important successes this year on the smaller on-site experimental projects, both in fusion energy science and in applications research. A highlight has been the documentation of enhanced ion heating during magnetic reconnection together with the discovery of turbulence in the lower-hybrid-frequency range in the Magnetic Reconnection Experiment. We are especially pleased with PPPL's new involvement with the technology side of the fusion program, through the liquid-lithium experiments on the Current Drive Experiment-Upgrade. This provides a unique opportunity for partnership between physics and technology, and we are highly committed to its success.

Robert J. Goldston

We also had excellent results in our off-site experimental research at the DIII-D tokamak in San Diego, CA, and at the Alcator C-MOD tokamak in Cambridge, MA. Our contributions to their systems for plasma heating with electron and ion cyclotron waves have been especially well received. Collaborations on the Joint European Torus and the Japanese Tokamak-60U and smaller collaborations on the Large Helical Device stellarator in Japan and the Mega-Ampere Spherical Torus in England, as well as at universities around the nation, have benefited both the PPPL program and those of our collaborators. In a joint effort with the University of California, Davis, we have developed a prototype of an innovative microwave reflectometer imaging diagnostic on the TEXTOR tokamak in Germany. PPPL is involved in ongoing diagnostic work at all of the devices mentioned above.

Theory and advanced computation have made great strides in the understanding of the dynamics of zonal flows, taking advantage of massively parallel processor computational capabilities available to us through the National Energy Research Supercomputer Center. The National Compact Stellarator Experiment design team, which includes members from a wide range of institutions, most prominently the Oak Ridge National Laboratory, made substantial progress toward a construction decision, also using massively parallel processing. Important advances were made, through the Virtual Laboratory for Technology, on the preconceptual design of the Fusion Ignition Research Experiment, a possible Next-Step Option if the International Thermonuclear Experimental Reactor does not go forward.

Internally, the Laboratory continues to utilize Science Focus Groups as its intellectual cartilage, to provide the cross-linkages that coordinate the diverse range of PPPL activities and interests. The Science Focus Groups tie together not only the various projects on-site and off, but also the theory and experimental teams themselves. These teams are also linked by the Computational Plasma Physics Group, which is providing modern computational skills in support of both experiment and theory.

In the wider fusion energy sciences community, the restructured program moved another important step forward, with the National Academy of Sciences, National Research Council's draft "Assessment of the DOE Office of Fusion Energy Sciences Program" (FuSAC Report). They stated that:

- The quality of the science funded by the United States fusion research program in pursuit of a practical fusion power source (the fusion energy goal) is easily on a par with other leading areas of contemporary physical science.

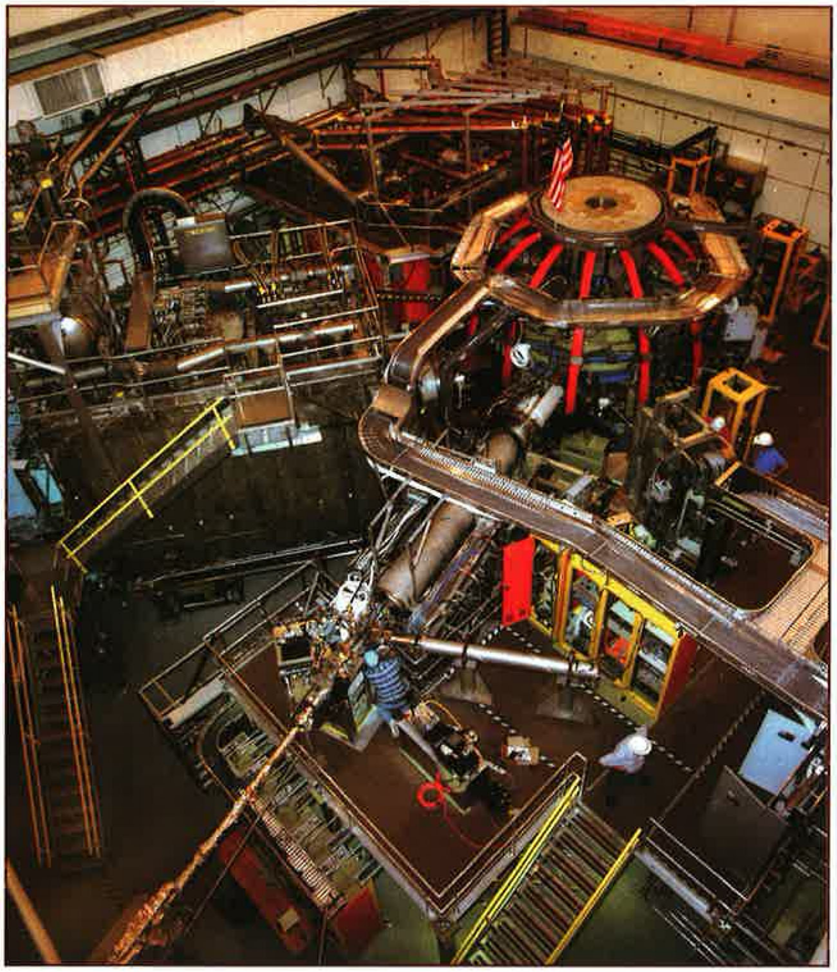
They also made important strategic recommendations that:

- The fusion program should be broadened both in terms of its institutional base and its reach into the wider scientific community, ... and
- The National Science Foundation (NSF) should play a role in extending the reach of fusion science... .

We are very pleased with the positive assessment of the science of magnetic fusion energy research by the National Academy of Sciences and with the vision presented that this science should be more closely coupled with the wider scientific research community. Increased involvement of the NSF in high-temperature plasma physics would be highly welcome.

Taking into account the 1999 Secretary of Energy Advisory Board report, "Realizing the Promise of Fusion Energy," and the 1999 Fusion Energy Sciences Advisory Committee report, "Priorities and Balance within the Fusion Energy Sciences Program," the fusion community is now well-positioned, with a clear set of priorities and accountable objectives, for advancing confidently into the future. PPPL is pleased to be an integral part of that future.

National Spherical Torus Experiment



The National Spherical Torus Experiment.

The National Spherical Torus Experiment (NSTX) is a major national fusion science facility whose mission is to establish the physics principles of the spherical torus (ST) concept, which has the potential to produce very high efficiency in magnetic containment and operation.

FY2000 was an exceptionally productive and exciting year. On December 14, 1999, the NSTX plasma current reached the design value of 1 MA, approximately nine months ahead of schedule. New research tools also became available during this period. High-harmonic fast-wave (HHFW) heating power of up to 4 MW was applied successfully and produced significant electron heating. The newly commissioned multipulse Thomson scattering system played a key role in confirming the

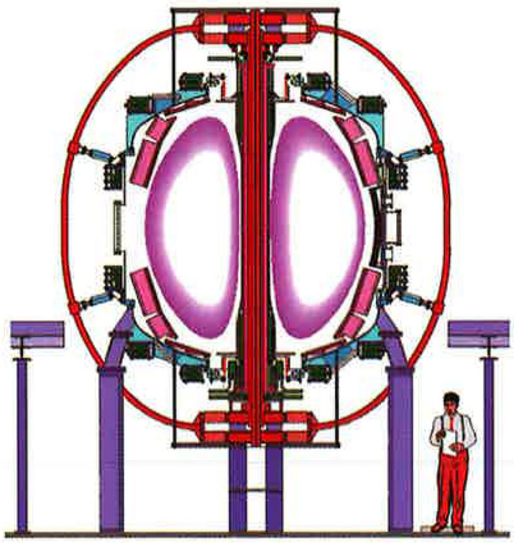


Figure 1. Cross-sectional schematic view of the NSTX device.

HHFW electron heating by measuring the electron and density profiles. The process of coaxial helicity injection successfully drove up to 0.26 MA of toroidal plasma current with the injection of about 1/10 of that amount. In September 2000, the NSTX neutral-beam-injection (NBI) system commenced operation ahead of schedule. Neutral-beam injection provided a very efficient plasma heating capability, enabling the NSTX team to increase the plasma stored energy, plasma pressure, and energy confinement time to record levels for an ST.

The cross section of the NSTX device is shown in Figure 1. In an ST plasma, the size of the minor radius approaches that of the major radius, and the cross section approaches a half circle. As a result, the ST plasma appears spherical, while the conventional tokamak plasma has the well-known “donut” shape. This difference in plasma shape is expected to provide several advantages for STs. In particular, the ST has the ability to contain plasma with a significantly higher pressure for a given toroidal magnetic field strength, i.e., a higher toroidal plasma beta, which is the ratio of the plasma pressure to the toroidal magnetic field pressure. Since the amount of fusion power produced is proportional to the square of the plasma pressure, the ST plasma configuration may lead to smaller and more economical magnetic fusion reactors. The recent rapid progress in achieving high toroidal beta plasmas is shown in Figure 2.

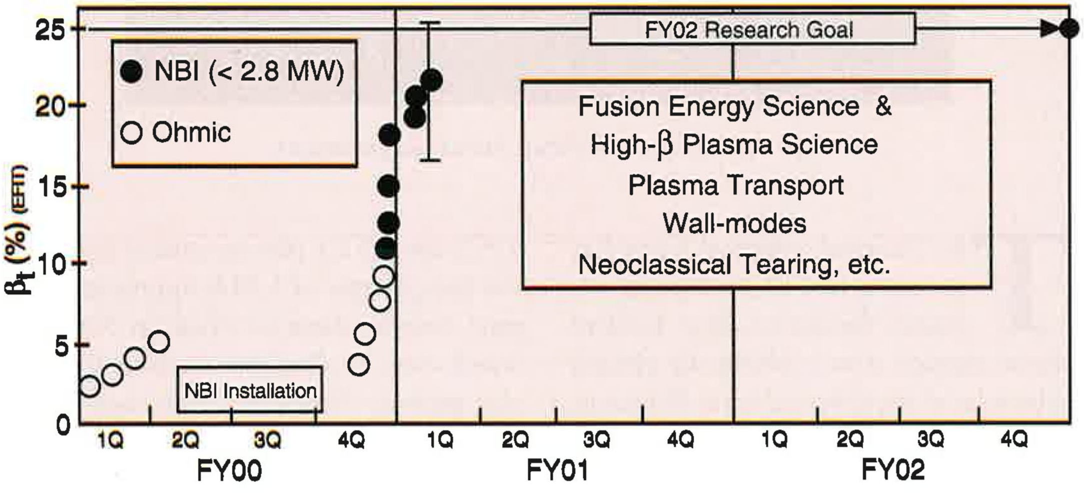


Figure 2. Progress toward high toroidal beta spherical torus plasmas.

NSTX Mission

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

- noninductive start-up, current sustainment, and profile control;
- global confinement and local transport physics;
- pressure limits and self-driven currents;
- scrape-off layer and divertor physics; and
- stability and resilience to disruptions.

Successful demonstrations of ST performance in these areas will make possible cost-effective ST devices capable of increases in the plasma current and pressure by an order of magnitude. These devices could include a pulsed Performance Extension (or Proof of Performance) experiment at 10-15 MA in plasma current and a steady-state Energy Technology Development experiment at a similar current.

Plasma Current Milestone

Of particular note is the achievement in December 1999 of a 1-MA plasma current, the physics design value. This Level 1 Milestone for NSTX was reached well ahead of schedule. It was accomplished after experiments had determined the optimum elongation and rate of rise of the plasma current to minimize the poloidal flux consumption. The early attainment of 1-MA plasma current enabled the NSTX team to explore new ST plasma regimes in FY2000 as described in this report.

Wall Conditioning

An important effort that yielded continuing benefit in plasma performance and reproducibility was the development of wall-conditioning techniques. In September 2000, the capability to condition the wall via boronization through the introduction of trimethyl-boron gas during helium glow-discharge cleaning was achieved. As shown in Figure 3, reference deuterium discharges following boronization showed a 33% decrease in carbon-line emission, a factor of more than ten reduction in oxygen emission, and a reduction in copper emission to undetectable levels. Also seen was a reduction in radiated power in the post-boronized plasmas. The loop voltage in post-boronization discharges generally decreased by 20 to 30%, reducing the poloidal flux consumption and improving the ability to achieve high current routinely. The Ejima coefficient, a measure of the resistive flux

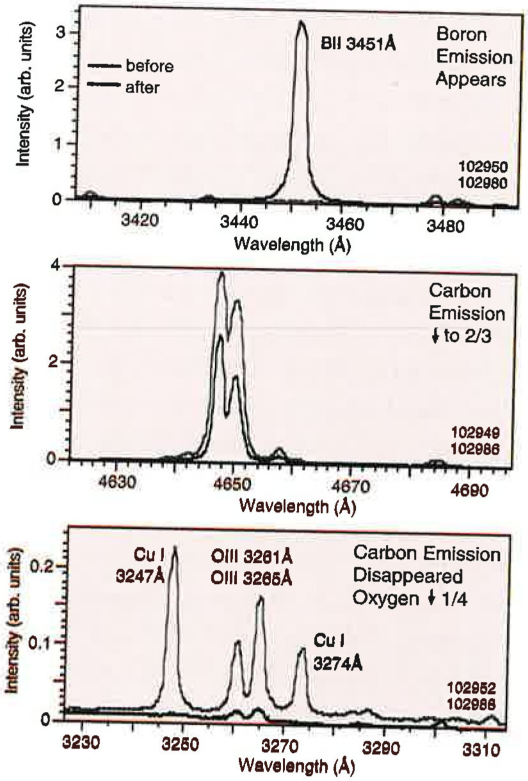


Figure 3. Comparison of characteristic emission line intensities from reference discharges before and after the first boronization in NSTX, showing the reduction in intrinsic impurity levels.

consumption, decreased to 0.3 with average current ramp rates of 5 MA/sec. Higher ramp rates reduced the inductive flux consumption (i.e., lower plasma inductance) but increased MHD (magnetohydrodynamic) activity and decreased discharge reproducibility.

Boronization was also crucial to increasing the maximum density in both deuterium and helium plasmas. Preboronized plasmas of either species attained line-averaged densities up to only $0.6n_{eGW}$where $n_{eGW} = I_p/\pi a^2$ is the Greenwald density limit. After boronization, the achieved densities were considerably higher, with deuterium plasmas reaching $0.8n_{eGW}$ (4×10^{19} m^{-3}) and helium $1.2n_{eGW}$ (5.5×10^{19} m^{-3}). One major difference between the two species was the amount of carbon III light emitted by the plasma, indicative of the level of carbon impurity in the plasma. This was much greater in deuterium, most likely due to chemical sputtering of the graphite tiles by deuterium ions. For both species, in both pre and postboronized plasmas, the radiated power increased with increasing density, but was still low, typically ≤40% of the ohmic power at the time of maximum density. The only MHD activity typically observed approaching the density limit was normal sawtooth oscillations. However, sawteeth were also observed at lower densities, which, along with the relatively low radiated power fractions, suggests that fueling limitations probably set the maximum density.

Ohmic Confinement

As shown in Figure 4, the confinement times of ohmically heated plasmas in both deuterium and helium exhibited trends that are similar to those at conventional aspect ratio. The confinement times are calculated by analysis of the plasma magnetic equilibrium with the EFIT code. The resulting plasma stored energies have uncertainties of ±20%. For low-to-moderate densities ($\leq 4 \times 10^{19}$ m^{-3}, corresponding to 0.8 n_{eGW} at $I_P = 0.7$ MA), the confinement time in both species increases approximately linearly with line-averaged density to a value of 45 msec. The maximum confinement time is approximately $1.4\tau_{ITER89P}$, where $\tau_{ITER89P}$ is the energy confinement time predicted by the ITER-89 low-confinement-mode scaling expression. At the highest density, 5.5 ×

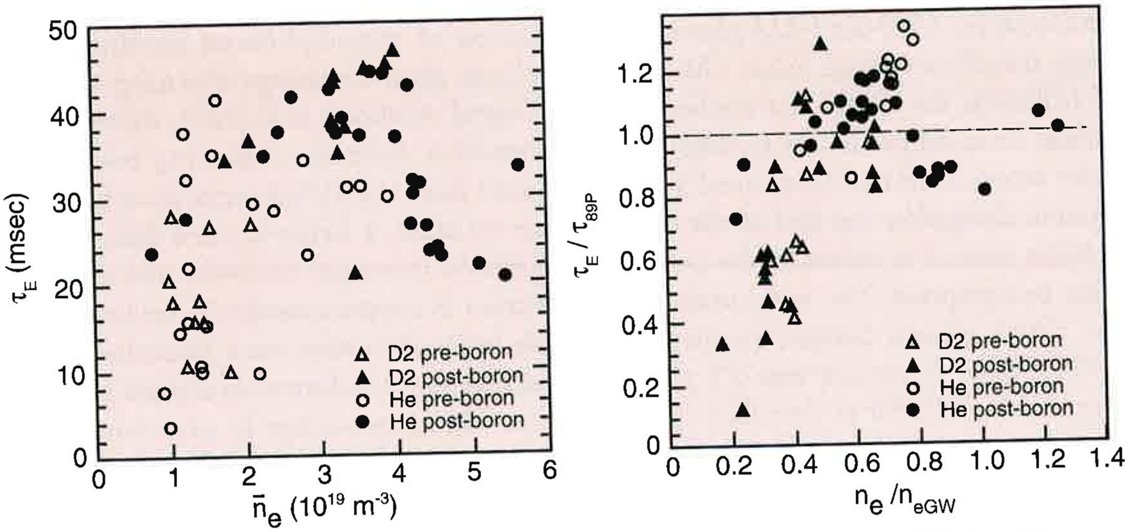


Figure 4. Energy confinement property of ohmic discharges. (Left) Energy confinement time vs. plasma density. I_p = 600-900 kA. (Right) ITER-89P normalized energy confinement time vs. Greenwald normalized plasma density.

10^{19} m^{-3}, corresponding to $1.2n_{eGW}$, the confinement time drops to about 20 msec and $\tau_E/\tau_{ITER89P}$ to 0.8-1.0. The maximum ohmic confinement times are comparable to values given by edge-localized, high-confinement mode scaling expressions.

The Role of MHD

The dominant MHD mode affecting plasma performance at present in both ohmic and auxiliary-heated plasmas is a large m=l/n=l mode, leading to sawteeth that result in a reduction in core pressure and a saturation and rollover in stored energy. The reason for the large effect of the sawteeth was the large radius of the q = 1 surface. The q-profile, as determined from EFIT code reconstructions, exhibited an extended region of low shear, where $q \leq 1$. The q = 1 surface was about 2/3 of the way out towards the edge of the plasma, and these positions agreed quite well with the sawteeth inversion layer as determined from the soft X-ray array.

Both internal and global reconnection events (REs) have been observed during all phases of NSTX plasma discharges. These events are characterized by Mirnov oscillations; spikes in plasma current, deuterium and carbon-line radiation, and modification of the plasma internal inductance and elongation. The REs depend strongly on vessel conditioning. As plasma discharge conditions improved, the frequency of REs decreased, and with proper gas programming, it was possible to avoid REs altogether during all phases of the discharge.

A comparison of the MHD-quiescent discharge with the MHD-active reveals distinct differences in the internal inductance parameter, ℓ_i, and the radius of the q = 1 surface. At the time of the onset of instability in the MHD-active discharge, ℓ_i was lower than in the MHD-quiescent one, indicating a broader current profile. In addition, the q = 1 radius appeared in the plasma sooner, and, consistent with the lower ℓ_i, was at an approximately 10-cm larger radius than that in the MHD-quiescent discharge. This comparison indicates the importance of controlling the current profile to avoid the deleterious effect of MHD activity.

Halo-induced Wall Current

The plasma disruption (i.e., rapid plasma current termination) and generation of wall halo currents remain critical issues for tokamak reactor designs due to the high stress on the wall and plasma facing components imparted by the $j_{pol} \times B_T$ force of the halo-induced wall currents. Halo currents arising from plasma disruptions have been measured on NSTX and have been found benign. The fastest current decay rates were found to be due to loss of vertical control, and these decay rates reached 400 MA/sec. Despite this high decay rate, halo currents measured on the center stack and passive plate support legs indicate peak magnitudes of 20-30 kA, corresponding to only 3 to 5% of the maximum current.

Electron Heating by HHFW

NSTX plasmas generally have a high dielectric constant, $\varepsilon \equiv (\omega_{pe}/\Omega_e)^2$, due to their high beta and high density. For example, NSTX plasmas typically operate in the 10-100 range compared to the typical tokamak plasmas where $\varepsilon \leq 1$. This situation in the ST is similar to that in other compact confinement devices such as spheromaks, reversed-field pinches, and field-reversed configurations. In this regime, the conventional electron heating and current-drive tools, such as electron cyclotron heating and lower hybrid current drive, cannot be used due to the lack of wave accessibility. However, the high-harmonic fast-wave (HHFW), at frequencies 10-20

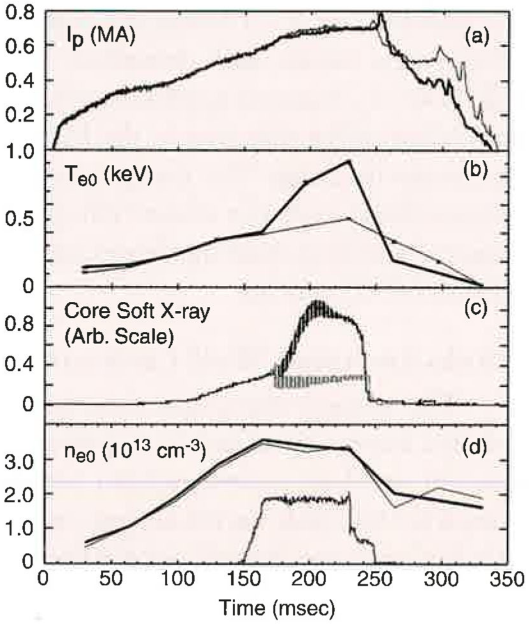


Figure 5. Time evolution of an HHFW-heated helium plasma discharge.

times the fundamental ion cyclotron resonant frequency, is predicted to be able to access these plasmas and heat electrons efficiently via transit time magnetic pumping and electron Landau damping. To study HHFW physics, NSTX is equipped with a sophisticated 6-MW radio-frequency system capable of varying the parallel wave number $k_{||}$ of the launched waves from 14 m^{-1} to about 4 m^{-1} by changing the phase of the antenna elements in real time. This will permit the waves to be coupled efficiently as the plasma evolves from low temperature (≈300 eV) during start-up to high temperature (a few keV) and high beta.

The HHFW electron heating experiments in FY2000 concentrated on producing efficient coupling of power into the plasma with a fixed phase. Plasmas with currents from 500 to 700 kA in helium and deuterium were explored. Center-stack-limited and double-null-diverted discharges were employed. The gap between the plasma boundary and the antenna shield was varied from essentially zero to 10 cm. A gap of around 5 cm was found to be optimal.

Figure 5 shows the time evolution of a 700-kA helium plasma discharge where 2.3 MW of HHFW power launched with the highest wave number, i.e., $k_{||} \approx 14$ m^{-1}, corresponding to the slowest wave velocity, was applied starting at 160 msec. In Figure 6, the density and electron temperature profiles from Thomson scattering at t = 230 msec are shown. The central electron temperature increased from about 500 eV to 900 eV during the HHFW heating, while the central density remained constant. The temperature increase is broad in radius. This is consistent with the slow-phase-velocity wave heating, because the heating deposition is expected to broaden as the central electron temperature increases. The loop voltage falls to 1.0 V as compared to 1.35 V on an identical plasma without HHFW heating. Confirmation of the temperature increase was obtained with an X-ray crystal spec-

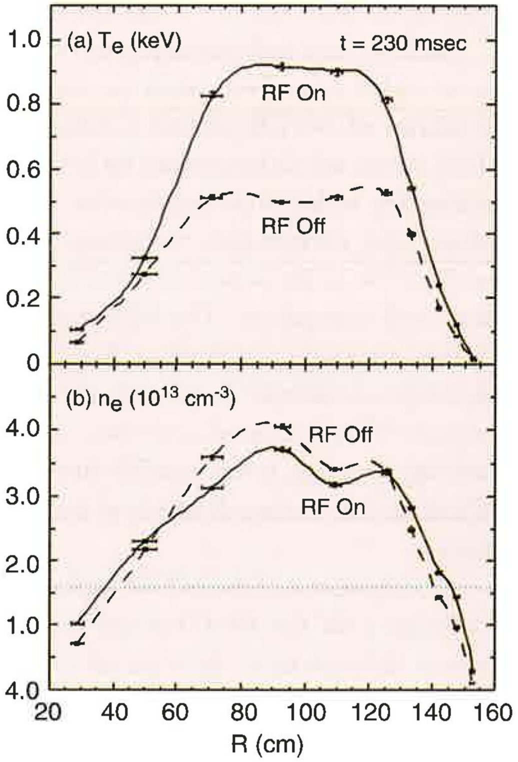


Figure 6. Thomas scattering electron temperature and density profiles of an HHFW-heated helium plasma at t = 230 msec.

trometer. The central plasma density was relatively constant at about 3.5×10^{19} m^{-3}, corresponding to $\varepsilon \approx 40$. A maximum stored energy of 58 kJ and $\beta_T \equiv 2\mu_o\langle p\rangle/B_{T0}^2 = 10\%$ (where B_{T0} is the vacuum toroidal magnetic field at the geometric axis) were obtained with 2.9 MW of HHFW power. The HHFW electron heating has been observed beginning with ohmic plasmas with electron temperatures as low as 200 eV. Plasma radiation as measured by bolometry shows an increase in edge radiation, which is attributed to carbon. The total radiated power however remains very low at less than 15%.

Coaxial Helicity Injection

For an attractive ST power plant, the ohmic-heating solenoid must be eliminated in the center stack. Although the relatively modest magnetic flux and helicity per unit plasma current for the ST tend to ease the situation, means for noninductive start-up will therefore be required. The main method for noninductive start-up being tested for NSTX is coaxial helicity injection (CHI). Applying CHI to NSTX is a significant extension beyond previous CHI experiments in that the plasma volume and pulse length are increased by a factor of about 30.

The CHI experiments on NSTX in FY2000 were quite successful in demonstrating that plasma current could be generated by this mechanism. Furthermore, CHI could be initiated at low fill pressures, showing that it should be possible to make CHI start-up compatible with ohmic-heating operation. In Figure 7, typical CHI discharge waveforms are shown in which the toroidal current is driven from zero without the ohmic solenoid. The discharge has 200-msec pulse length with a flattop toroidal current of 200 kA. To date, CHI in NSTX has driven toroidal plasma current of up to about 260 kA transiently with injection of about 27 kA, yielding a current amplification factor of approximately 10. Modeling using both the TSC and MFIT codes indicated, however, that the flux surfaces remained open during CHI operation. The CHI capability developed on NSTX will be used to assist the current ramp-up to about 1 MA and to provide edge current drive for current profile control. If the CHI plasma can be formed with about electron temperature $T_e \approx 200$ eV, then it would be possible to heat and drive current in the start-up phase of the plasma by HHFW. This would go a long way to realize fully noninductive current start-up for a spherical torus.

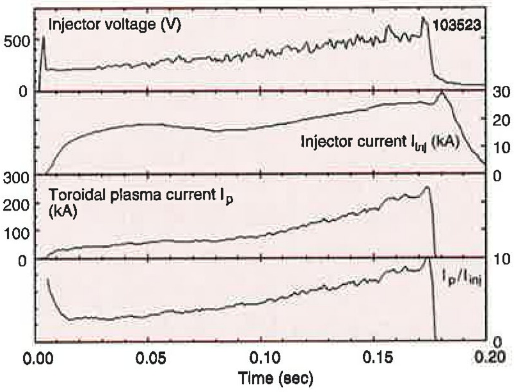


Figure 7. Waveforms of the injector voltage and current, the driven poloidal plasma current, and the ratio of the driven to injected current for a CHI discharge in NSTX. Note that the central solenoid, which drives the toroidal current in inductive discharges, was not used in this plasma discharge.

Neutral-beam Injection

Neutral-beam operation commenced in September 2000 using two of the three beam sources to inject up to 3.2 MW. The plasma current dependence for the two beam sources was investigated. As expected from calculations, with 700 kA of plasma current, the losses of energetic ions born on unconfined orbits was less for the source whose tangency radius was farther from the center stack (Source B) than for the source nearer the center stack (Source

C), as evidenced by a larger stored energy increase, more electron heating, and higher neutron emission at the same beam power comparing Source B to Source C. With 900 kA of plasma current, the differences between the two sources decreased, because the fast ions were better confined for both sources. However, at 500 kA, the loss rates for both sources were severe, reducing the heating effectiveness and causing noticeable influxes of carbon. The increased current in the equilibrium-field coils during neutral-beam heating provided additional poloidal flux, allowing increase of the pulse length slightly at high plasma current. In the highest current discharge in September 2000, the plasma reached a stored energy of 90 kJ, corresponding to β_T = 18% and a Troyon-normalized β_N = 3.1% mT/MA. The NBI-heated discharge evolution is shown in Figure 8. The first beam experiments showed an increase of plasma stored energy with plasma current beyond the expectation based on the improvement in beam-ion confinement, indicating an improvement of thermal plasma confinement with this parameter.

In Figure 9, the remarkable progress in the plasma operation made during FY2000 is illustrated by a comparison of 1-MA discharges at the beginning and end of the fiscal year. The earlier 1-MA discharge has very little flattop, while the 1-MA discharge at the end of FY2000 has a long flattop with much longer pulse duration with aid of neutral-beam heating. The plasma stored energy is also dramatically increased.

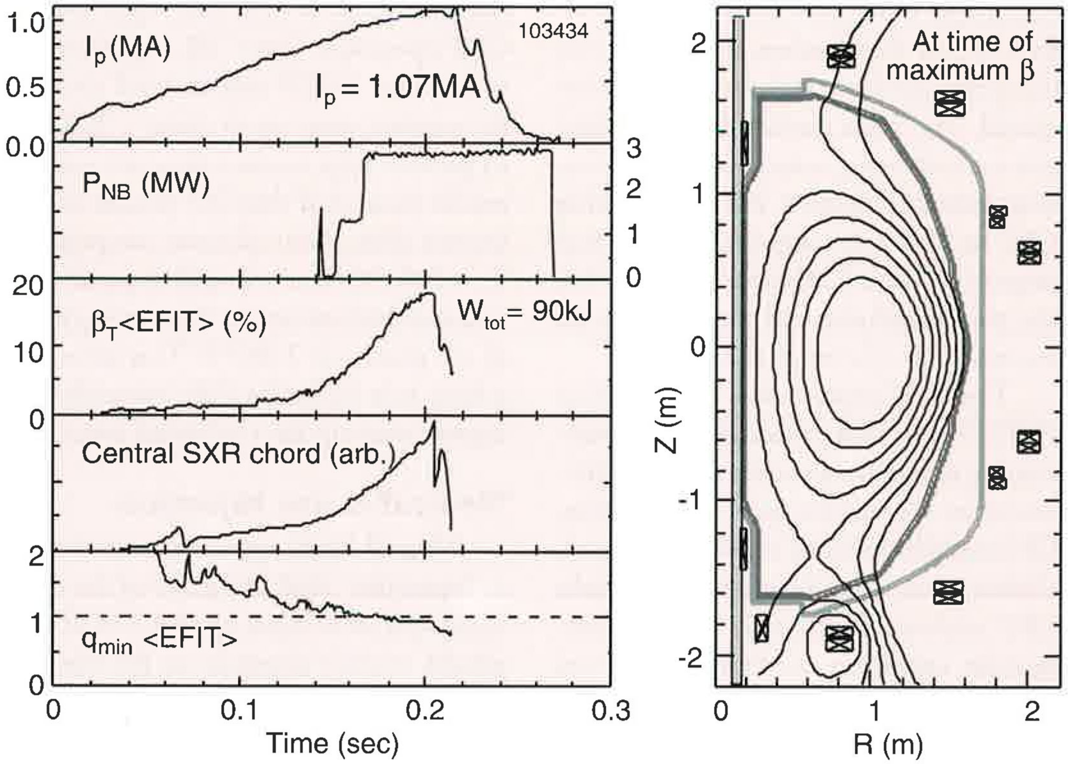


Figure 8. Characteristic waveforms and the contours of the poloidal flux in the cross section of NSTX for the discharge with injection from two neutral-beam sources. This discharge achieved the highest plasma current and toroidal beta (defined with respect to the vacuum toroidal field at the geometric center) during FY2000 experiments. The toroidal beta and the minimum safety factor q_{min} were calculated by the EFIT code based on external magnetic measurements.

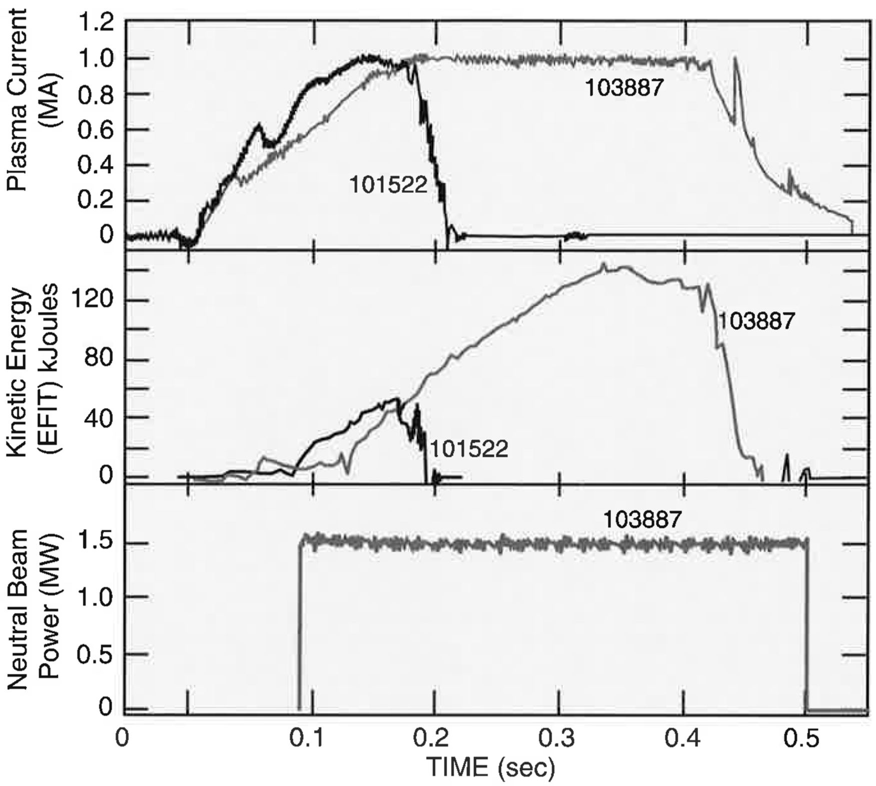


Figure 9. Progress in 1-MA plasma discharges in FY 2000.

Future Plans

The near-term research program objectives are to bring the NBI and HHFW systems to their full power capability in FY2001 (5 MW for NBI and 6 MW for HHFW) and the CHI to 500 kA of non-inductive start-up current in 2002. With these tools, plasma with beta values up to the no-wall stability limit of about 25% (with bootstrap current fraction of up to 40%) will be investigated in the near term (FY2001-2003). In the longer term (FY2004 and beyond), more advanced spherical torus regimes will be investigated with active current and pressure profile control (provided by CHI, HHFW, NBI, and other tools) and active wall-mode stabilization. Development of these plasma control tools is essential for accessing very advanced spherical torus regimes combining steady-state high beta (40%) with high bootstrap fraction (70%), and high-confinement discharges which would pave the way for the development of an attractive fusion power plant and volume neutron source.

Current Drive Experiment-Upgrade

Russ Doerner of the University of California at San Diego in front of CDX-U with the newly installed 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 eventual commercial development of fusion energy is the design of a reactor wall which can survive the high heat and neutron fluxes generated by an ignited plasma. A novel and exciting recent development that promises to solve this longstanding 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.

In FY2000, the Current Drive Experiment-Upgrade (CDX-U) became the world's first spherical torus (ST) to operate with a liquid lithium plasma-facing component (PFC). 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. Feedback control of radial and vertical position is also planned for early FY2002. The plasma major radius R = 34 cm, minor radius a = 22 cm, and aspect ratio A = R/a ~ 1.4.

Plasma Diagnostic Development

The ST represents a novel plasma regime for large confinement experiments such as the National Spherical Torus Experiment (NSTX), and in some cases novel diagnostics are needed for the particular characteristics of the ST plasma. As part of the CDX-U program, an effort is underway to develop a replacement for the electron cyclotron emission (ECE) diagnostic on which conventional tokamak programs have long relied for detailed, time-resolved measurements of the elec-

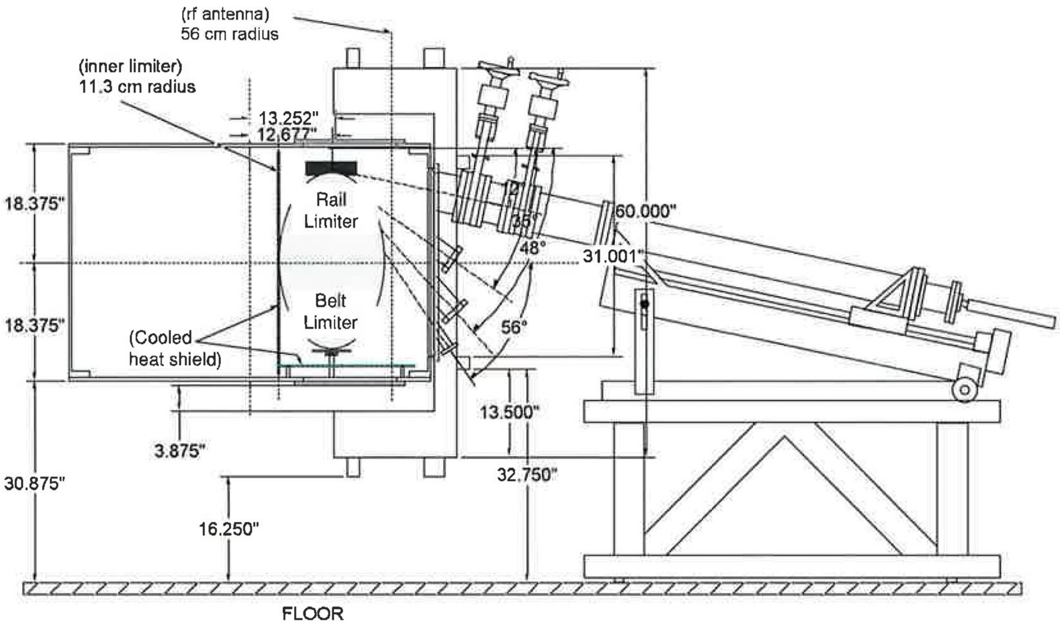


Figure 1. Elevation of CDX-U showing the UCSD rail limiter and the toroidal tray limiter.

tron temperature profile. The high density of an ST plasma relative to the magnetic field implies that $(\omega_{pe}/\omega_{ce})^2 >> 1$, where ω_{pe} is the electron plasma frequency and ω_{ce} is the electron cyclotron frequency. Under these conditions, electromagnetic radiation from the first 4-5 electron cyclotron harmonics cannot propagate from the emitting layer to the plasma edge, which prohibits conventional ECE diagnostics. The electrostatic electron-Bernstein wave (EBW) will propagate to the plasma edge, however, where it can be either detected directly or mode-converted to an electromagnetic wave and collected with a microwave antenna.

A first test of the EBW diagnostic has been performed in CDX-U, and the results have been compared with the data from the new Thomson scattering diagnostic. Initial results (Figure 2) have been obtained with microwave antennas to detect the mode-converted EBW. While both sets of measurements show a similar trend with the plasma major radius, there is a large discrepancy in the electron temperatures deduced from them. A collaborative effort is presently underway with researchers at the Massachusetts Institute of Technology to model the mode-conversion efficiency, one of the factors that may account for this difference. During FY2001, EBW detection experiments will utilize a new in-vessel detection system. This combines a receiving horn, which can be moved into the scrape-off layer plasma, with an array of Langmuir probes to characterize the edge plasma density and density gradient. The system is also equipped with movable local limiters to control the density gradient in front of the receiving horn. This instrument is expected to greatly improve the accuracy of EBW-based electron temperature measurements, and provide detailed density gradient data for modeling of the emission characteristics.

The plasma spectroscopy group at Johns Hopkins University (JHU) has been a major participant in the CDX-U program for several years. During FY2000, a set of mirrors was installed in the JHU Multi-Layer Mirror array to image the 135Å lithium line. The array was tested during experiments involving the injection into the CDX-U plasma of lithium carbide micropellets. Subsequently, the array has been used in combination with the JHU scanning soft X-ray spectrometer to diagnose the core lithium concentration in CDX-U discharges, during operation with the UCSD liquid lithium rail limiter.

The first experiments involving the use of solid and liquid lithium as a plasma limiter in CDX-U have recently begun, utilizing a lithium covered rail 5 cm in diameter and 20 cm long, which was developed at UCSD. The lithium limiter can be inserted or removed via a double gate valve airlock system to prevent exposure of the lithium to air. When the limiter is

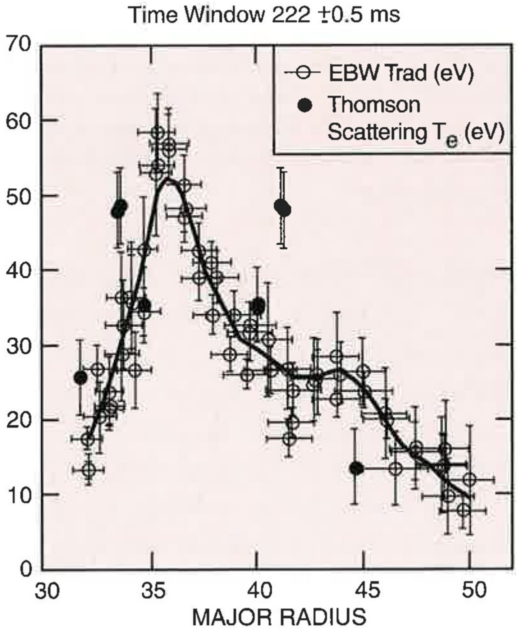


Figure 2. Comparison of electron temperature profiles derived from Thomson scattering and electron Bernstein wave emission.

fully inserted, it forms the upper limiting surface for the discharge and is intended to define the last closed flux surface for the discharge. If the limiter is retracted, ceramic boron carbide rods form the upper limiting surface for the discharge. The limiter has an internal heater and has been operated in contact with the plasma over the temperature range of 20-300 °C.

The results of the first operation of CDX-U with a solid lithium limiter are shown in Figure 3. Here the D-α emission at the limiter surface is compared with a lithium coating which has not been previously exposed to plasma to the emission from a lithium coating which has been deuterated by exposure to plasma and gas puffing. Note that although recycling is markedly reduced for the case of initial operation with a solid lithium limiter, it is not eliminated. No condition has been observed so far for liquid or solid lithium over the approximately 20-300 °C temperature range for which recycling is completely eliminated. At this point, it is unclear whether surface impurities may be responsible for the residual recycling. The deuterium prefill required to obtain breakdown was 60% higher in the case of a "fresh" lithium surface than for either the deuterated case or for normal operation with high-recycling boron carbide limiters.

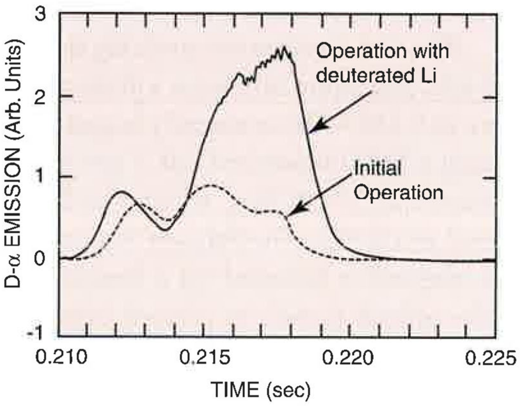


Figure 3. Recycling comparison for a "fresh" lithium limiter coating (exposed to a base pressure of 3×10^{-7} T but not deuterated) and a deuterated surface. Discharge line density was identical to 5%; traces are normalized to the plasma current.

Surface cleanliness has been a significant issue. Glow-discharge cleaning (GDC) in an argon glow with the lithium rail limiter serving as the cathode has been found to be reasonably effective at removing visible surface coatings. Ion bombardment is sufficient to liquefy the lithium and heat the surface to 200-300 °C. GDC is most effective if the lithium is liquefied.

Deuterium pumping by the limiter is significantly enhanced following an argon glow. Pump-out rates following a tokamak discharge are compared for the cases of a freshly discharge-cleaned and a deuterated lithium limiter in Figure 4.

Significant lithium influx has been observed in discharges using the liquid lithium limiter. In these experiments, the limiter was kept at 250 °C, which is above the melting point of lithium. Spectroscopic examination of the lithium light from the surface of the limiter shows strong Li I emission at 670.8 nm during the discharge. Fast camera images of the limiter using the same lithium interference filter show clear bands of emission that

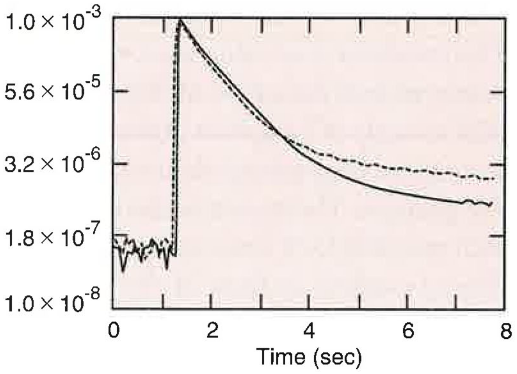


Figure 4. Deuterium pumpout following a discharge for a deuterated lithium limiter and a freshly discharge-cleaned surface.

correspond to contact with the plasma (Figure 5).

It should be emphasized that these are initial results; operation of the device with the UCSD lithium rail limiter will be continued for several months.

Future Plans

Following the rail limiter experiments, a full toroidal belt limiter, consisting of a 10-cm wide trough filled with liquid lithium, will be installed in CDX-U. This will increase the lithium surface area to 1,600 cm^2 and the in-vessel volume to approximately 0.5 liter. Later in FY2001, the ohmic power supply for CDX-U will be upgraded to permit longer discharges; the duration will be approximately doubled from the present 15-20 msec.

A collaboration with Oak Ridge National Laboratory (ORNL) will result in new fast gas-jet fueling for CDX-U. In FY2002, the poloidal-field coil system will be upgraded to permit single-null divertor operation, with strike points on the lithium tray. A new radio-frequency heating antenna, developed in another collaboration with ORNL, will also be installed at that time.

CDX-U Collaborations

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. UCSD personnel have also participated closely in the experiments with this limiter. 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 participants in the ALPS and APEX initiatives have been involved in the experiments, and will continue to be involved.

Figure 5. Image of the liquid lithium limiter taken through a lithium filter. The view shows the surface that faces the plasma at a framing rate of 1,000 frames per second. The emission is most conspicuous at the plasma contact point (upper band) and the tip of the limiter heat (lower band).

The CDX-U group and the plasma spectroscopy group at Johns-Hopkins University, Baltimore, MD, plan to continue their long-term collaboration in the area of diagnostic development for the spherical torus. 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 actively with ST researchers from the Small Tight Aspect Ratio Experiment at Culham Laboratory in England. A collaboration with Fisk University and Florida A&M University resulted in the installation and preliminary testing of a laser-induced fluorescence diagnostic for the study of edge plasma turbulence.

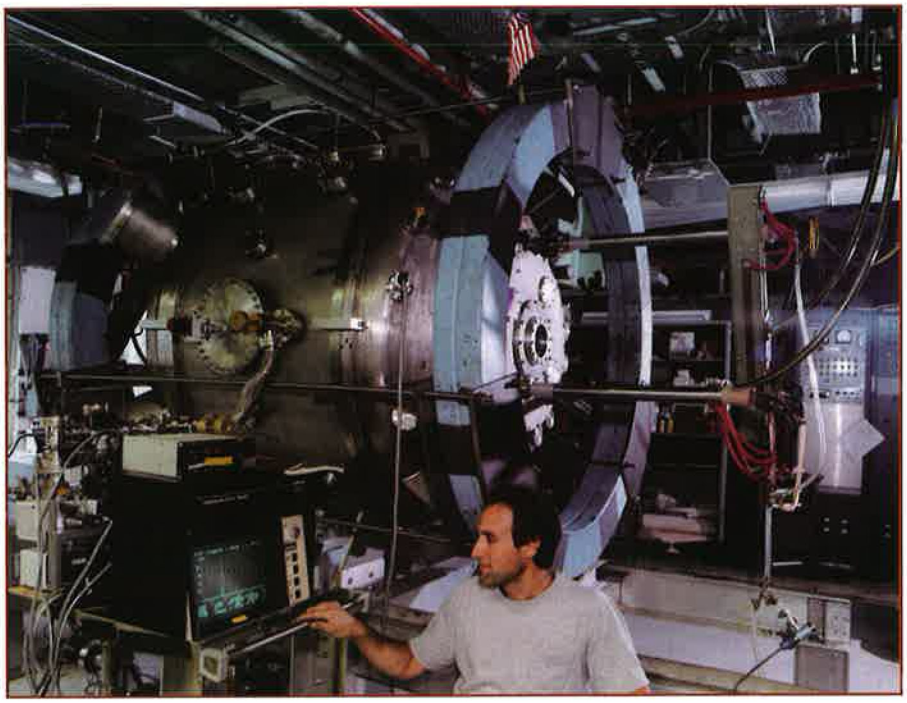
A number of collaborations with the Oak Ridge National Laboratory are underway. These include an ongoing collaboration on spectroscopic diagnostics of lithium and impurity concentrations at the lithium limiter and a new collaboration to provide fast-gas jet fueling inside the last closed flux surface. An ORNL collaboration to design a relatively new type of radio-frequency heating antenna — a combline — for CDX-U is planned for FY2001.

Graduate Studies

A primary role of CDX-U has always been to serve as a training ground for graduate students in experimental plasma physics. Vladimir Soukhanovskii, a graduate student from Johns Hopkins University, completed his thesis research on CDX-U in August 2000. Princeton University graduate student Tobin Munsat is preparing to defend his doctoral thesis on transport in an auxiliary-heated ST in early FY2001. Brent Jones (Princeton University), is currently collecting data for his thesis research into EBW emission on CDX-U. Jeffrey Spaleta (Princeton University) is beginning his thesis research, which will involve radio-frequency heating of ST plasmas using the new combline antenna. During the summer of 2000, CDX-U hosted a National Undergraduate Fellowship student, Steve Molesa of Hope College, who was involved in the installation of the UCSD lithium limiter.

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 now has a particularly simple control interface, it was possible for the teachers to design their own experiments and operate the machine as part of their summer research experience. Undergraduate and high school students have also worked with CDX-U as part of summer science honors programs. We hope to continue this strong commitment to education in FY2001 and beyond.

Magnetic Reconnection Experiment



The Magnetic Reconnection Experiment.

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

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

Figure 1. Coronal loops imaged in extreme ultraviolet by the TRACE satellite.

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

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

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

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

A set of carefully chosen diagnostics provides insight into the physics of magnetic reconnection and real-time monitoring of MRX plasmas. These include Langmuir probes (electron density and temperature), spectroscopic probe (ion temperature and flows), and arrays of magnetic probes (spatial profiles of the local magnetic field vector).

Highlights of Results

Experimental Test of the Sweet-Parker Model

The well-known Sweet-Parker model of magnetic reconnection predicts reconnection rates faster than that of resistive diffusion but much slower than those observed in solar flares. The model is a resistive MHD model and assumes a two-dimensional, incompressible, and steady-state plasma. Despite these constraints, however, the model captures many of the essential local features of the magnetic re-

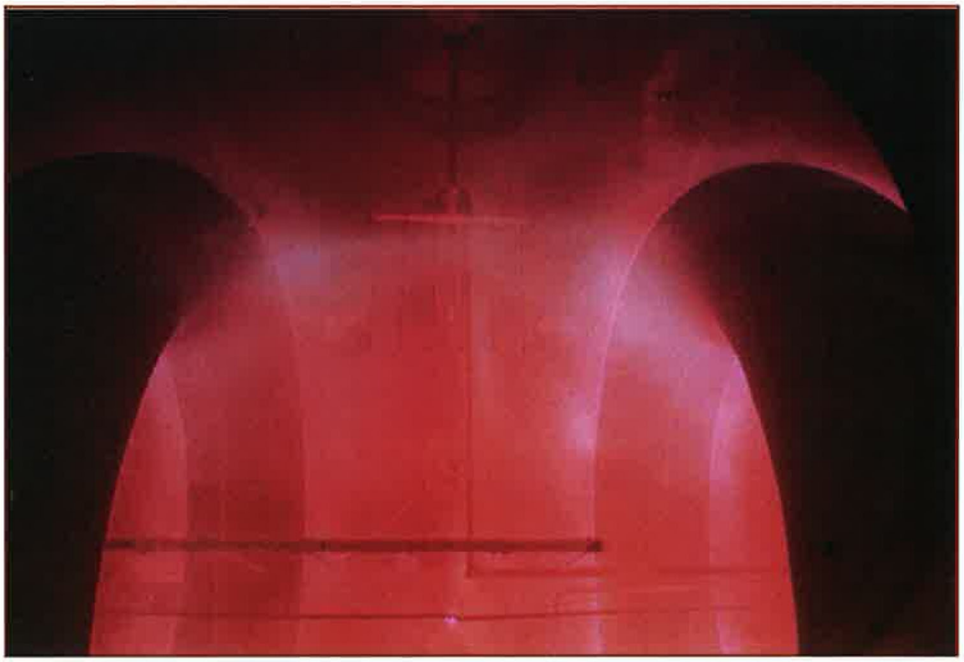


Figure 2. A plasma discharge in the Magnetic Reconnection Experiment.

connection layer. For forty years, the merits and shortcomings of this and other more elaborate models have been debated. The first laboratory experiments on the Sweet-Parker model were performed on MRX.

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

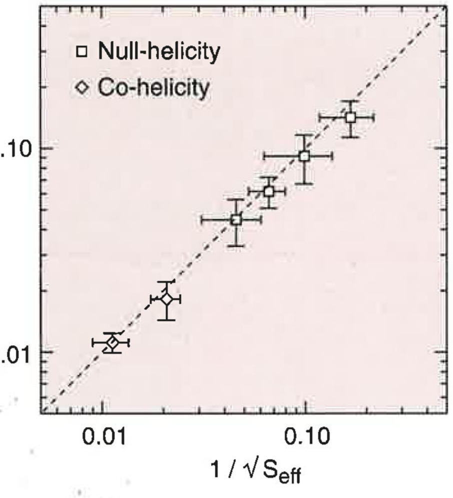


Figure 3. Experimentally measured reconnection rate (inflow speed V_R divided by Alfvén speed V_A) in MRX.

Nonclassical Ion Heating during Reconnection

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

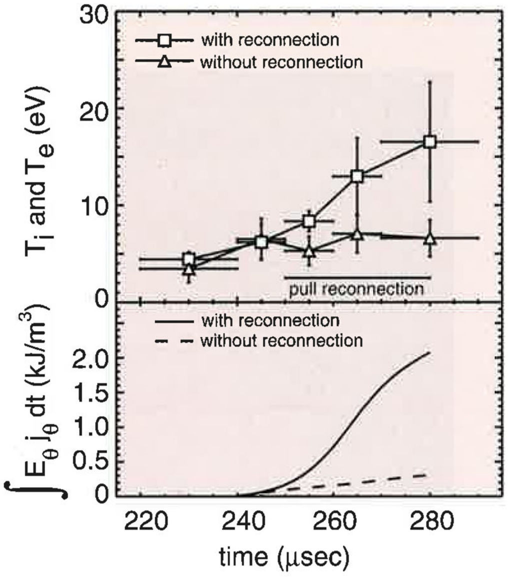


Figure 4. Time evolution of ion temperature (top) and magnetic energy dissipated per unit volume (bottom), both in the center of the reconnecton layer, indicating the causality between reconnection and ion heating.

eration and heating that is clearly consistent with the single reconnection event. In the laboratory this can be 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 the reconnection phase (see Figure 4), 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 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

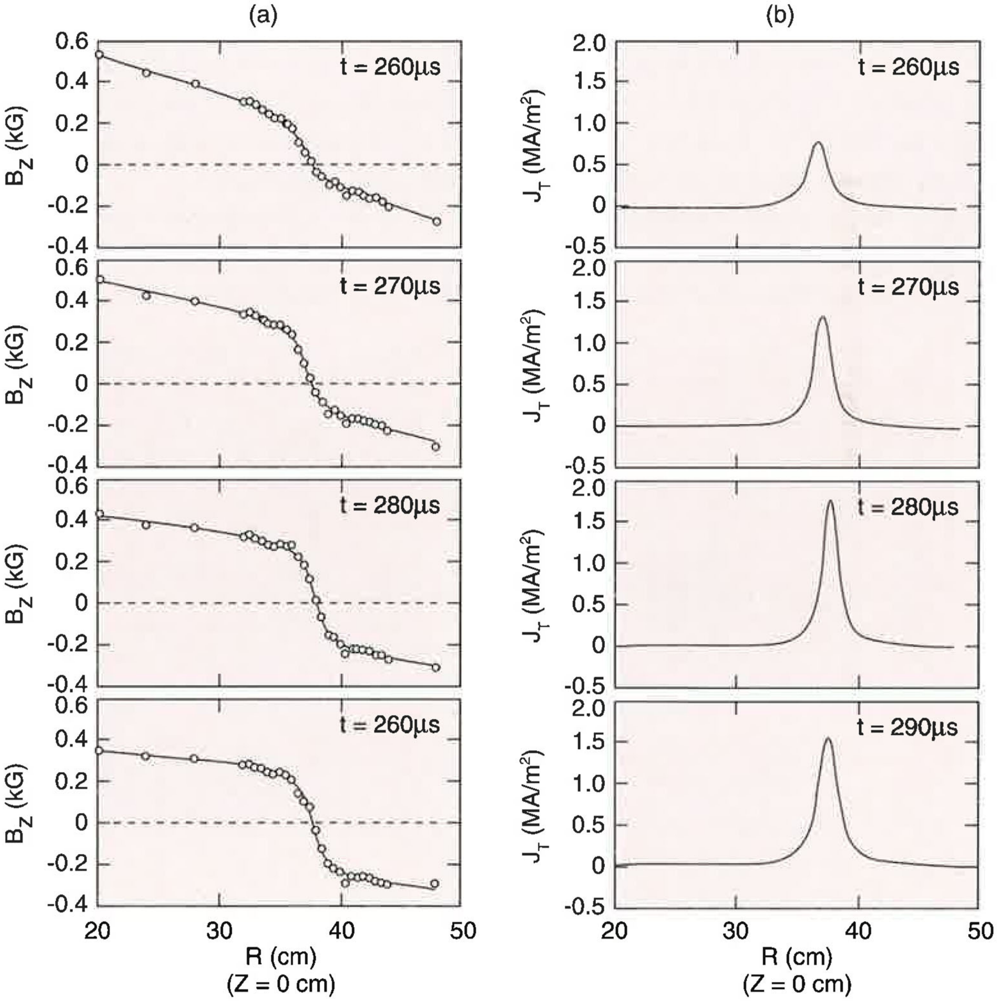


Figure 5. (a) Radial profile of reconnecting magnetic field (B_Z) measured by a high-resolution magnetic probe array. (b) Current sheet inferred from B_Z measurements. The thickness of the current sheet is approximately c/ω_{pi} and also ρ_i.

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 5. 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 0.4 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.

Studies of Fluctuations in MRX Current Sheets

Current sheets formed in MRX contain strong gradients in plasma density and 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 have investigated fluctuations in current sheets in MHD plasmas, where the ion gyroradius is much smaller than the experimental apparatus.

Recently, experiments studying electrostatic and magnetic fluctuations in MRX have found the presence of strong

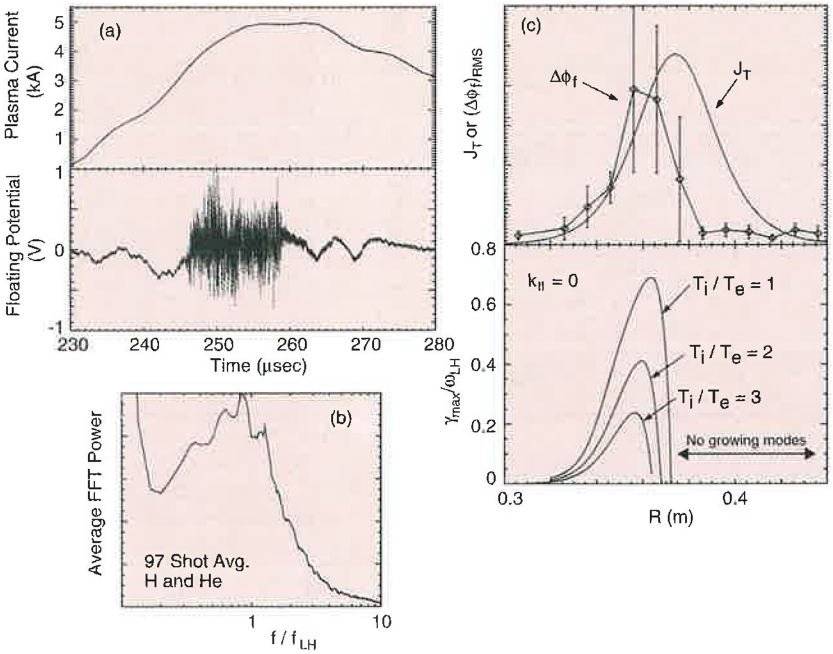


Figure 6. (a) Plasma current in MRX and raw floating potential measurement showing high-frequency fluctuations. (b) Average power spectrum of high-frequency potential fluctuations. (c) Radial profile of fluctuation amplitude (current density superimposed) along with theoretical calculations of the lower-hybrid drift-instability growth rate.

fluctuations in the lower-hybrid frequency range. An example raw fluctuation signal, along with a time trace of the plasma current, is shown in Figure 6(a). 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 Figure 6(b). 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 radial profile of the fluctuation amplitude is peaked at the inner edge of the current sheet, an observation consistent with asymmetric density and plasma beta profiles in MRX. Figure 6(c) shows the radial profile of the measured fluctuation amplitude along with a theoretical calculation of the LHDI growth rate based on measured profiles in MRX.

The role of the LHDI fluctuations in MRX current sheets was explored by observing the time behavior of the fluctuation amplitude and by studying the effect of collisionality on the fluctuation amplitude. Figure 7(a) shows a comparison between the time behavior of the reconnection electric field, neutral sheet current density, and the peak (in space) fluctuation amplitude in a set of 300 low-collisionality hydrogen discharges. This figure shows that while the fluctuation amplitude decreases rapidly early in the reconnection process, the reconnection electric field and current density remain relatively constant. This result suggests that the reconnection process is insensitive to the presence of the fluctuations, and that the LHDI is not the source of dissipation and fast reconnection in MRX. Further support for this conclusion comes from the dependence of the peak fluctuation amplitude with collisionality, as shown in Figure 7(b) and 7(c). As the collisionality is lowered (is increased), the amplitude does increase as shown in Figure 7(b). However, when the fluctuation amplitude is normalized to the electron temperature, as shown in Figure 7(c), there

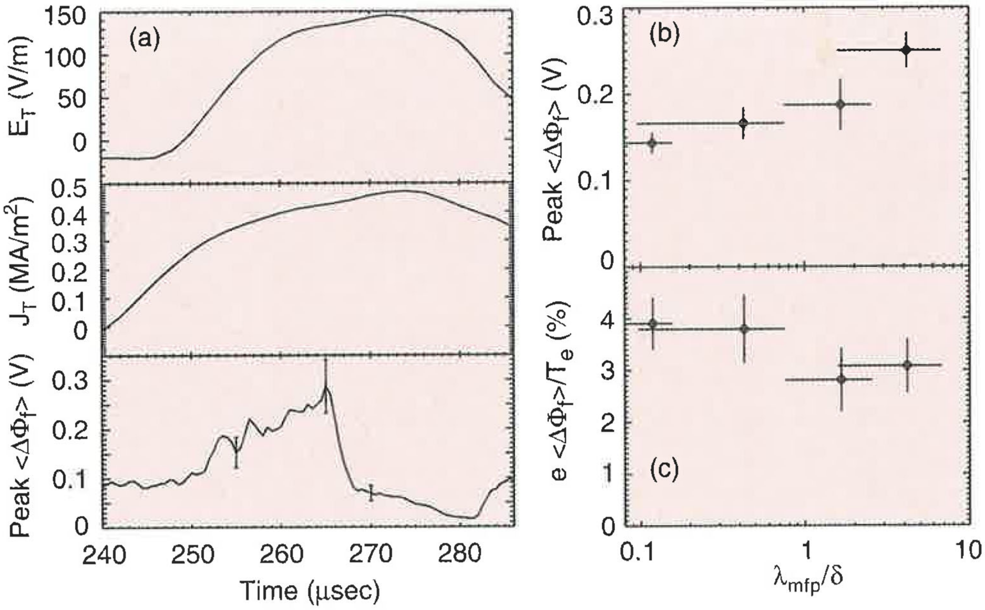


Figure 7. (a) Time behavior of reconnection electric field, neutral sheet current density, and peak fluctuation amplitude. (b) Peak fluctuation amplitude versus collisionality parameter. (c) Normalized fluctuation amplitude versus collisionality parameter.

is little change with collisionality. Because the measured resistivity in MRX changes dramatically over this same collisionality range, it is reasonable to conclude that LHDI is not to source of resistivity in MRX. The results from these studies make it difficult to theoretically explain reconnection in MRX using turbulent anomalous resistivity.

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. Advanced diagnostics will be brought to bear on 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 from these efforts should bring us closer to understanding the important process of magnetic reconnection.

Fusion Theory and Computational Plasma Physics

During FY2000, the Princeton Plasma Physics Laboratory (PPPL) Theory Department continued its lead role in helping the U.S. Department of Energy's (DOE) Fusion Energy Sciences Program attain the scientific understanding needed to establish magnetic confinement of plasma as an attractive, technically feasible fusion reactor option. The key contributions highlighted in this section are reminders of the lead role theory can play in the fusion program. They serve to underscore the fact that many of the advances have resulted from an improved understanding of the basic mechanisms involved in toroidal confinement and not only from the development of empirical scaling rules. The continuing improvements in operating regimes in magnetically confined plasmas and in diagnostic techniques should enable even more realistic comparisons of experimental results with theoretical models. As more reliable physics-based models emerge, it is expected that the pace of technical advances will be accelerated by more efficient harvesting of key results from experimental facilities and from identification of attractive new approaches and the associated designs for new facilities. The endorsements and requests from the national and international plasma science communities for enhanced collaborations in both tokamak and alternate concept research areas have been stimulated not only by the group's record for generating key seminal concepts, but also by its development and maintenance of the most comprehensive set of toroidal design and analysis codes.

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

- generating the physics knowledge required for realistic extrapolation of present experimental results;
- 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;
- providing a stimulating research environment which effectively enables the Laboratory to attract, train, and retain the young talent essential for the excellence of the plasma sciences.

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

Three-dimensional Nonlinear MHD

The capabilities of the three-dimensional extended-MHD code, M3D, have been 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.

On the computational side, a massively parallel option of M3D has been developed to run on 100's or 1,000's of processors in parallel. Good parallel scaling has been obtained (Figure 1). Thus, the same code can be run both on serial and on massively parallel processors.

On the physics side, energetic ions represented as gyrokinetic particles have been incorporated in the unstructured mesh version of the code, thereby enabling the study of hot particle driven modes in general geometry fusion devices. The stabilization of sawteeth and destabilization of fishbone modes due to hot ions have been simulated, and the linear regime results have agreed well with existing linear codes.

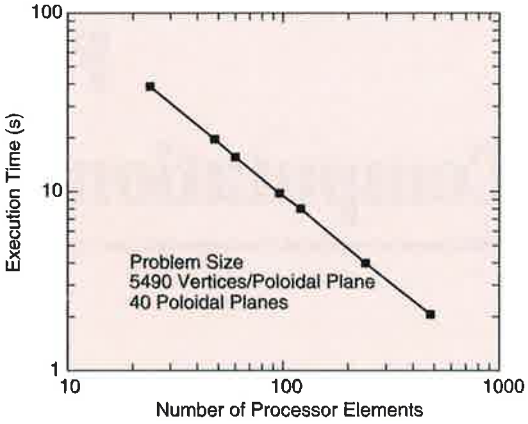


Figure 1. The M3D code exhibits good scaling as shown here in a series with up to 12 processors per plane and 40 poloidal planes.

The M3D version with all-real-space representation is capable of simulating stellarators, and has been applied to the National Compact Stellarator Experiment (NCSX) designs. The onset of fast ideal growth of localized ballooning modes is found to be consistent with the beta limits obtained with the TERPSICHORE code. In the simulation, such a mode steepens nonlinearly to form ribbon-like structures (Figure 2). The M3D code has

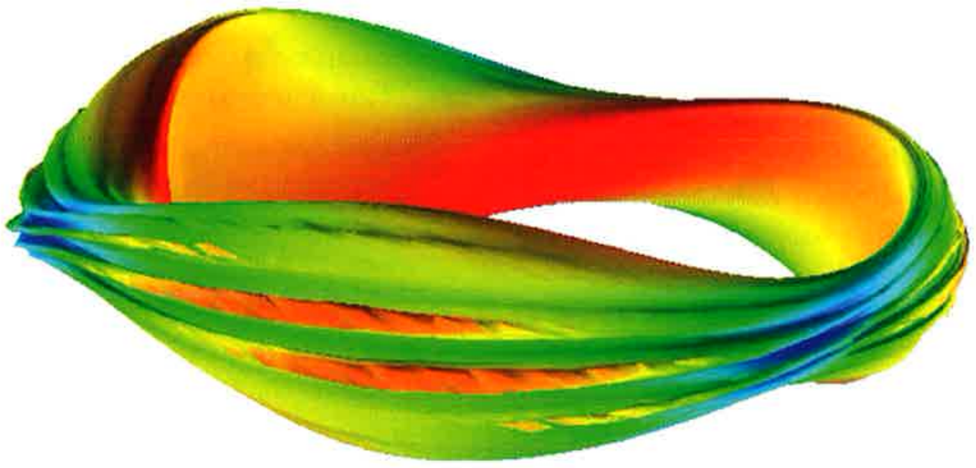


Figure 2. A three-dimensional MHD simulation using the M3D code shows that a toroidally localized ballooning mode develops in the National Compact Stellarator Experiment when the design beta limit is exceeded. The equi-pressure surface reveals the mode steepening nonlinearly to form ribbon-like structures.

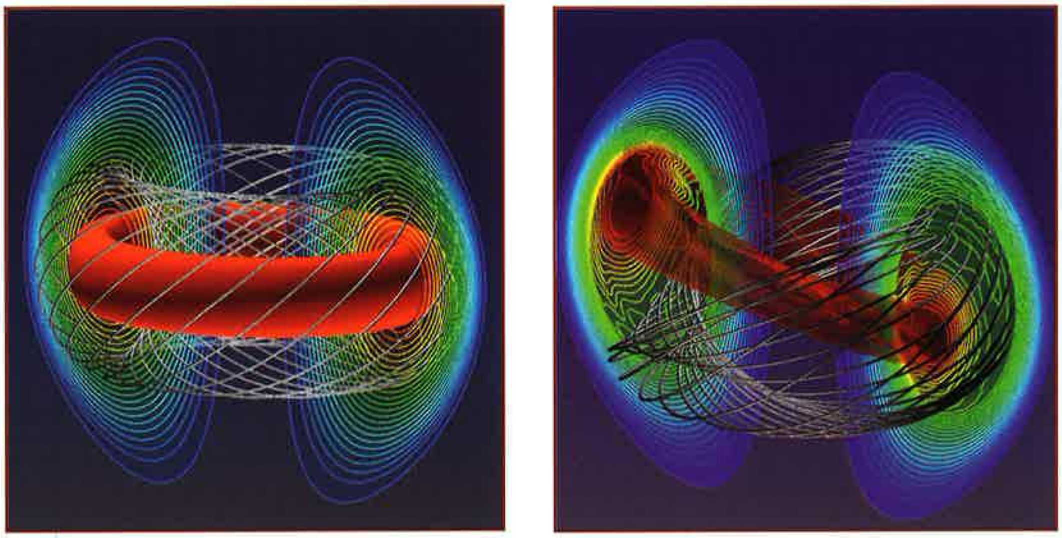


Figure 3. A three-dimensional nonlinear simulation of the National Spherical Torus Experiment using the M3D code shows an internal reconnection event, in this case similar to a large sawtooth crash. Each figure shows equi-pressure contours, an equi-pressure surface, and magnetic field lines. The initial state on the left is unstable to an internal kink mode and evolves into the state on the right. The hot portion depicted in red eventually disappears, representing a crash. Were the extent of the crash less severe, the plasma would recover to the state on the left, and the entire cycle would repeat, thus forming sawtooth oscillations.

been also applied to study Internal Reconnection Events (IRE's) in the National Spherical Torus Experiment (NSTX), and some of them were found to be similar phenomena to large sawtooth crashes in tokamaks (Figure 3). For other kinds of IRE's, the experimental soft X-ray data are being compared to those obtained from M3D nonlinear simulations.

Turbulent Transport Simulations and Analysis: Gyrokinetic Simulations

The main activities of the gyrokinetic particle simulation effort have centered around the use and improvement of the three-dimensional full-torus gyrokinetic toroidal code (GTC) in general geometry. Utilizing the massively parallel computers at the National Energy Research Supercomputer Center (NERSC), large-scale full torus simulations with device-size scans using realistic parameters have been performed. The results have indicated that the scale lengths of the microscopic fluctuations are independent of the machine size in the presence of zonal flows (see Figure 4). However, the energy transport driven by these fluctuations still exhibits Bohm-like scaling, that is, its magnitude increases with the machine size. These results are consistent with recent DIII-D fluctuation measurements. Electromagnetic simulations are also under way based on improved algorithms for handling fast-moving electrons in field-line-following coordinates for the shear-Alfvén physics. The code has also been upgraded for efficiently handling arbitrary equilibria and has been used for neoclassical calculations in three-dimensional stellarator geometry. With the development of a mixed-mode parallel model in the code, GTC is now ready for the next generation of supercomputers.

Laser-plasma Interaction

Inertial confinement is an alternative to magnetic confinement as a path to a practical fusion power. In the inertial fu-

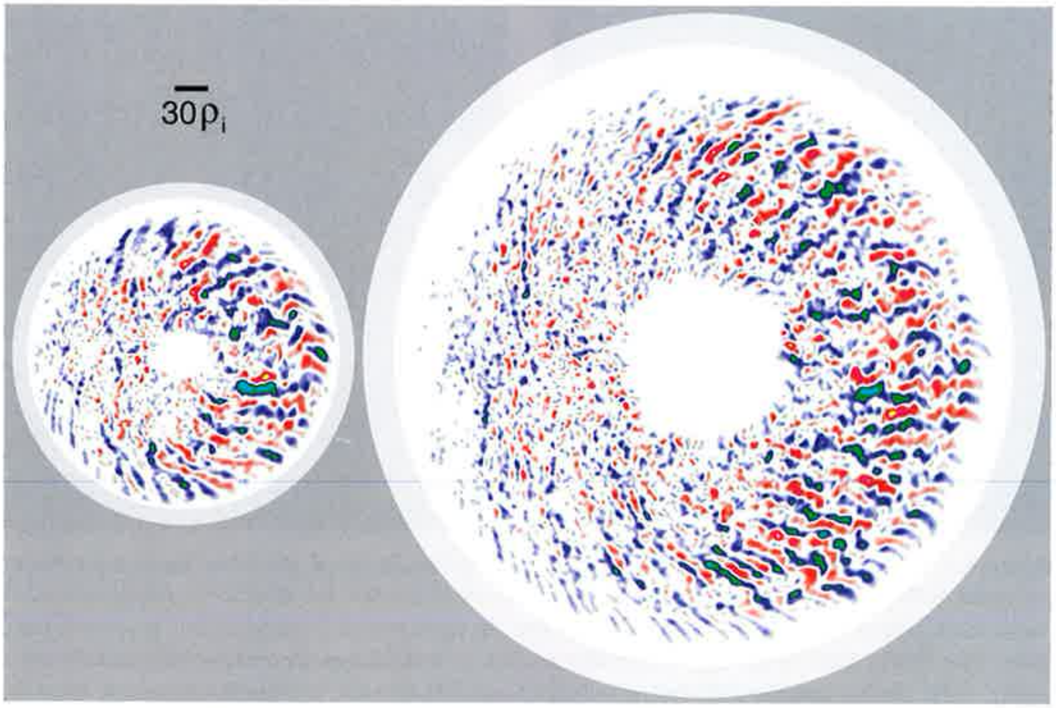


Figure 4. Size scaling from global gyrokinetic simulation.

sion 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 — up to a thousand times its initial density — leading to a high rate of fusion reactions.

Clear understanding of how the laser beams propagate through the expanding plasma is a key issue in this context. In particular, the laser light may be subject to different types of instabilities leading to a less efficient implosion. One such instability is so-called Stimulated Raman Scattering. This instability is initiated by some low-level deviations in the plasma between the electron and the ion charge densities, from which the laser light starts to reflect. The reflected light then interacts with the incident laser light in such a way as to reinforce the charge deviation, which further increases the reflection, and so on.

A numerical simulation of Stimulated Raman Scattering is shown in Figure 5. Each set of three figures represents the state of the simulation at a given time; the ones on the right are at a somewhat later time than the ones on the left. In the upper figures, one can see the combined electric field of the laser and the reflected light. Indicated are the emission points of the laser light (from Ant. 1) and the seed of the reflected light (from Ant. 2). The laser light propagates to the right, and the reflected light progates to the left; one can clearly see the level of reflected light to the left of Ant. 1. The electric fields related to the charge deviations are presented in the middle figures. Finally, the bottom figures show the state of the plasma in the so-called phase space, representing the different possible velocities of particles (here electrons) at each position. A transition has taken place between the coherent state

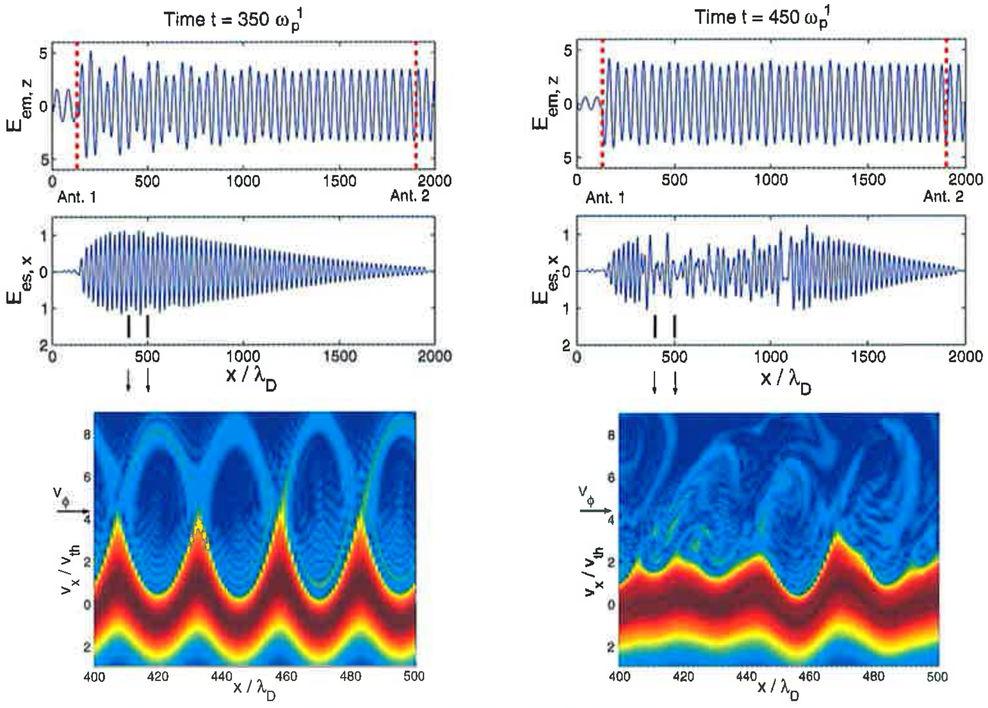


Figure 5. Laser-plasma interaction: electric fields and phase space.

on the left-hand side and the more turbulent one on the right. A better understanding of such phenomena is an issue of current research.

Stellarator Theory

Critical physics issues relating to NCSX were resolved in preparation for the NCSX Physics Validation Review. Progress was also made in developing sophisticated new numerical diagnostics for the M3D and PIES codes, and in implementing an improved stellarator optimization algorithm. Highlights in these areas are given below.

Equilibrium Flux Surfaces: An algorithm was developed and implemented for designing stellarators with good flux surfaces (Figure 6). This is a problem which 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 magnetohydrodynamic (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 has been implemented in the stellarator optimizer. The global optimizer is found to require less human interven-

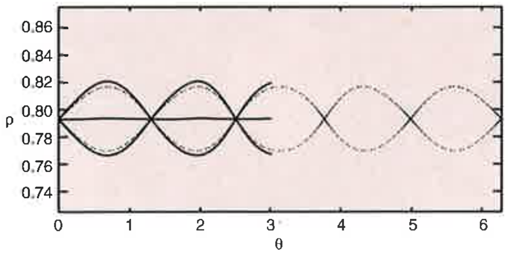


Figure 6. The solid line indicates an estimate of the location of an island separatrix, provided by a new diagnostic. The dots are the points from a Poincaré plot of the island separatrix.

tion and adjustment in the optimization process than the standard algorithm.

NCSX Robustness and Flexibility

A substantial effort has been invested to demonstrate the ability of NCSX coils to support the wide range of variations in plasma configuration about the reference baseline equilibrium, necessary to achieve the scientific goals of the NCSX mission. Figure 7 shows various views of the modular coil set used for the flexibility and robustness studies. There are seven coils in each of the three periods of the machine. Stellarator symmetry implies that within any given period, only four coil currents are independent. An auxiliary toroidal-field system is added to allow maintenance of a constant average toroidal-field strength when varying the modular coil currents. In addition to the five independent coil systems mentioned so far, a system of axisymmetric poloidal-field currents is included.

The primary computational tool used for the flexibility and robustness studies was STELLOPT, a VMEC MHD equilibrium code based free-boundary optimizer which determines coil currents which produce free-boundary equilibria consistent with a chosen set of plasma profiles and desired physics properties. The desired physics properties are 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.
- The NCSX coils have the flexibility to control the degree of quasi-axisymmetry, allowing exploration of the physics of quasi-axisymmetry plasmas.

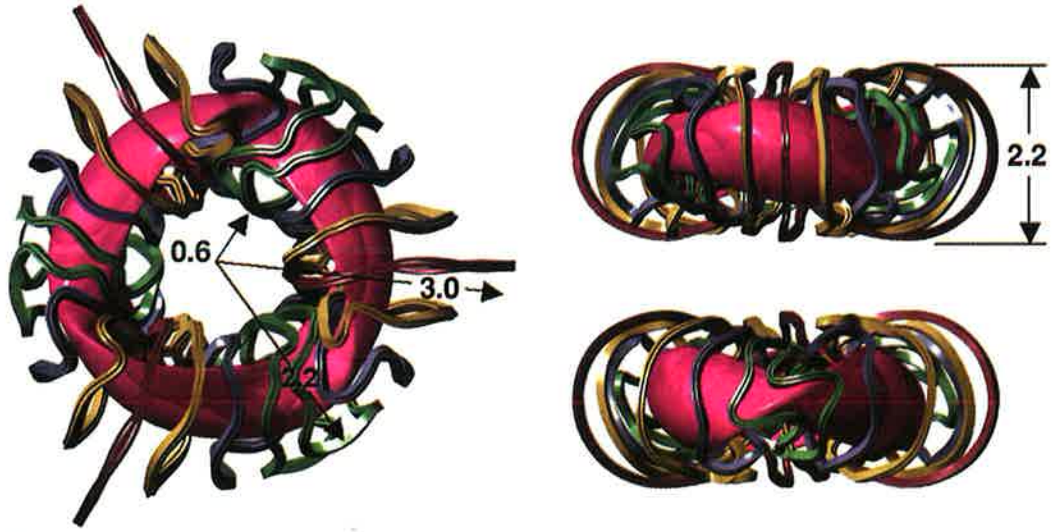


Figure 7. General arrangement of the National Compact Stellarator Experiment modular coil set used for flexibility and robustness studies.

Plasma Boundary Physics

The DEGAS 2 neutral transport code was used to simulate neutral gas behavior in a series of divertor baffling experiments in the Alcator C-Mod tokamak at the Massachusetts Institute of Technology. A series of movable louvers allowed experimentalists to alter the gas conductance between the divertor region and main chamber and to examine the resulting impact on the core and divertor plasmas. Their measurements showed, surprisingly, that the flow rate of neutral gas between the divertor and main chamber did not depend on whether the louvers were open or closed. DEGAS 2 simulations of one of these discharges supported the explanation that the flow rate was being limited by friction between the neutral gas and the divertor plasma and not by the state of the louvers. Neutral-ion and neutral-neutral elastic scattering processes recently added to DEGAS 2 were crucial in reproducing the qualitative character of the experimental results.

ICRF-induced Plasma Rotation

Control of rotation in tokamak plasmas provides a method for suppressing fine-scale turbulent transport by velocity shear and for stabilizing large-scale magnetohydrodynamic instabilites. The experimental discovery of rotation in a plasma heated by the ion cyclotron process is important both as a potential control method for a fusion reactor and as a fundamental issue, because rotation arises even though this heating process introduces negligible angular momentum.

This process is simulated with the Monte-Carlo ORBIT code. Energetic ions are followed as they lose energy and redistribute themselves. The particle displacements, which are both outward and inward, produce a torque density. Angular momentum is also transferred from the energetic particles to the bulk plasma by collisions, creating a second source of torque density. These torques produce plasma rotation, and the results are compared with observed rotation in Alcator C-Mod.

Significant toroidal rotation velocities are routinely measured in Tore Supra, a tokamak at Cadarache in France. Rotation velocities increase with heating power and can reach 40 km/s or more. The role of ion cyclotron range of frequencies (ICRF) heating in producing plasma rotation and the role of toroidal rotation and its associated radial electric field on ripple losses have been investigated. This has been studied by computing the ripple losses versus rotation with the Monte-Carlo code ORBIT which computes the particle trajectories in exact equilibria, including the ripple perturbation. In the absence of rotation, losses are dominated by ripple-trapped particles for both the bulk plasma Maxwellian distribution and for the ICRF high-energy non-Maxwellian distribution. For both distributions, the ripple-trapped loss decreases with rotation, as expected from analytic estimates, but banana orbit losses increase.

Field-reversed Configuration Stability Calculations

In order to properly assess the properties of innovative confinement configurations such as field-reversed configurations (FRCs), a new three-dimensional nonlinear hybrid code (kinetic ions and fluid electrons) has been developed. The code is used to study the role of kinetic effects on the n=1 tilt mode and on higher-n MHD modes in the FRC (Figure 8). The stability properties of both prolate and oblate configurations have been examined. Simulations indicate that the prolate FRC stability observed in the experiments cannot be explained within

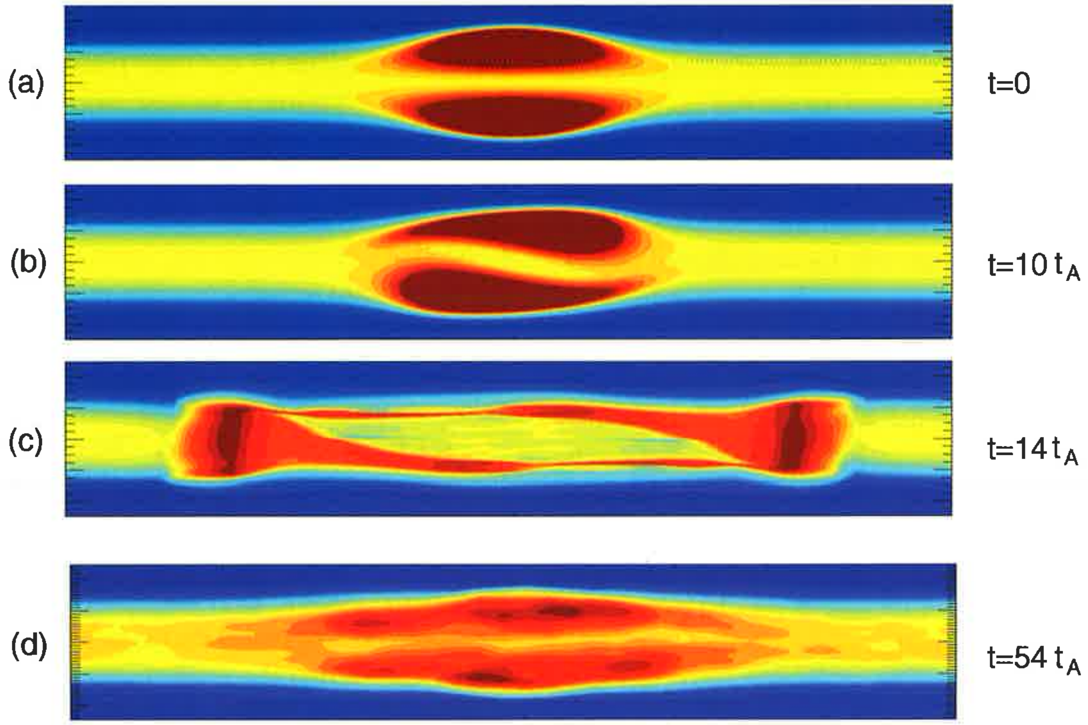


Figure 8. Nonlinear evolution of the n=1 tilt mode in a field-reversed configuration; pressure contours in the poloidal plane from MHD (a)-(c) and hybrid simulations (d) .

linear theory. However, results from the nonlinear simulations indicate that in the kinetic regime, the instabilities saturate nonlinearly. For an oblate FRC, it has been shown that all n=1 modes can be effectively stabilized in the MHD regime by a combination of a close-fitting conducting shell and profile effects.

High-resolution Display Wall

PPPL installed and operated a high-resolution display wall during FY2000 (Figure 9). The wall was a collaborative project with the Princeton University Computer Science Department, where a similar wall exists. The original concept came from Computer Science, but PPPL provided mechanical engineering and fabrication for the projector mounts used in both walls, and developed new uses for the PPPL wall very different from the way the Computer Science wall is being used.

PPPL's wall is a tiled display consisting of a 3 × 3 array of aligned rear projections. Each projection has a resolution of about 1,000 × 800 pixels, so the entire wall has an effective resolution of 3,000 × 2,400 pixels. This creates a very high-resolution facility that can be used to view complex simulation data and look for fine-scale features or patterns.

Each of the nine individual contiguous displays is produced by a separate rear projector that is connected to a separate computer, and there is a master computer to control the others. When the computers are not being used to power the display, they are used as a parallel cluster of computers by researchers for intermediate-scale calculations that are too big for an individual workstation, but do not require a facility as large as the National Energy Research Supercomputer Center.

The software package WireGL, from the Stanford University Computer Graph-

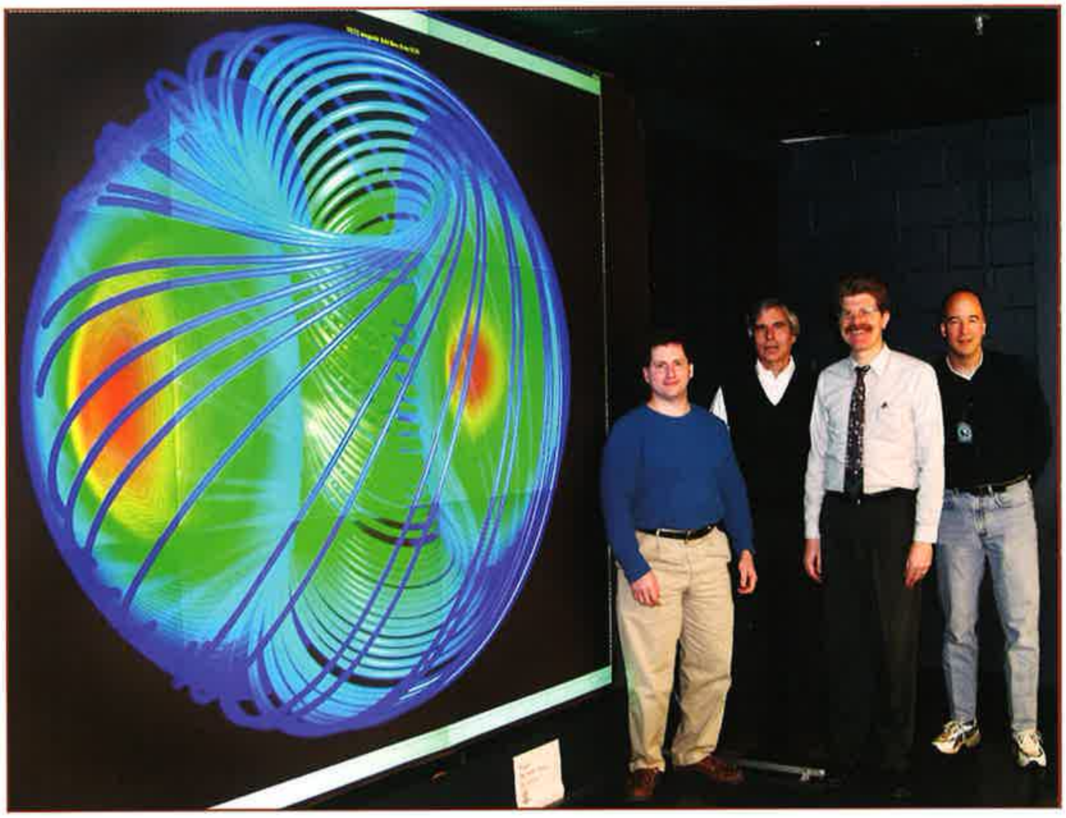


Figure 9. At the High-resolution Wall are, from left, Scott Klasky, Steve Jardin, Irving Zatz, and Doug McCune. The image displayed on the wall is of National Spherical Torus Experiment magnetic-field lines.

ics Lab, has been installed on PPPL's display wall cluster and interfaced with the graphics package OpenDX. This allows the wall to utilize graphics applications by making use of the computing power of ten clustered computers for rapid rendering on a tiled high-resolution display.

The facility saw a lot of use during the year. It was first used for the Theory Department Review presentations and the PPPL Open House. During the remainder of the year, it was widely used both as a tool for individual researchers and small research groups to examine their simulation data and as a premier display facility used for visitors and small conferences.

New directions being pursued include a Laboratory Program Development Activity project to fully automate the alignment of the nine displays; extension of the parallel rendering described above to the more commonly used graphics package AVS-Express (once the interface software is available); and use of the wall as the screen of a high-resolution video conference facility to communicate with remote groups, including experimental sites with similar capability display walls.

Off-site Research

Collaborative pursuit of answers to key fusion science questions is the quest of the Off-site Research Department. Princeton Plasma Physics Laboratory (PPPL) scientists and engineers identify appropriate high-impact scientific questions and then participate in leading programs across the country and around the world. They work as members of integrated teams to acquire enhanced understanding and advance fusion energy science. Researchers work either at the remote facility or via remote access to the experimental equipment and data of the distant laboratory.

Participation in the world's leading experimental programs permits the U.S. to acquire a greater understanding of physical phenomena by joint experiments on multiple facilities; to extend innovations and discoveries from the U.S.'s medium-scale tokamaks (C-Mod and DIII-D) to larger scale devices (Joint European Torus, JT-60U, and Large Helical Device); and to bring back both questions and answers from the other programs. 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 experiment-design, diagnostics, data analysis, experiment and theory comparison, engineering design and operations.

As described in the following sections, PPPL has made significant contributions to major discoveries and accomplishments in FY2000.

On the Alcator C-Mod tokamak at the Plasma Science and Fusion Center (Massachusetts of Technology in Massachusetts):

- improved performance of the 4-strap radio-frequency antenna for plasma heating and current drive;
- start of a new collaborative project to drive plasma current by microwaves; and
- new diagnostics to visualize edge turbulence.

On the DIII-D tokamak at the DIII-D National Fusion Facility (General Atomics in California):

- initial studies of stabilization of slow-growing large-scale helical plasma instabilities that grow because of electrical resistance in the vacuum vessel wall (resistive wall modes);
- driving plasma current in precise locations by microwaves, to stabilize plasma instabilities (neoclassical tearing modes); and
- creation of layers of "thermal insulation" inside the plasma by both microwave and radio-frequency waves.

On the Joint European Torus (JET) tokamak at the Culham Science Centre (in England):

- studies of enhanced confinement modes at larger spatial scale than on domestic facilities, aided by measurement of the plasma current profile;
- transport of impurities and screening of injected impurities;
- comparison between transport and theoretical predictions of turbulence; and
- stabilization of sawteeth by energetic particles.

On the JT-60U tokamak at the Japan Atomic Energy Research Institute (in Japan):

- effects of energetic particles in inducing new modes of plasma instability;
- improved confinement at high density and associated comparisons with theoretical analyses; and
- improved understanding of an advanced negative-ion neutral beam for plasma control.

On the Large Helical Device (LHD) stellarator at the National Institute for Fusion Studies (in Japan):

- novel magnetics diagnostics.

On studies of tritium:

- improving understanding of the retention of tritium in graphite tiles; and
- exploration of advanced techniques for removing tritium.

Alcator C-Mod Collaboration

PPPL physicists and engineers have continued to be closely involved in all aspects of the Alcator C-Mod research program at the Massachusetts Institute of Technology (MIT). The performance of the 4-strap ion cyclotron range of frequencies (ICRF) antenna has steadily improved, and new physics results have been achieved. A new project to add lower-hybrid current-drive capability has been approved, and launcher design and prototype coupler fabrication have been initiated. New plasma diagnostics have started to yield experimental data, and further upgrades are in progress. Theoretical modeling of ICRF wave physics is now giving better agreement with experimental data, and transport modeling studies are indicating model evolution needed to obtain agreement with experiments in Alcator C-Mod's unique parameter space.

ICRF Antenna Upgrades and Operational Support

PPPL had supplied a new 4-strap ICRF antenna to Alcator C-Mod in 1998. Initial operation was started in 1999, and serious antenna arcing accompanied by high levels of impurity influx were found at heating power levels above about 1.3 MW. Antenna inspection early in 2000 revealed severe arcing between adjacent protection tiles at the top and bottom of the antenna front face, as well as arcing from the high-voltage portion of the current straps to adjacent ceramic terminations of the antenna's Faraday screen. Shorting straps were installed between the tiles, and the ceramic terminations were protected from arcing by small concentric stainless steel cups. Antenna fault protection circuits were also modified to reduce available fault energy. These modifications reduced the impurity problem and allowed the power to be pushed up to 2.5 MW, but a careful comparison of the new 4-strap antenna's heating efficiency with that of the older 2-strap antennas revealed an efficiency only approximately 60% that of the older antennas. A reconfiguration of the 2-strap antenna for 4-strap operation by grounding the outer two straps and changing the antenna feed gave heating efficiency identical to the other two antennas.

In a second C-Mod opening in July, 2000, the 4-strap antenna's molybdenum protection tiles were replaced by boron nitride in order to totally eliminate remaining metallic impurities. The observed low heating efficiency was thought to be due to possible radio-frequency (rf) leakage from the rear of the antenna coupling to the plasma edge. This area was closed with stainless steel strips, and the horizontal antenna ends were bypassed with ceramic capacitors mounted in the vacuum. This modification is shown in Figure 1.

Figure 1. The PPPL 4-strap ion-cyclotron range-of-frequencies antenna inside Alcator C-Mod with new boron nitride tiles.

Further testing revealed strap phasing errors, which were corrected outside the machine. Antenna operation with all four straps driven properly for heating phasing (0°, 180°, 0°, 180°) now gave heating efficiency identical to the two older antennas, as shown in Figure 2. Power into the new antenna was raised to 2.8 MW, with total power from all three antennas above 5 MW, but plasma-rf interaction resulted in front surface arcing along magnetic-field lines above approximately 2 MW. A third inspection and rework was planned for January, 2001.

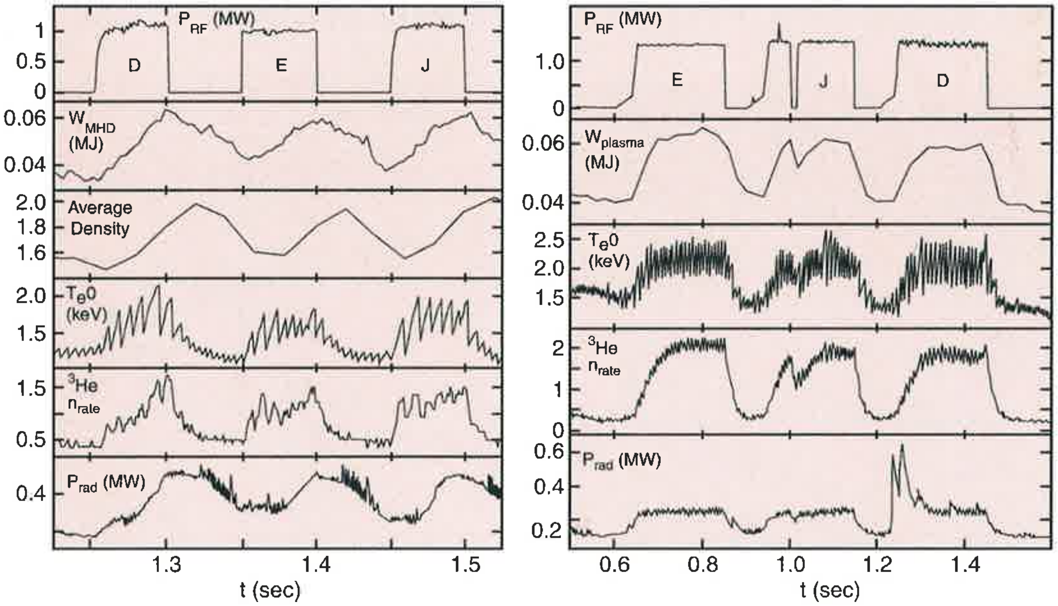


Figure 2. Heating comparison of the 4-strap antenna (J) with the two 2-strap antennas (D and E). The three antennas were energized sequentially in the same plasma discharge. The H-mode discharge is on the left plot and the L-mode discharge is on the right plot.

The PPPL rf engineering group has continued to assist Alcator C-Mod with transmitter maintenance and tuning, both by giving advice and providing hands-on participation at MIT.

ICRF Physics Results

The physics results from ICRF heating experiments using both the two older antennas and the new 4-strap antenna were quite good. As mentioned above, a comparison of heating efficiency of the 4-strap antenna with the older 2-strap antennas yielded identical values of stored energy, electron temperature, neutrons, and radiated power. Total rf power with all three antennas operating simultaneously came up to about 5 MW, stored energy was increased to 0.23 MJ, peak electron temperature on axis came up to 5 keV, and the peak neutron rate came up to 1.8×10^{14} $nsec^{-1}$. These results are shown on Figure 3.

Toroidal plasma rotation has been observed in Alcator C-Mod plasmas even without direct external momentum input to the plasma both in ohmically and ICRF-heated discharges. A theoretical idea proposed by F.W. Perkins and R. White of PPPL suggested that the direction of rotation could be influenced by the placement of the minority ion resonance with ICRF-heated discharges. A change in resonance location from the high-field side of the magnetic axis to the low-field side was predicted to reverse the direction of rotation. Experiments were performed to test this hypothesis using the 2-strap antennas set at 80 MHz. Placement of the hydrogen minority resonance was varied by scanning the toroidal magnetic field from 4.1 to 6.05 T, varying the location of the resonance from -15.2 to +9.9 cm with respect to the magnetic axis. The toroidal rotation was observed not to change direction with the resonance location change (Figure 4), contrary to the predictions of the theory, but a new internal transport barrier appeared in addition to the usual high-confinement mode (H-mode) edge barrier when the resonance was moved to the high-field side (Figure 5).

Initially only a density barrier was observed, as indicated by the strong central peaking of the plasma discharge without any central fueling, $n_e \sim 7 \times 10^{20}$ m^{-3}.

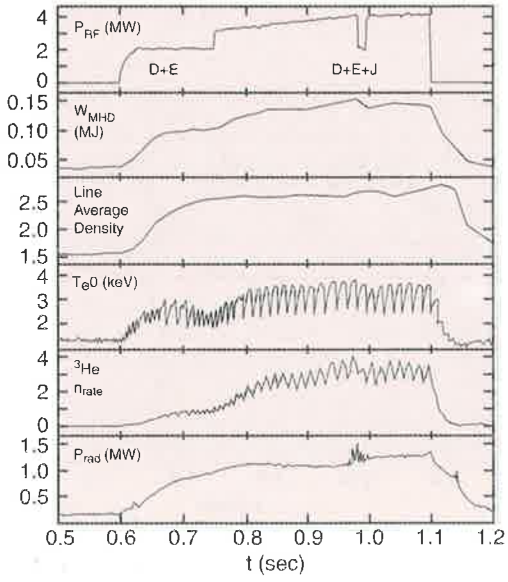


Figure 3. High ICRF heating power discharge.

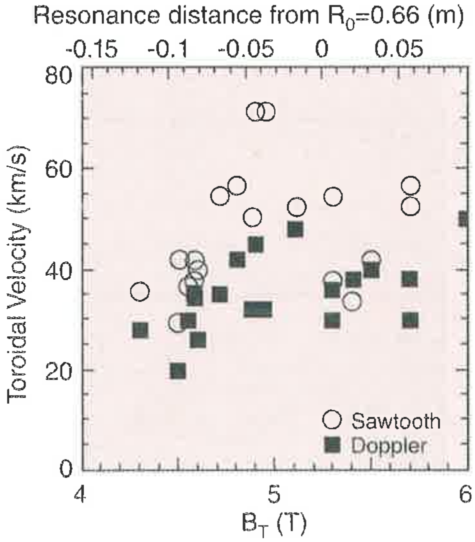


Figure 4. Plasma toroidal rotation velocity as a function of hydrogen minority resonance location (toroidal magnetic field).

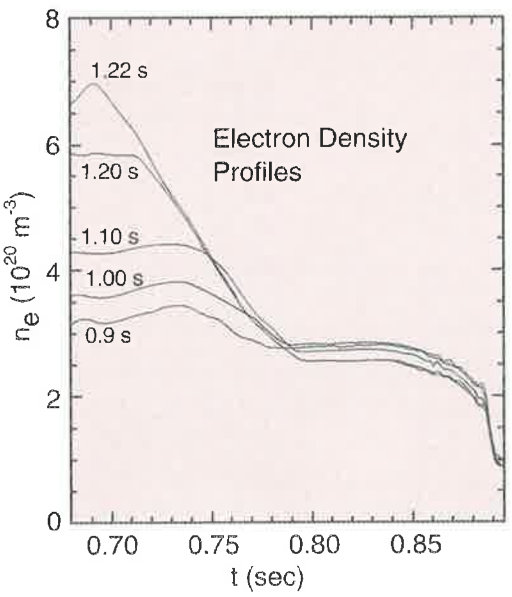


Figure 5. Electron density profile as a function of time showing the strong on-axis density peaking as the internal transport barrier is formed following the application of off-axis ICRF heating power.

Analysis with the PPPL transport code TRANSP indicated a barrier in the electron thermal diffusivity as well.

The 4-strap antenna and its transmitters were retuned to 70 MHz, allowing the two 80-MHz antennas to form the transport barrier through off-axis heating while the 70-MHz antenna heated on-axis, within the barrier. An increase in neutron rate of 2-3 times was observed with 0.6-1.0-MW heating power. This experiment illustrates the unique applicability of multifrequency rf heating.

Lower-hybrid Current-drive Project

The addition of off-axis current drive via directed lower-hybrid waves has been proposed for Alcator C-Mod. The resulting current profile modification has been modeled and is expected to allow exploration of the advanced tokamak regime of operation, with high (~70%) bootstrap current fraction, high plasma pressure (β_N ~ 3), and high confinement (H_H = 1-2) under pulse lengths approaching steady state in the plasma (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 and MIT is assembling the power system. The project was approved by the U.S. Department of Energy (DOE) in February 2000 and the 16 klystrons that had been on loan to PPPL's Princeton Beta Experiment-Modification (PBX-M) were returned to MIT, a successful project Conceptual Design Review was held, and prototype coupler fabrication is in progress at PPPL. Because of funding limitations, the first coupler will not be supplied to MIT until March, 2003. The coupler, its support and drive mechanism, and its high-power phase shifters and splitters are shown in Figure 6.

Motional Stark Effect Diagnostic

The motional Stark effect diagnostic is crucial to the determination of the spatial distribution of currents driven in the Alcator C-Mod plasma by ICRF or directed lower-hybrid waves. The vacuum optics were installed inside the Alcator C-Mod vacuum vessel late in 1999; the external optical system including image dissector, fiber optics, photoelastic modulators, and photomultipliers have now been added, connected to digitizers, calibrated and checked out. First light from the University of Texas' diagnostic neutral beam was observed in June, 2000. Optical component damage as a result of plasma disruption mechanical shocks was detected during the July, 2000, opening and corrected. Further measurements with the neutral-beam diagnostic were performed, but in general initial neutral-beam signal levels were found to be considerably lower than predicted by modeling. Improvements in beam operation are expected to bring the signals up to the proper levels.

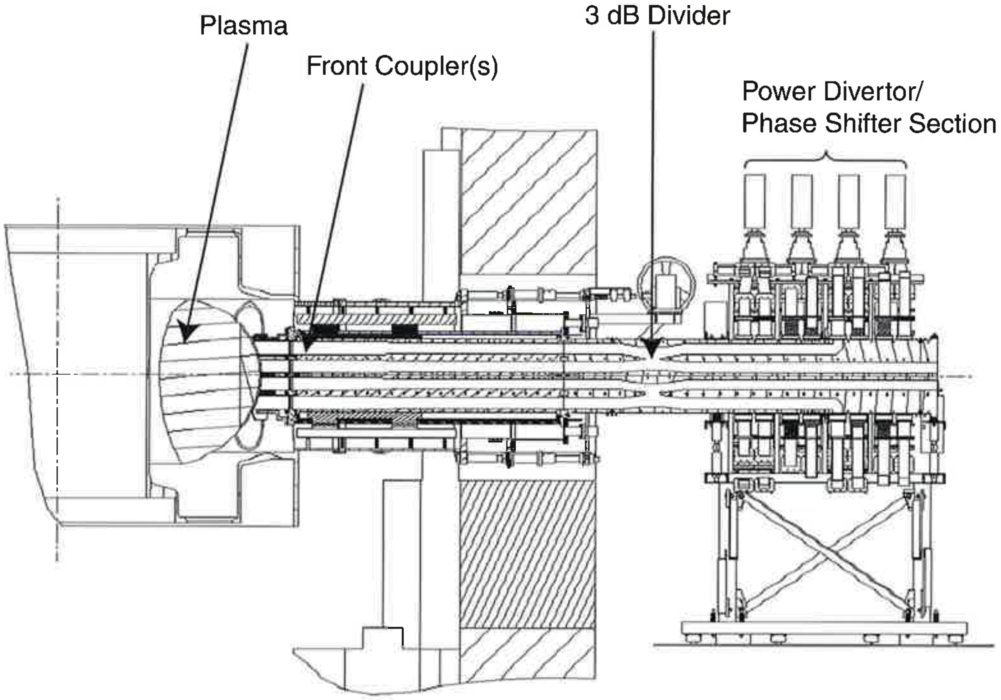


Figure 6. Drawing of the PPPL lower-hybrid launcher installed on Alcator C-Mod.

Gas Puff Imaging Diagnostic

A new "gas puff imaging" diagnostic for measuring the radial versus poloidal structure of edge density turbulence in Alcator C-Mod was installed this year. This diagnostic measures the spatial fluctuations in the visible light emission from a localized neutral gas puff near the outer wall. These fluctuations are related to the local small-scale plasma density fluctuations. Two-dimensional images of this gas puff emission were obtained at a rate of 60 frames per second over an area of 6 cm by 6 cm centered around the separatrix near the outer limiter, each frame being gated to have typically a 1-µsec exposure per frame. The two-dimensional patterns of light emission show a strongly turbulent edge structure in ohmic and low-confinement mode (L-mode) plasmas, with average correlation lengths typically one cm in the radial and poloidal directions, and with frequent isolated "blobs" of plasma associated with large local density fluctuations in the scrape-off layer. Examples are shown in Figure 7. In H-mode and the enhanced D_α (EDA) H-mode, the fluctuation levels seem to be lower, but systematic studies have not yet been completed. In the near future, these gas puff imaging measurements will be correlated with other Alcator C-Mod edge measurements and with theoretical modeling to obtain a better understanding of the edge turbulence and transport.

A fast exposure/fast framing camera upgrade is planned in order to generate "movies" of the "blob" behavior under the different plasma conditions.

Microwave Reflectometer Diagnostic Results and Upgrades

PPPL has proposed an upgrade to the Alcator C-Mod microwave reflectometer which will increase the number of channels to higher frequency and allow density and fluctuation measurements to be made further up the plasma edge density pedestal. While the microwave hardware was being upgraded and checked out by

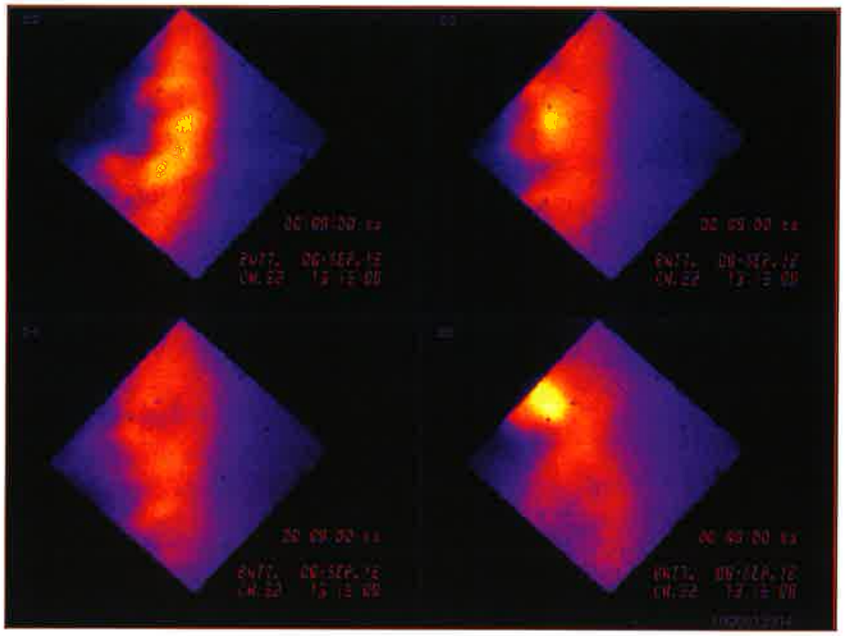


Figure 7. Gas puff images of plasma edge turbulence. Each image is taken with a 2-msec exposure time, and successive images are separated by 16 msec. Images arrayed in normal reading order.

an industrial vendor, PPPL participated in experiments on Alcator C-Mod using the existing system. A quasi-coherent mode had been observed in Alcator C-Mod EDA H-mode discharges within the H-mode pedestal region, with a poloidal wave number of approximately 3-6 cm^{-1}, correlated with the D_α enhancement of the EDA mode and which affects transport. The reflectometer was used to attempt to localize the mode in both the ICRF-heated and ohmic EDA H-modes; it was found to be within the pedestal region, but not related to a specific pedestal feature.

An additional microwave hardware upgrade which will allow plasma fluctuation measurements to be extended to the plasma core is in engineering design preparation and will be ready for installation in 2002.

ICRF Modeling

The two-dimensional wave absorption modeling code TORIC developed by M. Brambilla (Max-Planck-Institut für Plasmaphysik at Garching, Germany) and P.T. Bonoli (MIT) has now been compared to the one-dimensional code METS developed by D.N. Smithe (Mission Research Corporation) and C.K. Phillips (PPPL). The simpler dimensionality of METS is thought to have allowed a more accurate description of the wave physics phenomena to be incorporated in the code. Good agreement was found for relative power splits and power deposition profiles in hydrogen minority D(H) heating regimes. Reasonable agreement was found in the $D(^3He)$ regime for on-axis heating of ^3He. Differences were found in off-axis $D(^3He)$ mode-conversion regimes that are believed to be due to poloidal resolution limits in TORIC for the large $k_\perp \rho_i$ ion-Bernstein wave (IBW) fields excited via mode conversion. Scans of TORIC with increasing poloidal mode number showed good agreement with METS and C-Mod experimental data at $N_m = 161$; simulations with $N_m \approx 200\text{-}250$ are required to obtain fully converged wave fields.

These TORIC enhancements have now been implemented into the PPPL transport code TRANSP for analysis of Alcator C-Mod experiments. The new internal transport barrier discharge resulting from off-axis ICRF heating has been analyzed. The calculated ICRF power deposition profile is shown in Figure 8, with a small amount of power absorbed via direct electron Landau damping of the fast wave near the axis. Of the 2.4 MW absorbed via H minority cyclotron damping at r/a ≈ 0.4, about 1 MW of the minority ion tail power equilibrates on background deuterons, and about 1.4 MW slows down via electron drag.

Time behavior of the computed effective thermal diffusivity χ_{eff} at two positions, one near the axis and one outside the transport barrier, suggests the formation of the barrier soon after the ICRF power is applied, as evidenced by the reduction in central χ_{eff} by a factor of 2-3. This behavior is shown in Figure 9.

Transport Modeling

In order for plasma energy and particle transport models to be believable in a predictive mode, they must be carefully benchmarked against experimental data. The high magnetic field, high plasma density, and high auxiliary heating power density of Alcator C-Mod present a unique region of parameter space in which to test transport models.

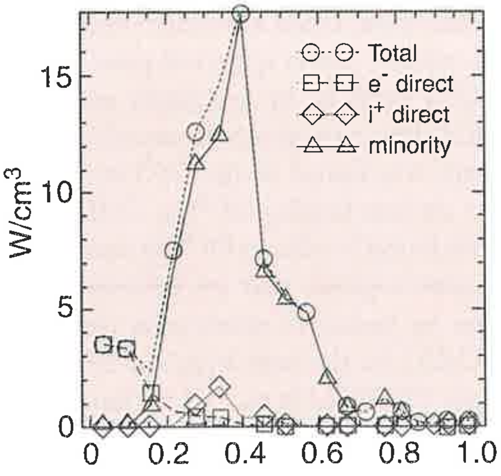


Figure 8. TRANSP code modeling of the ICRF deposition profile for the off-axis heating leading to an internal transport barrier discharge.

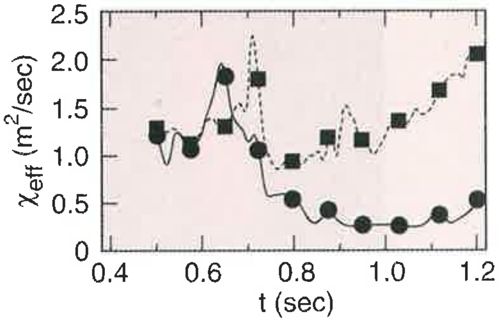


Figure 9. Time behavior of effective diffusivity as computed by the TRANSP code for the internal transport barrier discharge. The ICRF turned on at 0.7 sec. Trace with square symbols corresponds to r/a = 0.6 (outside barrier) and trace with circles corresponds to r/a = 0.05 (inside barrier).

In 1999, working in close collaboration with theorists and experimentalists at Alcator C-Mod and the University of Maryland, PPPL modelers showed that predictions of linear ion-temperature gradient/trapped-electron mode (ITG/TEM) microturbulence are not consistent with the measured ion-temperature gradient scale length of typical H-mode plasmas in Alcator C-Mod. In 2000, whether theory and experiment can be reconciled by nonlinearly generated zonal flows, which may cause an upshift in the effective critical ion-temperature-gradient scale length, was investigated. Nonlinear turbulence simulations produced by GS2, a gyrokinetic turbulence code, indicate that such an effect may occur in Alcator C-Mod conditions. Work will continue in 2001 to determine whether this result is robust, as important parameters (such as magnetic shear) are varied within their measurement uncertainties.

Doublet-III-D Collaboration

PPPL's collaboration in the tokamak program at the DIII-D National Fusion Facility at General Atomics (GA) is of great benefit to both PPPL and GA. It affords the opportunity for PPPL scientists and engineers to share in leading research at the nation's largest tokamak facility, and it has directly led to some of the most notable achievements of the program during the past year. These results included active magnetic feedback stabilization of resistive wall modes (RWMs) in high performance plasmas, complete stabilization of a neoclassical tearing mode (NTM) by electron-cyclotron current drive (ECCD), and validation of the highly localized nature of electron-cyclotron heating (ECH) and 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

The collaborative experiments (with Columbia University and General Atomics) on active magnetic feedback stabilization of resistive wall modes are a major component of the DIII-D tokamak research program. It is widely recognized that control of these slowly growing, long wavelength, magnetohydrodynamic (MHD) instabilities is crucial for the development of high-performance advanced tokamak plasmas, and that DIII-D is the only large tokamak with a major effort in that area. In the FY2000 DIII-D experiments, the radial magnetic-field perturbations arising from growth of RWMs were detected by large-area external sensor loops provided by PPPL in FY1998, and various logic schemes were used to generate commands for applying power to the three diametrically opposed pairs of DIII-D correction coils. The experiments were preceded by a comprehensive series of tests to establish the transfer characteristics of the feedback power supplies procured by PPPL in FY1999 and to optimize corrections of error fields.

Experiments in FY2000 conclusively demonstrated closed-loop feedback stabilization of resistive wall modes under a variety of conditions. In one case, a mildly unstable RWM was controlled for about one second. To show that active stabilization was indeed achieved, feedback control was gated off for a 20-msec period during the discharge. The mode began to grow in the absence of feedback control, but it was promptly suppressed when closed-loop feedback control was resumed.

In the course of these experiments, twenty-four new external sensor loops, installed by PPPL in FY2000, became operational. They were used in conjunction with the original six-loop equatorial array to measure the helical structure of resistive wall modes. Analysis of soft X-ray measurements from two identical poloidal arrays, separated toroidally by 150 degrees, together with data from the 30-loop external sensor system for measuring radial magnetic-field perturbations and a diametrically opposed pair of internal magnetic probes for measuring poloidal-field perturbations, demonstrated the expected global kink nature of resistive wall modes. A significant result of that study is that the n=1 global kink structure remained unchanged in the presence of magnetic fields from the active coils, except for the expected reduction in amplitude.

During FY2000, PPPL completed the design and began fabrication of an extensive new set of sensor loops and magnetic probes to be installed in DIII-D early in FY2001. The new sensors will be situated inside the vacuum vessel underneath the protective carbon tiles. Modeling indicates that the new internal sensors should be more effective than external sensors in active control of resistive wall modes.

Wave-plasma Interactions

Many of the major results of the FY2000 DIII-D experimental campaign were enabled by the articulated, remotely steerable ECH/ECCD launcher developed by PPPL and installed before the experimental run period. The launcher played a crucial role in ECH/ECCD experiments by allowing precise remote control of poloidal and toroidal injection angles of two powerful microwave beams. It performed flawlessly during the entire campaign.

In an experiment early in the campaign, the PPPL launcher made it possible, for the first time in DIII-D, to change the direction of current drive on successive plasma discharges and to accurately test the localization of deposition and the radial dependence of current-drive efficiency. The current drive was large, localized, and unmistakable in both directions and quantitatively in good agreement with expectations.

Another significant achievement was the complete stabilization of m/n=3/2 neoclassical tearing modes (NTMs) by precisely controlled ECCD. 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, the instability could be completely stabilized. After termination of ECCD, the instability did not reappear, even though sawteeth, which sometimes trigger the growth of NTMs, were present in the discharge. The NTM could not be fully stabilized if injection was not in the co-current direction, if the location of beam deposition was more than a few centimeters from the island, or if only one gyrotron was used. The results are in agreement with expectations and consistent with experience on the ASDEX Upgrade (Max-Planck-Institut-für Plasmaphysik, Garching, Germany) and JT-60U tokamaks.

Operational experience with the first steerable ECH/ECCD launcher is being taken into account in the specification and design of a second, more robust, steerable ECH/ECCD launcher capable of supporting ten-second operation of two gyrotrons. Measured temperature increases of the steering mirrors during the FY2000 experiments were roughly as expected. By incorporating an actuation mechanism completely different from that used in the first launcher, PPPL designed a two-gyrotron antenna with a 20-fold increase in torque handling capability without compromising toroidal and poloidal angular pointing range and accuracy. This allows 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. It also affords the possibility of steering the beams during a plasma discharge, as well as between discharges. A design sketch of the new launcher is shown in Figure 10. The launcher is scheduled for delivery and installation at the end of FY2001, so that four steerable gyrotron beams will be available for FY2002 experiments.

PPPL physicists completed analysis of two types of instabilities observed in previous years during radio-frequency heating experiments on DIII-D.

A fishbone-like instability that sometimes occurs in beam-heated plasmas when ECH is applied on the high-field side of the magnetic flux surface was attributed to wave-particle interaction with the barely trapped suprathermal electrons produced by off-axis ECH. It is a very

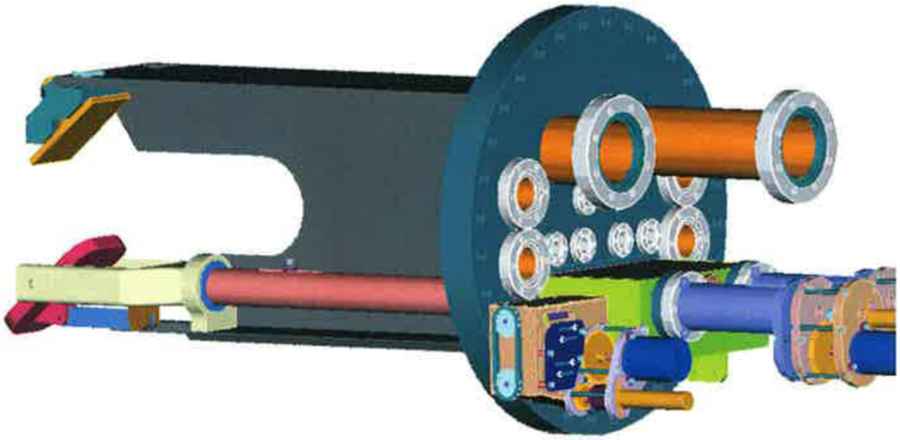


Figure 10. Design sketch of the second PPPL electron-cyclotron heating and current-drive steerable launcher.

special situation where the diamagnetic drift velocity and the precession velocity of the barely trapped suprathermal electrons at the q = 1 surface are parallel to those of the deeply trapped energetic ions so that they can resonate with the same m/n=1/1 mode and drive it together. The instability cannot exist in plasmas with $q_{min} > 1$. When there is a q = 1 surface in the plasma, the instability may be avoided by placing the ECH location far enough from the q = 1 surface.

The chirping Alfvén instabilities that are sometimes observed during ICRF heating have been positively identified as Energetic Particle Modes (EPMs). The EPMs are core-localized modes, generated by a strong population of fast ions. They transport fast ions radially and are the leading cause of the monster sawtooth crash.

Confinement and Transport

PPPL continued its collaborative investigation of the formation and sustainment of internal transport barriers in DIII-D. The foremost result of that activity during the past year is the discovery of a Quiescent Double Barrier (QDB) operating regime. This essentially steady-state mode of operation has both an internal transport barrier and an edge-localized-mode-free H-mode edge and does not appear to suffer from accumulation of impurities in the plasma core. It is accompanied by a multi-harmonic MHD oscillation at the plasma edge, which may account for the absence of impurity buildup. The QDB was obtained with neutral-beam injection counter to the plasma current at power levels above 3.7 MW when the edge neutral density was minimized by using divertor cryopumping and maintaining a separation of about 10 cm between the plasma and the outer wall. The QDB regime will be vigorously investigated during the coming year as a possible high-performance alternative to conventional H-mode tokamak operation.

In other experiments, ECH was injected in the vicinity of an internal transport barrier in an attempt to expand the minor radius of the barrier and improve plasma performance. Marginal improvement was observed using three gyrotron sources, two of which were controlled by the PPPL steerable launcher. Two gyrotrons were ineffectual.

Theory and Modeling

In support of the collaborative experiments on stability, the VACUUM code was modified to provide a framework for modeling the feedback stabilization of external modes in toroidal plasma discharges. The code relates the perturbations on the various surfaces, i.e., the plasma, both sides of the resistive shell, and the active feedback coils. The sensor coils can be placed arbitrarily, most easily on the plasma or shell. Simulation of active feedback stabilization of resistive wall modes has been computationally implemented by coupling VACUUM to the GATO ideal-MHD stability code. For the cases studied so far, mode deformation due to feedback was not significant so that a rigid helical displacement model could be sufficient. This is in agreement with experimental results discussed above.

In the area of wave-plasma interactions, a theoretical model was developed to account for toroidal rotation in plasmas heated by ICRF alone, as has been observed in Alcator C-Mod. A mechanism was proposed and evaluated for driving rotation in tokamak plasmas by minority ion-cyclotron heating, even though this heating introduces negligible angular momentum. In the model, angular momentum transport is governed by a diffusion equation with an assumed boundary condition at the separatrix. Calculations with the Monte-Carlo ORBIT code show that ion-cyclotron energized particles will provide a torque density source which has a zero volume integral but separated positive and negative regions. For a 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; overall agreement with experiment is good. When the resonance lies on the high-field side, the predicted rotation becomes counter-current for a no-slip boundary while the observed rotation remains co-current. The surface boundary condition remains a source of uncertainty.

Diagnostic Development

The principal PPPL diagnostic development activity during FY2000 was a conceptual design study for a tangentially viewing, two-dimensional hard X-ray imaging system. The purpose of the camera is to measure the asymmetric X-ray emission from the plasma during ECCD experiments for the study of the energetic electron distribution function. In order to provide the required shielding for the sensitive components of the camera in the available space around DIII-D, a two-module design was proposed. A module near the machine would house a vacuum interface cone and beryllium window, a pinhole camera with apertures and foils, and a fiber-optic faceplate and scintillator and would be surrounded by X-ray and neutron radiation shielding. A module further away would include an image intensifier and a high-speed CCD camera and would be surrounded by X-ray, neutron, and magnetic-field shielding. The two modules would be connected by a coherent fiber-optic bundle. Implementation of the camera appears to be feasible, but funding is not yet available.

The primary emphasis of the first DIII-D experiments of FY2000 was on characterizing plasma behavior and control with the new closed upper divertor. The experiments made use of five new gas puffing valves installed by PPPL during the previous shutdown period. The valves supply gas to a number of capillaries distributed toroidally and poloidally in the upper and lower divertor structures and allow great flexibility in the choice of gas injection locations for puff-and-pump experiments while maintaining toroidal uniformity. The valves were ready for operations on the first day of upper divertor pumping experiments, well ahead of the estimated completion date.

International Collaborations

The primary goal of PPPL's International Collaborations Program is to follow the recommendations of the Fusion Energy Sciences Advisory Committee (FESAC) in making use of outstanding facilities abroad to enhance the capability of the U.S. fusion program. Studies of transport issues for advanced tokamak plasmas, International Thermonuclear Experimental Reactor-relevant, edge localized mode (ELMy) H-mode plasmas, and radiative improved (RI) confinement mode plasmas have been carried out on the large Joint European Torus (JET) and the Japanese Tokamak-60U (JT-60U). Energetic particle physics has also been extensively studied, particularly the effects these particles have on macroscopic stability. Some studies in boundary physics have also been made.

In support of these physics studies, development of diagnostic components to assist in improving the operation of the JT-60U high-energy negative-ion-based neutral-beam (NNBI) continued. An exciting new collaboration has been started with the Korea Superconducting Tokamak Advanced Research (KSTAR) Project, where PPPL staff provided consultation on the diagnostics design and worked with the KSTAR physicists on a prototype X-ray crystal spectrometer. Some of the design issues for KSTAR's lower-hybrid heating launcher were also addressed. KSTAR is a long-pulse tokamak with superconducting magnetic-field coils now under design and fabrication in Taejon, Korea; it is scheduled to begin operation in 2005.

The JET device in Abingdon, England had a successful year of operation during which its management structure was completely changed. Consequently, new contacts had to be developed, causing some delays in implementing PPPL's contributions. JET is the only device capable of carrying out burning-plasma physics experiments, a key element of the FESAC recommendations. It therefore behooves PPPL to maintain as strong a collaborative contribution as possible.

The plasmas in JT-60U, the large tokamak at Naka, Japan, continued to demonstrate excellent performance. A major aspect of PPPL's contribution has been in the effect of energetic particles in inducing new fast-particle instability modes. The performance of the NNBI is continuing to improve, making this physics accessible, with its potential impact on burning plasma performance.

With PPPL's intention to build and operate a compact stellarator, collaborations on the Large Helical Device (LHD) in Toki, Japan, are an important part of our International Collaborations Program. Much of this work involves the use of codes for use in the design of the PPPL device, but a little work on the LHD experiment has also continued.

These and some smaller collaborative activities are addressed in the following sections. In addition, the collaborative program on aspects of the use of tritium in the Tokamak Fusion Test Reactor (TFTR), undertaken as an Annex to the DOE/ Japan Atomic Energy Research Institute (JAERI) Collaborative Agreement, carried out in collaboration with the Los Alamos National Laboratory, is also briefly described. The main studies have been on the removal of tritium from components, such as graphite tiles from the TFTR first-wall, and developing potential capabilities for measurement and removal of tritium in-situ inside a next-step fusion device.

Plasma Turbulence and Transport

The collaboration in motional Stark effect (MSE) measurements of the magnetic-field pitch angle of JET plasmas has continued successfully. These measurements provide a powerful constraint on reconstructions of JET magnetic equilibria which yield the radial profile of the safety factor, q(R). The JET MSE diagnostic, constructed and implemented jointly by PPPL and JET, operated reliably. Measurements and analysis concentrated on characterizing the q-profile in JET optimized shear (OS) plasmas. A major concentration was on the use of lower-hybrid current drive (LHCD) to produce strongly reversed q-profiles, in contrast to the flat or mildly reversed profiles obtained in the standard OS scenario. The strongly reversed profiles allow formation of internal transport barriers at relatively low-heating power levels and which are not linked to rational q values. An example is shown in Figure 11. Results were presented at the annual European Physical Society Conference in 2000. A paper on the initial OS results with LHCD has been submitted for publication.

An experiment has been carried out in JET to compare ICRF and neutral-beam-injection (NBI) heated, ELMy, H-mode plasmas to learn if the confinement and transport are similar. The experiment resulted in a careful measurement of the toroidal rotation profile in the ICRF-heated plasmas and in creating pairs of similar plasmas. The toroidal rotation in the ICRF case was about 15% of that measured in NBI-heated plasmas. The results are being analyzed.

Gyrokinetic analysis has been performed for JET ELMy H-mode plasmas. The results show that the growth rates of the microturbulence, believed to cause anomalous transport, are large, especially near the pedestal. The shear in the poloidal flow, caused by the radial electric field is calculated for NBI-heated plasmas to be sufficiently large to stunt the growth of the microturbulence. This shear arises mainly from the large toroidal velocity. When the rotation is slowed, either by increasing the plasma density or by spontaneous transitions from Type I to Type III ELMys, the confinement degrades and the local transport increases.

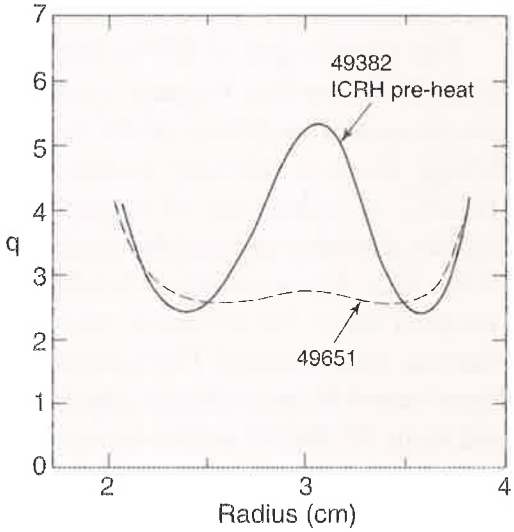


Figure 11. Comparison of q-profiles in a JET standard (ohmic preheat only) optimized-shear discharge with a strong reversed-shear discharge produced with preheat by lower hybrid and ICRF.

For similar ELMy H-mode plasmas in JT-60U, the 'stiffness' of thermal transport was examined; four scans of pedestal temperature T_{ped} with constant heating power and one heating power scan with constant T_{ped} were studied. It was found that 30-80% increases in T_{ped} are associated with 10-70% increases in core temperature, even though the total heating power is constant. Similarly, increasing the heating power by 45% gives almost the same core temperatures in a group of five plasmas with the same pedestal temperature. The results, shown in Figure 12, can be characterized as having relatively 'soft' transport in the plasma periphery and relatively 'stiff' transport in the core. Transport models were tested by solving the power

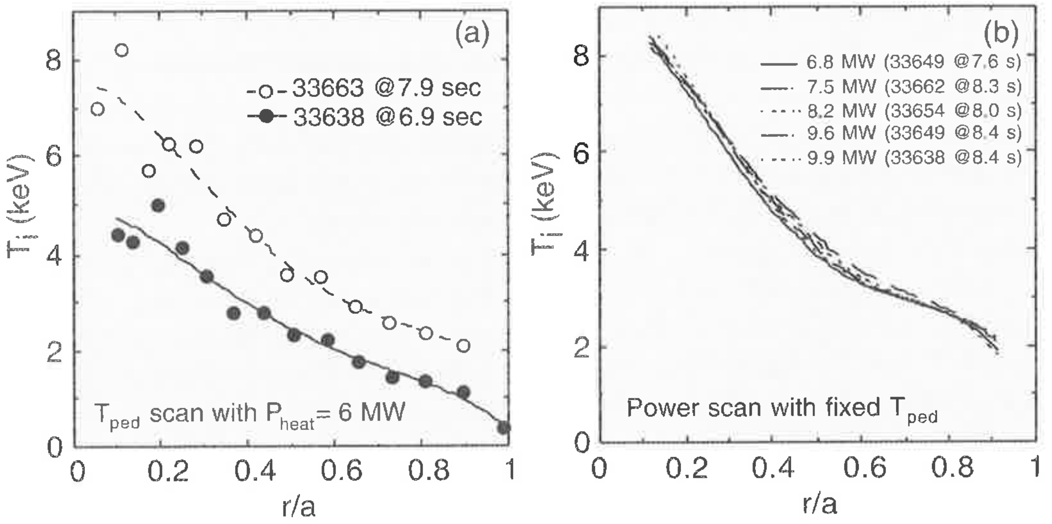


Figure 12. (a) Ion temperature measurements and fits for a T_{ped} scan. (b) Fits only for a P_{heat} scan.

balance equations to predict temperatures, which were compared to the measurements. The Rebut-Lallia-Watkins-Boucher and Institute for Fusion Studies/PPPL models' predictions generally agree with the measured temperatures, but the multimode model uniformly predicts temperatures that are too high except for the central sawtoothing region.

The analysis of internal transport barriers (ITB) has been a major focus of worldwide tokamak programs, and PPPL has participated in the work at JT-60U. One aspect has been the use of the axisymmetric version of the FULL code, with its recently extended E × B rotation model, in the analysis of electrostatic toroidal drift modes (ion-temperature gradient and trapped-electron modes).

In extension of the use of PPPL codes developed for tokamak plasmas, transport studies in the LHD device have included analysis of microinstability properties of electrostatic toroidal drift waves. This work employs a recently extended, non-axisymmetric version of the comprehensive linear kinetic microinstability code, FULL.

Understanding the relation between turbulence and transport in advanced confinement regimes continues to be a major challenge to the fusion community. Experimentally, the challenge is to relate unambiguous local turbulence measurements to local changes in profiles and transport. Theoretically, the challenge is to determine the complex feedback dynamics that regulate fluctuations, transport, and the transitions between different confinement regimes.

The reflectometer diagnostic collaboration on the JT-60U tokamak is aimed at providing unambiguous measurements of the density turbulence during the formation of the internal transport barrier. Early measurements suggested the possibility that a dramatic reduction of the radial turbulence correlation length occurs in the transition to enhanced core confinement. A major limitation in the analysis of the reflectometer measurements is the lack of a quantitative description of the scattering process of the microwaves taking into account realistic plasma geometry and antenna structures. Hence a development effort was undertaken to simulate reflectometer measurements in a two-dimensional geometry for the quantitative interpretation of JT-60U results. The analysis results have been prepared for a tutorial paper, where it is shown that an upper bound of 0.4 cm can be placed on the radial correlation length of density fluctuations in the ITB in JT-60U. Further quantitative analysis of the fluctuation properties during ITB formation is planned for the coming year.

A new collaborative study of pellet injection into JET plasmas has been started. The JET pellet fuelling configuration with both inside and outside launch capability, combined with the physically large, high-temperature JET target plasmas at high toroidal field offers a special opportunity for a detailed study of the pellet mass redistribution phenomena. High time resolution electron temperature measurements can be used to study pellet mass redistribution during and immediately following pellet ablation. For normal JET operations, such electron temperature measurements are typically subject to plasma cutoff during the ablation process however. But several pulses for which cutoff was avoided have been identified. Detailed analysis and simulation of this inside launch data and similar JET data from outside launch will be continued.

PPPL provided a large fraction of the transport analysis of JET experiments using the TRANSP code. One example was a study of local transport in edge-localized, high-confinement mode plasmas with the different hydrogen isotopes. The TRANSP code has been generalized this year to allow multiple impurities and multiple impurity charge states in its simulation. Previously, only one "model impurity" was allowed. TRANSP can now take advantage of multiple impurity profile data available from JET charge-exchange measurements, improving profile estimates of depletion of main plasma ions, and hence, better estimates of fusion rates.

Fast Particle Physics and Macroscopic Stability

The sawtooth period observed in JET ELMy-free H-Mode plasmas increases with neutral-beam injection power. For injected power $P_{NBI} > 12$ MW no large sawtooth crash is observed during the ELMy-free period. However, as the edge stability is improved and external kink modes and ELMys are delayed, a possible sawtooth crash at a high plasma beta becomes a concern. In JET deuterium-tritium experiments, delaying sawteeth was found to be crucial in the quest for high fusion power. Fast particles are known to provide a stabilizing effect on sawteeth; however, sawtooth stabilization by NBI ions is not clearly understood, since NBI ions are usually not "fast" enough to stabilize the $m/n = 1/1$ internal kink mode which is believed to cause the crash. In order to understand the observed sawteeth stabilization in tokamak experiments with NBI heating, the internal kink $m/n= 1/1$ mode stability of JET plasmas was modeled using the NOVA-K code, which is also benchmarked with the nonperturbative version of NOVA and the M3D code.

A JET high-performance discharge was chosen to study the properties of hot particle stabilization of the $m/n=1/1$ mode. TRANSP was used to provide the plasma parameters, which in this case were magnetic field $B = 3.7$ T, major radius on axis $R_0 = 2.92$ m, minor radius $a = 0.94$ m, deuterium neutral-beam heating power $P_{NBId} = 11.9$ MW, tritium neutral-beam heating power $P_{NBIt} = 10.5$ MW, ion-cyclotron range of frequencies heating power $P_{ICRH} = 3.1$ MW at 13.3 sec. A summary of the basic calculations of a stability study by NOVA-K with sheared plasma rotation velocity is given in Table 1 with growth rates contributing to the dispersion.

Table 1: Summary of Growth Rates Showing Stabilizing Effects.

	MHD	ICRH, $\lambda_0=R/R_0$	NBI-D	NBI-T	Alpha Particles
Distribution		Maxwellian Resonant Layer at $\lambda_0 = 0.96$	Slowing Down	Slowing Down	Slowing Down
Energy (keV)		$(T_H=)$ 200	76	150	3520
β_0 (%)	5.81	0.65	0.25	0.44	0.6
γ/ω_A (%)	1.5	-0.9	-0.07	-0.17	-0.53

Stabilizing effects on the m/n=1/1 internal kink mode by hot ions are demonstrated for JET NBI alpha experiments in high-performance discharges. The alpha particles offer a strong contribution to the sawtooth stabilization in high fusion rate plasmas.

Other results from the study prove that the mass dependence of the fast beam ion contribution to δW is consistent with the increased sawtooth period for experiments with a larger concentration of tritium neutral-beam ions. While the ω_*-stabilization model by L. Zakharov appears to be consistent with TFTR sawtooth suppression in supershots, it cannot explain the increased sawtooth period with increased NBI ion beta, because of the low ω_* in JET experiments.

A new collaboration with the JET group was initiated to determine the dominant damping mechanism of Toroidal Alfvén Eigenmodes (TAE) in tokamak plasmas. The TAE damping rates of several JET discharges were calculated using the NOVA-K code and compared with the measurements. The calculated damping rates are smaller by an order of magnitude than the observed experimental damping rates for some of the discharges. This could be due to the uncertainties in the assumed safety factor q profiles or breakdown of the damping model. The discrepancy will be investigated in future collaborations.

One of the most important experimental results of Alfvén instabilities excited by negative-ion-based neutral-beam injection (NNBI) in JT-60U was the discovery of two new types of TAE modes: (1) a strongly chirping mode with frequency changing from the lower continuum (about 20 kHz) upward to the TAE continuum gap (about 60 kHz) in a timescale of about 200 msec, and (2) a bursting instability appearing in the TAE continuum gap with a bursting change in frequency by about 20 kHz in 1-5 msec. These two new types of modes were discovered in addition to the observation of the usual TAE modes. In order to understand these two new types of modes, theoretical modeling employing the HINST code was performed.

The strongly chirping mode is excited as a result of strong NNBI fast-ion drive and is interpreted as a kinetic ballooning mode at lower frequency which transforms into a RTAE (resonant TAE) mode at higher frequency. Although modeling was not performed for the bursting modes, the magnetic-field oscillation versus time for bursty modes that last for 1-2 msec and occur repetitively every 10 msec or so were examined. It was found that these burst modes are quite coherent with small variations in the wave period by about 20%. The envelope of the wave amplitude also varies by about 30% in a few (5-10) oscillation periods. These features may be responsible for the large frequency spread in 1-2 msec obtained with frequency analysis. These features suggest that the bursty modes are also RTAE modes that are excited via strong resonant interaction with fast ions by releasing both the spatial pressure-gradient-free energy as well as the bump-on-tail velocity-space free energy of the NNBI fast ions.

Fast-ion loss due to different types of TAE modes (regular TAE, frequency chirping modes, and bursty modes) was also studied with new analysis of neutral particle analyzer (NPA) data. The NPA measures mainly the passing fast ions. The NPA (fast-ion loss) data show that different types of TAE modes produce fast-ion losses in different energy ranges of the NPA in the same discharge involving NNBI. This result can be explained in terms of fast-particle resonance with these three types of modes. The decrease of neutron emission rate and the increase of measured neutral particle flux are consistent with the fluctuation levels of these modes. For discharges involving large amplitude bursting modes, the neutron emission rate can drop by 7%, which corresponds to a loss of NNBI beam power of about 25% with fast-ion energy confinement time of about 0.3 sec, which is comparable to the classical fast-ion slowing-down time.

The magnetic safety factor profile before and after sawtooth crashes were investigated by examining the behavior of the toroidicity- and ellipticity-induced Alfvén eigenmodes (TAE and EAE, respectively) during ICRF heating in JT-60U. From the TAEs that are observed before sawteeth and reside inside the q = 1 surface, an upper limit is set for q in the plasma center at the time of the crash. After the sawtooth crash, EAEs that reside at the q = 1 surface are often observed.

The time behavior of these EAEs were successfully modeled with the NOVA-K code. In a number of discharges, the start of the EAEs is delayed to up to 150 msec after the crash. This delay seems to be correlated with the electron temperature just before the crash. It is concluded from this delay that the q = 1 surface disappears from the plasma and hence q(0) relaxes to above one during these sawtooth crashes. This conclusion is also supported by the observation of TAEs immediately after the crash and from NOVA-K simulations of the post-crash TAEs and EAEs. This work clearly demonstrates that the q-profile within the q = 1 surface can be accurately deduced from TAE and EAE observations before and after sawtooth crashes.

As part of the program of evaluating the utility of ferromagnetic shims in reducing the magnitude of the toroidal-field ripple in the small JFT-2M tokamak in Tokai, Japan, a probe had been designed to detect the loss of ripple-trapped and stochastic-ripple-diffusing beam ions. This probe was developed as a collaboration between PPPL and JAERI. New image processing software was written to analyze and display data from this beam ion loss probe. Results derived from this probe and associated software show that reduction in the ripple leads to a tiny loss of ripple-trapped beam ions.

Studies of rotation and fast-particle loss have continued for plasmas in Tore Supra tokamak in Cadarache, France. Although plasma heating with ICRF imparts negligible angular momentum to a tokamak plasma, the high energy particles give significant torque to the plasma through diamagnetic effects. This effect has been directly modeled through guiding-center simulations. It is found that heating in Tore Supra, with the location of the resonance surface on the high-field side of the magnetic axis, can produce negative central rotation of up to 40 km/sec. Particle loss also contributes to negative rotation, but this is not the dominant effect in most discharges. In this work, the effect of collisions and strong plasma rotation on the loss of high energy particles is examined.

A study of the behavior of the transport of energetic ions in MHD-active high-beta spherical torus (ST) plasmas has been carried out in a collaboration with a group from the Institute for Nuclear Research in Kyiv, Ukraine. It is shown that high-beta plasmas may deteriorate the confinement of trapped energetic ions in ST plasmas during MHD events, such as sawtooth oscillations and internal reconnection events. This result indicates that moderate rather than very high-beta operation may be preferable in STs.

Plasma Boundary Physics

Methane screening experiments were performed in JET L-mode plasmas. The ultimate goal of this research is to understand the magnitude of tokamak impurities. Methane screening experiments relate to this goal by evaluating the ability of the scrape-off layer (SOL) to ionize and transport carbon to the divertor, preventing it from contaminating the plasma. This benchmarking is especially relevant for JET since chemical sputtering from the main chamber walls is thought to be a significant source of the dominant (carbon) impurity. Eventually the screening results will form the basis for understanding the intrinsic JET impurities using the DIVIMP code.

The purpose of the work has been to evaluate the methodology and accuracy of the JET methane screening experiments. The perturbations to the core and the SOL plasmas were measured as a function of deuterated methane (CD_4) and molecular deuterium (D_2) injection rates. The deduced screening was independent of the methane injection rate indicating that the methane itself did not significantly perturb the deduced screening. Identification of appropriate reference plasmas is also important. For JET L-modes, the reference plasma should have enough deuterium puffing to achieve the same density as occurred with the methane.

Investigations of improved confinement at high density with impurity puffing continued on JT-60U. Experiments using krypton puffing into ELMy H-mode discharges were performed to compare with previous experiments using argon and neon puffing into identical discharges. Results of the argon puffing discharges was presented by H. Kubo at the International Atomic Energy Agency *Fusion Energy* conference in October, 2000, in Sorrento, Italy.

Calculations using the TRANSP code, the microinstability growth rate GS2 code, and the TRV code to determine the $E \times B$ shearing rate were done to help understand the improved confinement with argon-puffing into ELMy H-mode discharges. Analysis using TRANSP indicated that both the electron and ion thermal diffusivities in the discharge with argon puffing were reduced by factors of two or more over much of the plasma, particularly in the outer one-third. Possible mechanisms for the improved confinement with argon puffing were identified. One mechanism is suppression of ion-temperature gradient (ITG) modes. It was suggested that higher Z_{eff}, as well as increased pedestal temperature, may improve core confinement by suppressing toroidal ITG modes. In a parameterization of the toroidal ITG threshold, based on gyrokinetic code results, the critical inverse ion-temperature gradient scale length scales as Z_{eff}. This parameterization indicated stability for toroidal ITG modes in the argon case, and instability in the reference case, over most of the plasma cross section.

A second possible mechanism for the improved confinement with argon puffing was shown by microstability calculations. Simulations, using the Dorland-Kotschenreuther-Liu GS2 toroidal electromagnetic gyrokinetic stability code with the GS2_PREP driver, of the growth rate spectrum of toroidal drift waves indicated a spectral upshift to shorter wavelengths in the outer region $\rho \sim 0.7\text{-}0.95$ in the argon case. This upshift is illustrated in Figure 13. The calculated phase velocity changes to the electron diamagnetic direction, which is consistent with suppression of longer wavelength ITG modes. Due to the shorter wavelength, the mixing length estimate of the thermal diffusion coefficient $\gamma_{lin}^{max}/ <k_{\perp}^{2}>$ is strongly reduced for $\rho > 0.75$ [see Figure 13(b)], even though the maximum linear growth rates glinmax are similar (also not shown).

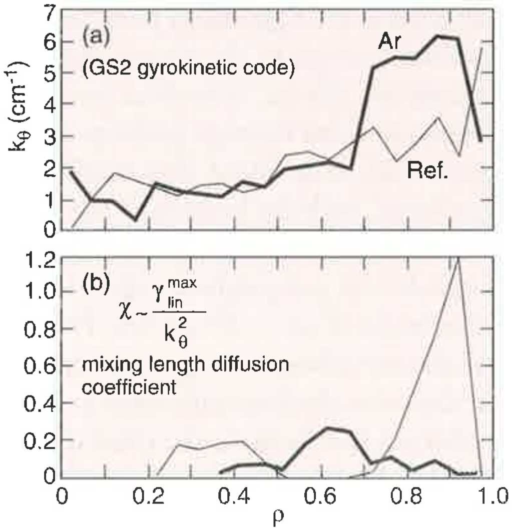


Figure 13. (a) Values of k_θ for maximum linear growth rate, and (b) mixing-length diffusion coefficient, calculated for a discharge with argon puffing (thick curves) and a reference discharge without argon puffing (thin curves).

Heating Systems

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-injection system on JT-60U. This year, the work concentrated on the task of improving the spatial uniformity of the plasma illuminating the extraction grid. Among many techniques tried, the most successful involved using exterior resistors of different values to offset the differences in the internal arc impedance among the eight filament groups. Experimentation with operating the cathodes in a mode where the electron current flowing across the plasma sheath is limited by the thermionic emission of the filament, rather than by the (higher) limit imposed by the space-charge self-repulsion of the current was started. Although more complicated, this permits enhanced control over the primary electron energy in order to optimize negative ion production. Emission-limited operation also improves electron emission uniformity across the whole cross section of the source, since it eliminates the amplification of plasma nonuniformities which occurs when the local plasma conditions determine the space-charge-limited flow.

Coupled with other improvements made in previous years, the best deuterium acceleration efficiency was increased from 55% to 74%. Because this results in a reduction in the fraction of the power striking the grids, the reliability of the ion sources has increased, with many more 1.5-2 second discharges at power levels sufficient for current-drive experiments and toroidal Alfvén eigenmode experiments in the JT-60U tokamak.

In support of the design effort of the KSTAR device, PPPL has been carrying out design studies of the system launcher for the lower-hybrid heating. A report on the comparison of various frequencies for the KSTAR lower-hybrid current-drive experiment was prepared with clear recommendations for the future system. This report is the basis of the conceptual design of the coupler which is expected to start next year.

Diagnostic Development

In order to facilitate the study of the time evolution of the radial correlation length of turbulent fluctuations during the formation of internal transport barriers in JET plasmas, a contribution to an upgrade of their reflectometer system was designed and proposed. This diagnostic will play an important role in transport studies. The reflectometer operates with the X-mode and comprises two channels, one with a fixed frequency of 102.9 GHz and the other with a tunable frequency in the range 100-106 GHz. Both channels make use of very stable oscillators in the K-band together with frequency multipliers (×6). The final stage comprises a group of four amplifiers operating in parallel with a total output power of 25 MW. The reflectometer, when operating with the existing large power loss in the existing waveguides of JET, has a dynamic range of 23 dB.

In order to support the physics studies of pellet ablation into JET plasmas, a phase-1 spectrometer configuration suitable for initial measurements both of pellet-line emission and of JET Bremsstrahlung emission was purchased. Parameters of the cloud can be investigated by measurement of the relative intensity of hydrogen-line emissions from the cloud and by measurement of the spectral shape of the emission lines. This pellet spectrometer, to be installed next year, will be capable of hydrogen-line emission measurements. The spectrometer will also be usable by JET to evaluate possible future Bremsstrahlung measurements for more general diagnostic purposes.

A new collaboration in X-ray spectroscopy was started with the KSTAR team. There were two main parts to the collaboration, one to provide a crystal spectrometer for the HANBIT mirror device in Taejeon, Korea and the second to support the design of an X-ray crystal spectrometer for KSTAR. The HANBIT spectrometer consists of a spherically bent mica crystal and a two-dimensional position-sensitive CCD detector and was designed for measurements of spectra of helium-like neon, NeIX, at X-ray energies of 900 eV. In order to calibrate the spectrometer, an X-ray tube with a copper target was built. The emitted bremsstrahlung spectrum was used for measurements of the integrated reflectivity of the mica crystal and measurements of the spectral resolution. The plasma in HANBIT has not yet reached the parameters, i.e., electron temperatures of 100 to 200 eV, which are needed for the observation of NeIX, in spite of efforts to heat the plasma with ICRF. Additional electron-cyclotron heating is planned, but the installation of the spectrometer at HANBIT will depend on the success of the auxiliary heating.

An imaging X-ray crystal spectrometer for KSTAR is included in the proposed basic set of diagnostics for the device. This instrument will provide radial profiles of the ion and electron temperatures and the ion-charge-state distribution, which will be of interest for transport studies. Conceptual design was started. In addition to this specific design activity, there was consultation for the design integration being carried out by the KSTAR diagnostics team and review of the documentation they have been preparing.

During FY2000, PPPL staff completed a successful collaboration on X-ray crystal spectroscopy on the TEXTOR tokamak at Jülich, Germany. A new method for absolute measurements of the toroidal plasma rotation was developed.

Tritium Studies in TFTR

The joint program with JAERI of studies of the retention of tritium in the graphite tiles that formed the plasma-facing first wall of TFTR advanced significantly. Three carefully controlled manned entries of the TFTR vacuum vessel were made for collecting tiles and other samples to allow investigation of the deposition of tritium on the graphite tiles and stainless steel surfaces defining the first wall of the interior of the vacuum vessel. The careful planning of the manned entry into the vacuum vessel included training in the mock-up of the vessel under as realistic conditions as possible. Figure 14 is a photograph of one of the technicians in a bubble suit with externally supplied air in the mock-up. An imaging system of tritium on surfaces was further developed. While still under development, it was deployed in the vacuum vessel as a test of potential future use as an in-vessel measuring tool for a next-step device.

Analyses of tiles, flakes from the tiles, and white powder scraped from the graphite surfaces from inside the TFTR vacuum vessel have been carried out both here and at other sites. Work continued on the employment of polyacrylates as a solidification agent for tritiated liquids, to ease disposal of dilute solutions.

There was also further development of processes for the removal (decontamination) of tritium from the TFTR graphite-based tiles and other materials (stainless steel, copper, ceramics). These decontamination processes included the use of hydrogen peroxide (H_2O_2), and ozone (O_3). Several expensive TFTR tritium-contaminated (in-vessel) components were successfully decontaminated for reuse on the National Spherical Torus Experiment. These included twelve TFTR radio-frequency feedthroughs that were decontaminated employing hydrogen peroxide from tens of millions of dpm/100 cm^2 to less than 1,000 dpm/100 cm^2.

Efficient removal of tritium retained in the next deuterium-tritium device continues to be a pressing issue. Promising laser-based techniques to release tritium have been explored. An ultraviolet (UV) laser, provided by JAERI, and a Nd:YAG laser were installed and commissioned in the TFTR Tritium Facility and initial results obtained. A pyrometer to measure the temperature rise under neodymium laser radiation was installed and experiments to characterize the release rate under different experimental conditions are underway.

Comparisons of tritium retention in JET and TFTR were made (see Table 2). In TFTR, about 5 grams of tritium were injected into circular plasmas over a 3.5-year period, mostly by neutral-beam injection. In JET, 35 grams were injected

Figure 14. A technician practicing in the TFTR vacuum vessel mock-up in preparation for entry into the contaminated TFTR vacuum vessel.

Table 2: Comparison of Tritium Retention in TFTR and JET.

	TFTR	**JET**
Edge n_e (m^{-3})	10^{18} - 10^{19}	10^{20}
Edge T_e (eV)	200 - 600	<30
Total T injected, NBI	3.1 g	0.6 g
Total T injected, Gas puffing	2.1 g	34.4 g
Initial retention during T gas puff fueling (mostly isotope exchange)	≈90%	≈80%
T retained during D-T operations (excluding cleanup)	2.6 g (51%)	11.5 g (40%)
Longer-term retention (mostly co-deposition)	51%	17%
T remaining in torus	0.6 g (May 2000)	2.1 g (December 1999)
Long-term retention	12%	6%

into divertor plasmas, mostly by gas puffing over a campaign of six months. A similar fraction of tritium was retained in both devices in the short term and after initial cleanup, but the details are very different. In TFTR a major part of tritium was co-deposited on the vessel wall with little tritium inventory in flakes. TFTR experiences co-deposition on the vessel wall because of the large carbon source from the TFTR bumper limiter. In JET, the wall is a net erosion area and much of the short-term holdup was due to isotope exchange with deuterium. Most of the tritium remaining in JET is believed to be in flakes in the subdivertor region.

Space Plasma Physics

The Earth's magnetosphere and the solar atmosphere provide a "natural" laboratory for understanding a broad range of plasma physics phenomena. Research at the Princeton Plasma Physics Laboratory (PPPL) has been primarily focused on understanding solar and magnetospheric activity, such as solar prominence formation and eruption, solar flares, coronal mass ejections, magnetospheric waves, and magnetospheric substorms, and how the coupling between solar activity, the magnetosphere, and the ionosphere can affect the dynamical evolution of the solar-terrestrial system. In this report is described progress on three topics for FY2000: (1) solar eruptive phenomena, (2) kinetic Alfvén waves at the magnetopause, and (3) quasi-static magnetospheric equilibrium.

Solar Eruptive Phenomena: Escape of Solar Plasmoids and Statistics of Solar Flares

Solar eruptive phenomena include coronal mass ejection (CME), prominence eruption, and solar flares among others. Coronal mass ejections appear as bright features that move outward through the solar corona at a speed of 10-1,000 km s^{-1} involving 10^{16} g of plasma. Often a CME is followed by a solar flare, which is an intense, abrupt flash in wide electromagnetic wave spectra observed in the lower corona and chromosphere. The kinetic energy in a large-scale CME and the electromagnetic energy in a large flare are about 10^{32} erg. Irrespective of CME involvement, solar flares are often observed preceded by expulsion of a plasmoid, which is believed to be a magnetic flux rope. It is reasonable to consider a CME loop as a large-scale flux rope. In the current solar research, however, it is not well understood how a flux rope could escape out of the siege of the overlying line-tied field. To address this problem, the interaction of an emerging flux rope with the overlying arcade field by magnetohydrodynamic (MHD) simulations has been studied.

The flux rope considered is diamagnetic in the sense that its toroidal current is in the opposite direction to the subsurface toroidal current which generates the overlying arcade field. Therefore, magnetic reconnection between the emerging field and the preexisting field naturally arises. If the toroidal magnetic fields of the emerging flux rope and the overlying field are in the same direction and strong, a new paramagnetic flux rope can be created between the emerging field and the overlying field and it hinders the escape of the underlying flux rope. If the toroidal magnetic fields of the emerging field and the overlying field are in the opposite direction, or if they are in the same direction but not strong, no paramagnetic flux rope is generated between them. If the emerging field has more flux than the preexisting field, continuing magnetic reconnection peels off magnetic flux from both systems and a net flux can escape out of the siege of the overlying arcade as required for plasmoid expulsion.

A statistical study was also performed on X-ray flares stronger than C1 class that erupted during the solar maximum between 1989 and 1991. The flaring time interval distribution (waiting-time distribution) and the spatial correlation of successive flare pairs were statistically analyzed. The observed waiting-time distribution for the whole data is found to be well represented by a nonstationary Poisson probability function with time varying mean flaring rates. The period most suitable for a constant mean flaring rate is determined to be 2-3 days by a Kolmogorov-Smirnov test. It has also been found that the waiting-time distribution for flares in individual active regions follows a stationary Poisson probability function. Therefore, the flaring probability within a given time, t, can be predicted by $(1\text{-}e^{-mt})$, when the mean flaring rate m for the active region in question is properly estimated. The above findings support the idea that the solar corona is in a self-organized critical state. A comparison of the angular distances of successively observed flare pairs with those of hypothetical flare pairs generated by random distribution shows a positive angular correlation within about 10 degrees (~180 arcsec in the observing field) of angular separation, which suggests that homologous flares occurring in the same active region should outnumber sympathetic flares occurring subsequently in neighboring active regions.

Kinetic Alfvén Waves at the Magnetopause

The magnetopause is a current layer which marks the boundary between plasma dominated by the Earth's magnetic field and plasma flow in the magnetosheath. Understanding physical processes at this boundary is among the major outstanding contemporary issues in space plasma physics because energy, mass, and momentum transported across this boundary determine the dynamic behavior of Earth's magnetosphere. Because ultra-low-frequency (ULF) waves (with frequencies below 500 mHz) dominate the spectrum of nearly every magnetopause crossing, it is expected that those waves should play an important role in the transport processes that occur at the magnetopause boundary.

The space plasma physics group at PPPL suggested that the ULF waves result from mode conversion of MHD waves in the magnetosheath to kinetic Alfvén waves (KAWs) at the magnetopause near field line resonance locations. Recently, theory and data comparisons have provided evidence that ULF waves at the magnetopause result from a mode-conversion process which transforms compressional MHD waves that originate in the magnetosheath into transverse KAWs at the magnetopause.

Because the interplanetary magnetic field changes orientation regularly, it is possible to characterize the magnetopause wave activity as a function of magnetic shear (defined to be the angle between the magnetic field in the magnetosheath and the magnetic field on the magnetospheric side of the magnetopause). Because the mode-conversion process exhibits a strong dependence on this magnetic field rotation, theory and data comparisons of expected wave signatures can be used effectively as a test of the mode-conversion process. A set of magnetopause crossings was considered where sizeable compressional magnetic field fluctuations were found in the magnetosheath. Windowed magnetic power spectra were obtained for parallel and transverse magnetic fluctuations during each crossing. The magnetosheath and magnetopause spectra were compared for each crossing to quantify the wave amplification for each crossing as a function of magnetic shear. From the study, it was deduced that: (1) the transverse wave component at the magnetopause is not significantly amplified below a threshold magnetic shear angle (approximately 50 degrees), (2) greatest amplification is for magnetic shear between 70 and 180 degrees, and (3) waves with higher frequencies are less amplified.

These observations were compared with theoretical wave solutions obtained by solving the kinetic-fluid equations (including finite Larmor radius effects and electron Landau damping) for a compressional wave scattering off a gradient in the Alfvén velocity, including magnetic field rotation. In the process of scattering, part of the wave energy is converted into kinetic Alfvén waves. The amount of wave energy converted to transverse waves based on the incident wave spectrum was computed. Maximum energy conversion occurs at magnetic shear angles greater than approximately 50 degrees. For smaller angles, a trough in energy conversion is found which is broader for larger frequency. These properties are qualitatively consistent with the wave observations and imply that mode conversion of compressional MHD waves to kinetic Alfvén waves occurs at the magnetopause. Moreover, based on previous studies, the kinetic Alfvén waves are expected to provide significant particle transport and plasma heating at the magnetopause.

3-D Quasi-static Equilibria of the Magnetosphere

The equilibrium of the magnetosphere in the quiet state is very important, as it can be utilized as a magnetic field mapping model useful for studying a vast array of topics such as plasma flow in the magnetosphere, substorm phenomena, wave generation and propagation, and plasma transport. Moreover, three-dimensional (3-D) magnetospheric equilibria involving the formation of a thin current sheet in the near-Earth tail can provide physical conditions for studying substorm onset mechanisms.

In order to obtain the physical picture characterizing general 3-D magnetospheric equilibrium, the structure of the magnetic field, plasma currents, and pressure have been obtained by numerically solving the force balance equation through employing an improved version of the 3-D quasi-static magnetospheric code (MAG-3D) previously developed at PPPL.

The MAG-3D code computes the magnetospheric equilibrium by reducing the full 3-D ideal-MHD equations to two quasi-two-dimensional equations, which are then numerically solved in an optimal flux coordinate system.

The newly improved code was applied to the case of magnetospheric equilibrium in the closed field-line region with flux boundary conditions obtained from the Tsyganenko magnetospheric field model, and radial pressure profiles similar to the observed ones were used, for both quiet-time and disturbed-time cases. The obtained physical quantities give insight into the physics of magnetospheric equilibrium, especially the formation of the ring current and thin cross-tail current sheets, as well as into the formation of the field-aligned (Birkeland) currents. Figure 1 presents a typical magnetospheric configuration for a "quiet-time" case, with the magnetic field lines shown in the noon-midnight meridional plane and the location of field lines that originate from the same latitudes on Earth in the equatorial plane.

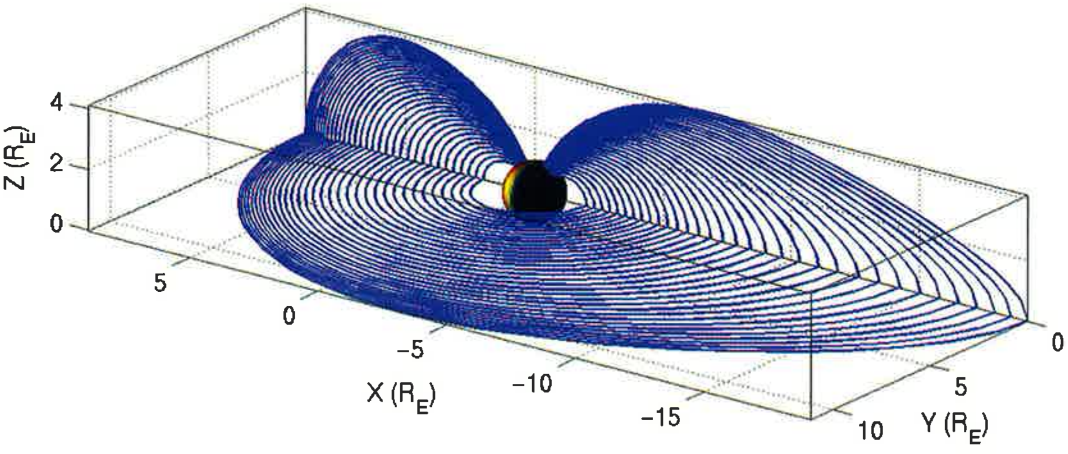


Figure 1. A typical magnetospheric configuration for a "quiet-time" case, with the magnetic field lines shown in the noon-midnight meridional plane and the location of field lines that originate from the same latitudes on Earth in the equatorial plane.

A field-aligned current (FAC) density distribution resembling the observed Birkeland currents in the 60 and 75 invariant latitude region was obtained. The FAC value is approximately proportional to the product of the pressure gradient and geodesic magnetic field curvature in the toroidal direction in a flux surface. The existence of the field-aligned current can thus be seen to be a feature of the 3-D geometry of the problem.

A very important feature currently being investigated is the possible appearance of a thin current sheet localized in the near-Earth tail region. The formation of the sheet is very sensitive to external magnetospheric parameters (solar wind dynamic pressure and interplanetary magnetic field — IMF). The current sheet is more likely to be formed and is much more elongated and of large current density values during disturbed (storm-like) magnetospheric conditions. This new result can be of great interest to tail current disruption and substorm onset studies. It is important to note that the result cannot be obtained straight away from Tsyganenko's empirical field model, since that model is not generally self-consistent, due to the fact that force balance in the model is not satisfied between the J × B force and the plasma pressure gradient.

Future work using the MAG-3D code will include additional physics in the model: consideration of the effects of pressure anisotropy (which might be important in disturbed times), azimuthal dependence of pressure, inclusion of plasma flow, as well as modifying the boundary conditions to include the open field line zone.

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 in orbit about 100 satellites with Hall thruster propulsion systems. However, the vast majority of satellites worldwide have relied on chemical thrusters and, to a lesser extent, ion thrusters.

During FY1999, a Hall Thruster Experiment (Figures 1 and 2) was established at the PPPL. The PPPL experiment is the

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

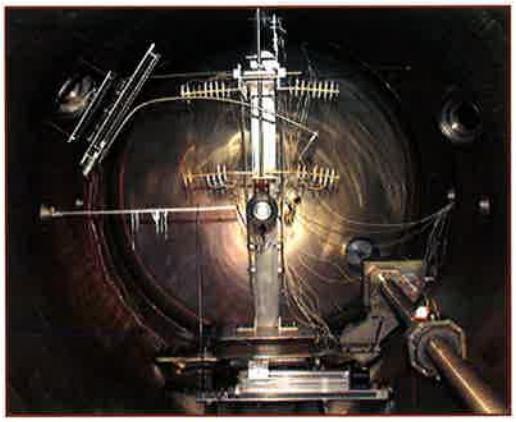


Figure 2. Interior view of PPPL Hall Thruster.

result of a collaborative theoretical research effort with the Center for Technological Innovation at Holon, Israel. This study, 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. After demonstrating state-of-the-art thruster operation, including decreased plasma plume, the project acquired broader support. During fiscal year 2000, the Defense Advanced Research Projects Agency, the New Jersey Commission on Science and Technology, and the U.S. Department of Energy all funded scientific or technological projects on the PPPL Hall Thruster facility.

Hall Thruster Operation

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

In a Hall thruster, electrons injected into a radial magnetic field neutralize the space charge. The magnitude of the field is approximately 200 gauss, strong enough to trap the electrons by causing them to spiral around the field lines. The magnetic field and a trapped electron cloud together serve as a virtual cathode (see Figure 3). The ions, too heavy to be affected by the field, continue their journey through the virtual cathode. The movement of the positive and negative electrical charges through the system results in a net force on the thruster in a direction opposite that of the ion flow.

Applications

Generally, thrusters are used to compensate for atmospheric drag on satellites in low-earth orbit, to reposition satellites in geosynchronous orbit, or to raise a satellite from a lower orbit to geosynchronous orbit. As a basic rule of thumb, for each kilogram of satellite mass one or two watts of on-board power are available. PPPL has a medium-size Hall thruster, which consumes several hundred watts of power, making it suitable for a satellite with a mass in the range of a few hundred kilograms.

PPPL physicists are now developing for the Air Force Office of Scientific Research Hall microthrusters with power outputs in the 100-watt range, useful for very small satellites with masses of 50 to

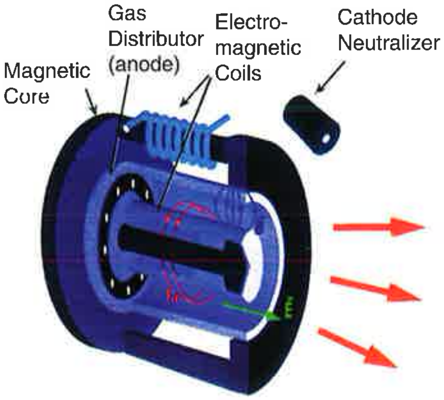


Figure 3. The Hall thruster concept.

100 kilograms. One could envision a large satellite disbursing hundreds of the smaller ones for the exploration of a planet or as a spaced-based radar array. The Hall thruster may be too power hungry for this application, but answers to these and other questions may emerge from research now underway at PPPL.

Hall Thruster Propellant

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

Hall Thruster Results

The PPPL Hall thruster experiment, operating at 900 watts, does so with an efficiency that is comparable to state-of-the-art thrusters. By segmenting the thruster, however, with each segment held at a specific electric potential, researchers have been able to control exactly where the voltage drop occurs along the length of the thruster. In some regimes, this has been used to decrease the plume divergence. A small plume divergence is a very important deign feature for Hall thrusters, in order to make practicable the spacecraft integration.

Magnetic Nozzle Experiment

The purpose of the Magnetic Nozzle Experiment (MNX) (Figures 4, 5, and 6) is to study 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.

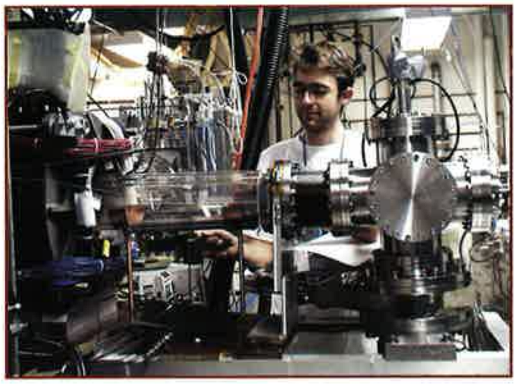


Figure 4. Graduate student Tom Kornack stands next to the nozzle expansion region of the Magnetic Nozzle Experiment.

During FY2000, much progress was made in developing the techniques for the experimental research program. The three primary technological advances were:

- the design, construction, and operation of an m = 0 helicon antenna that allowed the generation of steady-state helium plasmas;

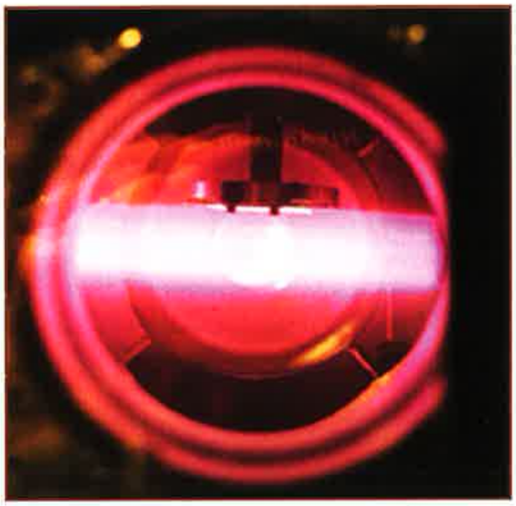


Figure 5. View of an argon plasma in the region between the Helmholtz coils.

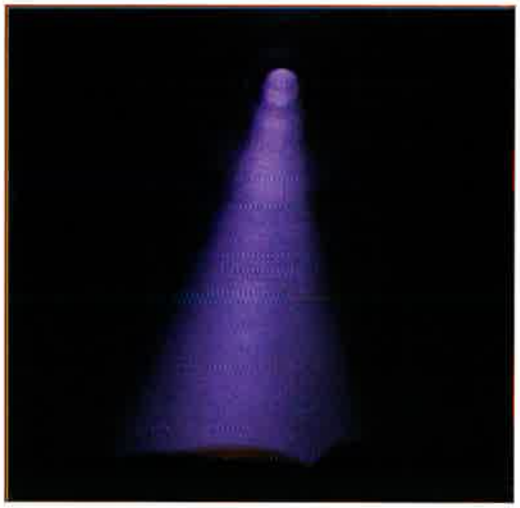


Figure 6. View (looking into nozzle) of an argon plasma expanding from the nozzle.

- the design of a magnetic coil system that creates large magnetic-field expansion ratios; and
- the installation of an improved pumping system to control the neutral density in the expansion region.

With the new helicon antenna, long-duration (more than 8 hours) helium plasmas were formed and detailed diagnostic measurements begun. Prior to development of the new antenna, helium runs were typically limited to subhour durations, with the runs terminated by melting of the pyrex vacuum section under the antenna. With the new antenna, a coupled power of 800 watts was achieved. Spectroscopic measurements were made in the main plasma region and high-quantum-number states, up to n = 22, were observed, giving definitive proof of recombination. Plasma operation scenarios were developed that produced bright helium ion spectra. These are necessary for measurements of ion acceleration by the nozzle.

During this year, the proposal submitted to the U.S. Department of Energy by Professor E. Scime (West Virginia University) to perform laser-induced fluorescence measurements on the MNX was approved. A collaboration was initiated with Dr. F. Chang-Diaz (National Aeronautics and Space Administration — NASA), who is performing similar experiments on a NASA facility in Houston, Texas. A new graduate student, Kristy Stokke, joined the MNX group.

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 wave 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;
- coherent electromagnetic radiation generation by energetic electrons interacting with applied magnetic field structures, including free electron lasers, cyclotron masers, and magnetrons;
- advanced accelerator concepts with high acceleration gradients;
- investigation of nonlinear collective processes and chaotic particle dy-

namics in high-intensity charged-particle beams propagating in periodic-focusing accelerators, such as those envisioned for heavy ion fusion, tritium production, and spallation neutron sources;

- measurement of background neutral pressure and electron collision cross sections with neutral atoms and molecules.

Research on nonneutral plasmas and high-intensity accelerators at PPPL 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 PPPL is performed on a Malmberg-Penning trap called the Electron Diffusion Gauge Experiment (see Figure 7). The pure electron plasmas studied are confined with cylindrically symmetric fields: a uniform, static, axial magnetic field provides particle confinement radially, and applied potentials on the electrically isolated, cylindrical, end-wall electrodes provide confinement axially. The electrons trapped in the device are introduced from a directly heated spiral of tungsten wire. By varying the bias on the filament, the size and density of the plasma can be changed. The plasma column rotates because of the radial electric field generated by space-charge effects that produce an E × B rotation in the azimuthal direction.

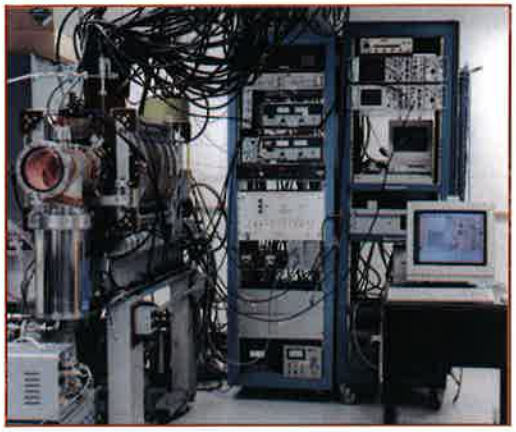


Figure 7. Electron Diffusion Gauge Experiment.

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.

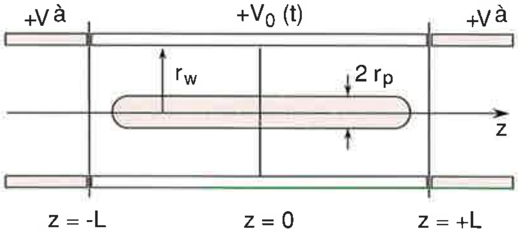
There have been one Ph.D. thesis and three referred publications associated with this productive facility during fiscal year 2000.

Paul Trap Simulator

Construction of the Paul Trap Simulator Experiment (PTSX) began at PPPL in fiscal year 2000. Figure 8 gives a cross-sectional view of the experiment. Axial confinement of trapped barium ions is provided by applied dc voltages on the end electrodes, and 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.

(a) Side View



(b) End View

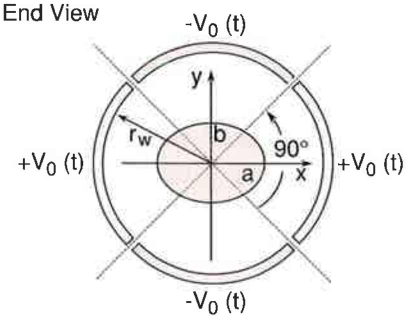


Figure 8. Cross-section diagram of the Paul Trap Simulator Experiment.

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 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. 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 one thousand equivalent lattice periods is illustrated in Figure 9.

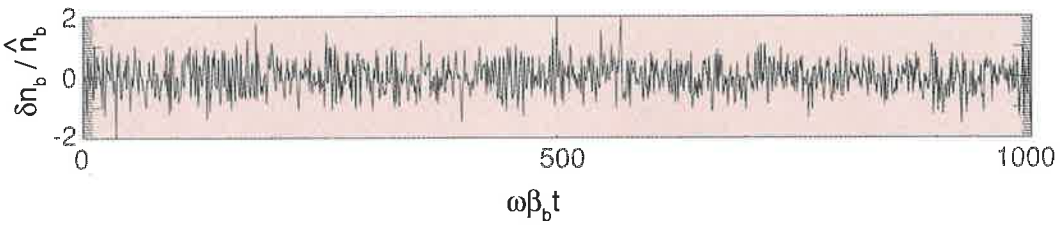


Figure 9. Numerical simulations using the BEST code showing quiescent propagation of a high-intensity thermal equilibrium beam over large distances.

A macroscopic warm-fluid model has also been developed to describe collective processes in high-intensity beams, including preliminary investigations of a collective instability driven by pressure anisotropy. In addition, a test-particle model has been used to explore chaotic particle dynamics and halo formation induced by collective mode excitations in high-intensity ion beams, including estimates of the maximum radial excursion of the halo particles. 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.

Multi-electron Loss Events

One of the approaches presently being explored as a route to practical fusion energy envisions using heavy ion beams focused upon a metallic target to produce X-rays, which then drive the compression and ignition of a deuterium-tritium pellet. Some of the more prominent driver schemes require propagating a beam of singly ionized xenon at an energy of 10-20 MeV/amu across a target chamber with a radius of a few meters and a background density of beryllium difluoride vapor of about 5×10^{13} cm^{-3}. Collisions with this vapor will not only ionize the vapor, they will also change the ionization state of the beam. Previously it had been assumed that beam ionization would proceed by removing one electron per event. However, based upon past experiments, it was thought more likely that multi-electron loss events would be significant, which would result in both higher charge states and a larger range of charge states in the evolving beam as it progressed toward the target.

Singly-charged heavy ions at the energies anticipated for heavy ion drivers cannot be produced in existing accelerator facilities. However, in a collaboration with staff at the Texas A&M Cyclotron, measurements with the closest available approximations to heavy ion driver beams were performed.

Using a thin nitrogen gas cell, which is a good approximation to beryllium difluoride vapor, the change in charge state in the single collision regime for beams of incident Kr^{+7} and Xe^{+11} at 3.4 MeV/amu was measured. It was found that multi-electron loss events play a prominent role, even for the beams where the electron cloud of the beam is more tightly bound than would be the case with a singly charged driver. The relative cross section for loss of n+1 electrons is 0.3 to 0.7 times that for loss of n electrons, depending upon n. The average number of electrons removed in a single collision was 1.86 for Kr^{+7} and 1.97 for Xe^{+11}. Since the deflection of the driver ions in the residual space charge fields is proportional to the ion charge state, it is important to explore mechanisms to ensure a high degree of space charge neutralization of the driver beams. Several theoretical models of the collision process were compared to the data. A plane wave Born approximation

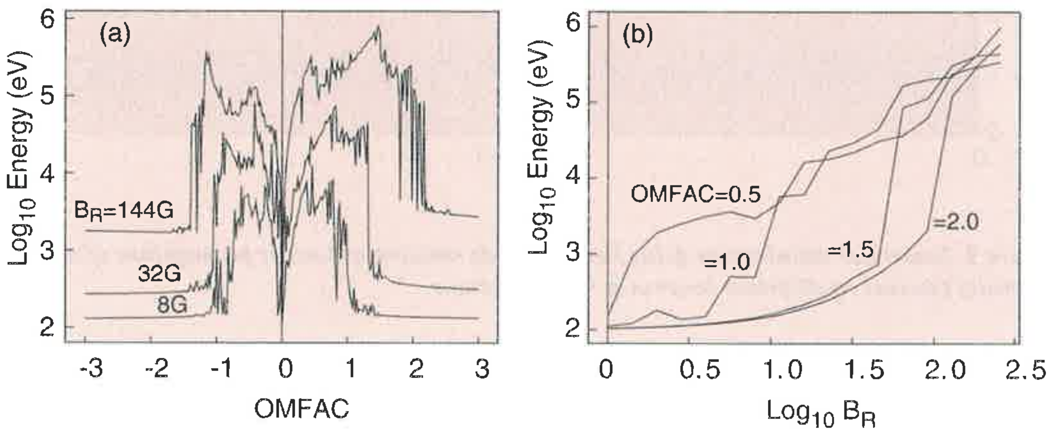


Figure 10. (a) Calculated maximum energy attained by deuterons in a 10-cm radius, 1-m long, 20-kG FRC vs OMFAC = ω_R/ω_{ci}, for rotating magnetic fields of strength B_R = 8, 32, and 144 G and $\tau = 10^4$. ω_R is the angular frequency of the rotating magnetic field, ω_{ci} is the ion cyclotron frequency, and τ is the time measured in units of the ion-cyclotron period. (b) Maximum energy attained by deuterons in FRC versus B_R for OMFAC = 0.5, 1.0, 1.5, and 2.0, and $\tau = 10^4$.

was found to give a better description of the results than did a classical approximation.

Field-reversed Configuration Heating

A proposal to perform experimental tests of field-reversed configuration (FRC) plasma heating by rotating magnetic fields was submitted to the Department of Energy in February 2000. In late summer, the proposal was approved and work began immediately.

Two theoretical papers were accepted by journals. The first paper, written in collaboration with R.D. Milroy (Redmond Plasma Physics Laboratory, University of Washington) showed that a novel rotating-magnetic-field geometry, that of odd parity, would maintain the closed field lines of the FRC. The second paper, written in collaboration with A.H. Glasser (Los Alamos National Laboratory), showed that fully penetrated odd-parity rotating magnetic fields would cause explosive ion heating, if the rotating magnetic field frequency was near that of the ion-cyclotron frequency (see Figure 10). This paper also showed preferential localization of high-energy ion orbits near the FRC's midplane, consistent with dynamic stabilization of the internal tilt mode, previously predicted for the odd-parity rotating magnetic field.

Charge Neutralization Experiments

Recently, heavy ion fusion research has developed a reactor design requiring multiple heavy ion beams to be focused together in the target chamber at the emittance limit. Near-term experiments, the planned High Current Experiment (HCX), and the Integrated Research Experiment (IRE), 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 propagating 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}-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 will develop plasma sources capable of producing large-volume plasmas to support neutralization studies on a heavy ion beam facility at the Lawrence Berkeley National Laboratory. Previously, the sources have 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 theoretically studied. 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 in supporting charge neutralization experiments. Theory suggests that the plasma volume and density can be controlled with weak magnetic fields (10-50 gauss). Recently, an electron cyclotron resonant plasma source was built for study. The source is driven with 13-MHz wave power and operates in the 1-10 milliTorr range with magnetic fields of 20-40 gauss. Figure 11 shows a photo of plasma produced by this source.

Liquid Metal Experiment

A small-scale laboratory experiment has been initiated at PPPL to study the fundamental physics of magnetohydrodynamic (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 plasma physics research. Recent interests in the application of liquid metal to fusion devices also add new demands for a better understanding of MHD physics of electrically conducting fluids. This 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:

- When and how do MHD effects modify surface stability, either in linear regimes or nonlinear regimes, such as solitary waves?

Figure 11. Photo of electron-cyclotron resonant plasma source during operation ($p = 4$ mTorr, Argon, $B = 20$ gauss, $f = 13$ MHz).

- When and how do MHD effects modify a free-surface flow, such as by surface deformation?
- When and how do MHD effects modify thermal convection?

Surface stability is an important physics issue for liquid metal wall applications in fusion devices. It is also relevant to the mixing processes in many astrophysical phenomena. 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.

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. Magnetohydrodynamic effects can be examined by imposing 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 in the perpendicular direction of wave propagation, while the waves are damped with a parallel magnetic field. Preliminary data is shown in Figure 12 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 agreement with preliminary results.

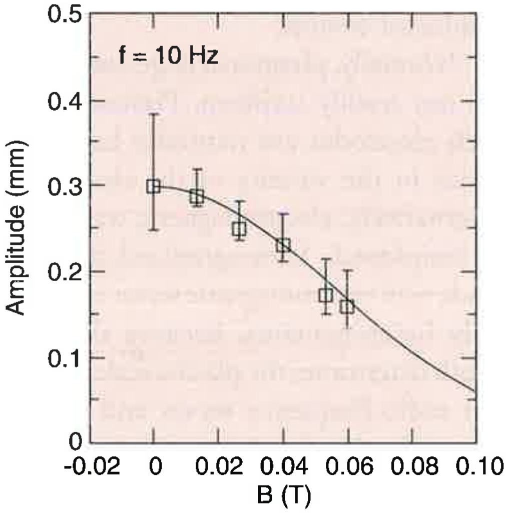
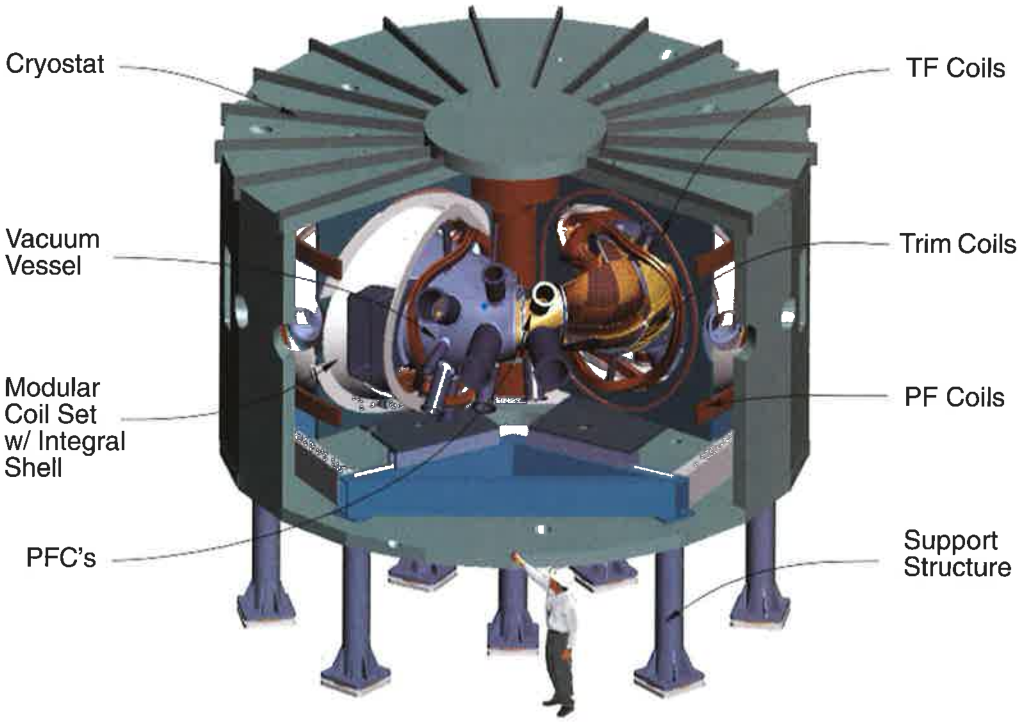


Figure 12. Measured wave amplitudes propagating along magnetic field. When the magnetic field is increased, the wave amplitudes are suppressed in good agreement with a linear theory (solid line).

National Compact Stellarator Experiment



The National Compact Stellarator Experiment.

A key challenge for magnetic fusion energy researchers is finding a high-beta plasma configuration that can be sustained in steady-state without disruptions. Toward this goal, most magnetic fusion research is performed on two toroidal plasma configurations, the advanced tokamak and the stellarator.

Tokamaks have demonstrated excellent short-pulse plasma performance in configurations in which the aspect ratio is typically less than 4. Stellarators have demonstrated levels of performance approaching those of tokamaks, but generally at aspect ratios in the range of 6 to 12, which makes them less compact than tokamaks. The world's largest stellarator, Japan's Large Helical Device, has demonstrated significant confinement enhancement (a factor 1.6 over the standard stellarator confinement-time scaling) and high beta (a heating-power-limited 2.4%) in configurations with aspect ratio around 6.

The Advanced Stellarator (AS) concept, developed by German researchers in the 1980s, pioneered the use of stellarator magnetic fields in plasma configurations numerically optimized for desired physics properties such as magnetic surface quality, high-beta stability, and reduced transport. In the AS optimization approach, which is being developed experimentally using the Wendelstein 7-AS (operating since 1988) and Wendelstein 7-X (under construction), finite-beta plasma currents from the bootstrap and Pfirsch-Schlüter effects are suppressed by design, which results in a high aspect-ratio (11) configuration.

Researchers at the Princeton Plasma Physics Laboratory (PPPL), in collaboration with colleagues from the U.S. and abroad, are developing the physics of a new toroidal concept, the compact stellarator — an innovative hybrid of advanced tokamaks and stellarators that builds on the scientific foundations of both concepts. This is leading to the development of a proposal for a new research facility, the National Compact Stellarator Experiment (NCSX), which would be constructed at PPPL in partnership with the Oak Ridge National Laboratory (ORNL). NCSX would be the central element of a U.S. research program to develop the compact stellarator concept during the next several years. This program would further both the science and the energy goals of the U.S. fusion program.

Compact Stellarator Science

Compact stellarators use the self-generated bootstrap current in combination with three-dimensional stellarator magnetic fields to sustain a stable high-beta (4-5%) plasma configuration, without the conducting wall or feedback control that advanced tokamaks require. While existing stellarator concepts, without the benefit of bootstrap current, have aspect ratios in the range of 6 to 12, compact stellarators would be significantly smaller, with aspect ratios ≤4.5.

The physics of toroidal magnetic plasmas is determined by their fundamental configuration properties: rotational transform (the helical magnetic field-line "twist" that keeps charged particles confined in a magnetized torus), plasma shaping, and magnetic symmetry. Compact stellarator research broadens toroidal physics understanding by providing additional variables with which to optimize and study these properties. Rotational transform can be generated either by coils external to the plasma (advantageous for stability) or by currents in the plasma (advantageous for coil simplicity). In a compact stellarator, these can be combined in varying ratios. Three-dimensional magnetic fields provide degrees of design freedom not available in axisymmetric devices such as tokamaks and spherical tori. These can be used to tailor a plasma configuration to obtain desired physics properties. Though three-dimensional in shape, a stellarator plasma can have a symmetry coordinate (either axial, helical, or poloidal) in its magnetic field structure.

In the early 1990s, J. Nuehrenberg of Germany and P. Garabedian of the U.S. developed the concept of quasi-symmetric stellarators, including the quasi-axisymmetric stellarator (QAS). A QAS has very low helical magnetic field ripple, and therefore can have tokamak-like confinement physics characteristics: well-confined particle drift orbits, low toroidal flow damping, and bootstrap current sufficient to generate a significant fraction (around half) of the rotational transform. A QAS plasma, shown in Figure 1, can be shaped three-dimensionally to make it passively stable against magnetohydrodynamic modes that can otherwise limit beta or prematurely terminate a toroidal plasma discharge.

In recent years, compact stellarator researchers have learned how to shape a QAS plasma so as to stabilize ballooning modes, neoclassical tearing modes, external kink modes, and the vertical instability, all of which can cause disruptions in tokamaks. The same configuration can also have good-quality magnetic surfaces and good quasi-symmetry, such that the calculated neoclassical transport due to helical ripple is much

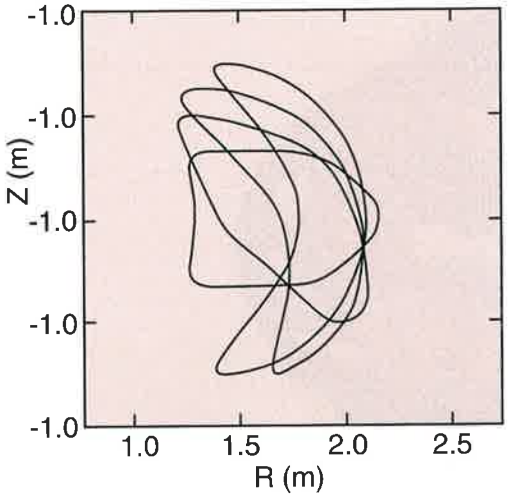


Figure 1. Overlay of cross sections of a quasi-axisymmetric stellarator (QAS) plasma configuration at several toroidal locations.

less than the axisymmetric contribution. With aspect ratios of 4.4 or less, such a QAS is significantly more compact than currentless stellarators. Coil designs that are suitable for the production of the reference QAS plasma and that provide the flexibility needed for physics studies have been developed. A QAS configuration will be the foundation for the NCSX, a flexible experimental facility which would support the research needed to develop the concept through the proof-of-principle stage.

NCSX Design Progress

In FY2000, the NCSX team advanced the physics and technology of compact stellarators, resulting in an updated machine configuration that is a substantial improvement over the one presented in 1999. In the earlier design, re-use of the toroidal and poloidal field coils from the Princeton Beta Experiment-Modification (PBX-M) tokamak device was explored. This objective was motivated by the desire to minimize construction costs. While this design showed that a stable high-beta (4%) QAS plasma configuration could be realized, further physics improvements, completed in 2000, were necessary to satisfy all requirements. Improved physics design tools allowed more accurate targeting of physics and engineering properties, which led to dramatic improvements in both. Better coil design tools made it possible to explore a wider range of coil topologies and to compare their physics and engineering properties. It was concluded that the needed design improvements could not be realized within the geometrical and coil topology constraints imposed by the existing PBX-M coils. So the 2000 NCSX design is based on constructing all new coils.

The first step in updating the NCSX design was choosing a reference high-beta QAS plasma configuration, the foundation for the experiment design, that incorporates all the physics properties needed for the planned research. The new configuration, which is depicted in several cross sections in Figure 1, is a dramatic improvement over its predecessor, as shown in Table 1(page 76). The final step was choosing the coil concept for producing the three-dimensional magnetic field that the reference plasma requires and for providing the flexibility needed for the physics studies. Among the options evaluated, the one chosen (termed "modular coils") provided the best physics properties. The new NCSX plasma configuration with its modular coils is shown in Figure 2 (page 76).

The design of a reference stellarator configuration meeting physics requirements for the NCSX proof-of-principle research program was a large step toward completing the physics basis for the program in preparation for a peer review scheduled for March, 2001. Following a successful validation of the physics basis, conceptual design of NCSX will be performed to establish a firm cost and schedule baseline for project execution. Approval to construct NCSX would depend on a successful outcome of a conceptual design review, scheduled for April, 2002.

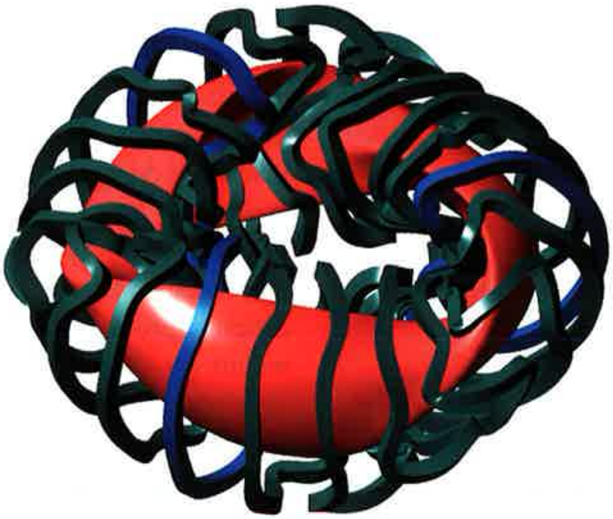
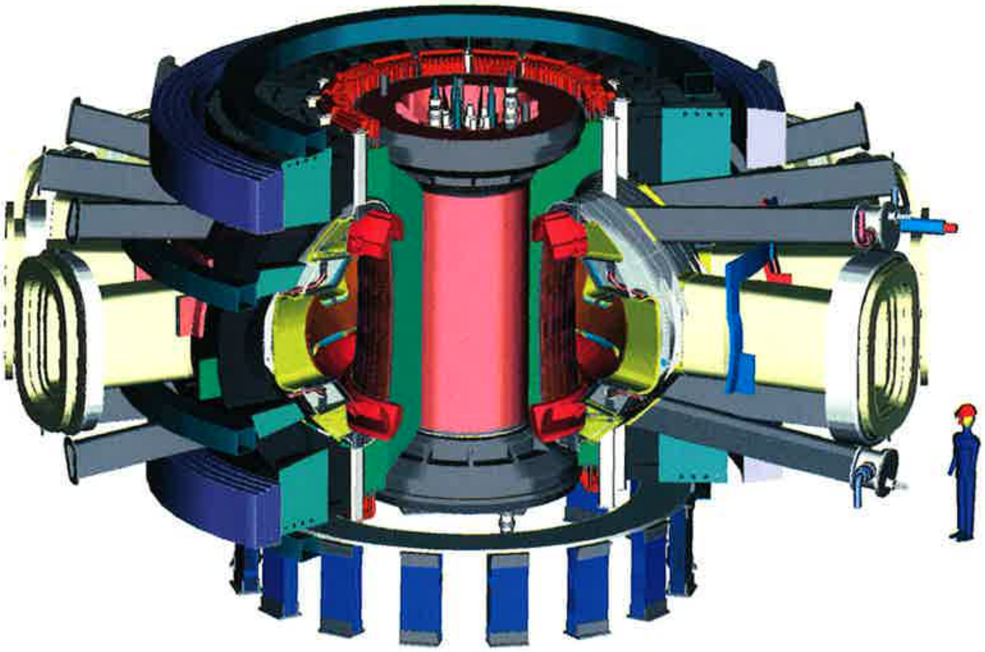


Figure 2. NCSX plasma configuration and modular coils.

Table 1. Comparison of NCSX Reference Plasma Configurations.

Parameter	1999 Configuration	2000 Configuration	Comment
Number of periods	3	3	
Beta (%)	4.0	4.1	
Aspect ratio	3.4	4.4	Major radius/average plasma radius
τ at edge	0.47	0.66	higher τ favorable for confinement
$\tau_{external}/\tau_{total}$ at edge	0.62	0.74	higher ratio favorable for stability
Magnetic surface quality (fixed-boundary)	stochastic for r/a > 0.75	good surfaces out to r/a = 1, small internal islands.	island reduction methods subsequently developed
Effective helical ripple at r/a=0.7	1.0%	0.6%	lower ripple favorable for confinement
NBI fast ion loss	23%	19%	Hydrogen beams and plasma, fixed volume, and magnetic field
Coil complexity measure	3.1	2.1	lower number means smoother coils
Relative coil current density measure	1.0	0.5	saddles with 1/R background field

Fusion Ignition Research Experiment



The Fusion Ignition Research Experiment.

The behavior of a plasma dominated by self-heating is a key issue for magnetic fusion science. An experiment is needed to test and extend present understanding of confinement, macroscopic stability, alpha-driven instabilities, and particle and power exhaust in plasmas dominated by self-heating. The issue is to what extent pressure profile evolution driven by strong self-heating will act to self-organize advanced configurations with large bootstrap current fractions and internal transport barriers.

A design study of a Fusion Ignition Research Experiment (FIRE) is underway to assess near-term opportunities for advancing the scientific understanding of self-heated fusion plasmas. The emphasis is on understanding the behavior of fusion plasmas dominated by alpha heating ($Q \geq 5$, where Q = fusion energy/plasma heating power) that are sustained for a duration comparable to the characteristic plasma timescales ($\geq 20t_E$ and $\sim t_{skin}$, where t_{skin} is the time for the plasma current profile to redistribute at fixed current). The programmatic mission of FIRE is to attain, explore, understand, and optimize alpha-dominated plasmas to provide knowledge for the design of attractive magnetic fusion energy systems. A major goal is to develop a design concept that could meet these physics objectives with a construction cost in the range of $1 billion.

A National Collaboration

The FIRE design team consists of scientists and engineers from more than 15 institutions in the U.S. fusion community and is managed through the Virtual Laboratory for Technology. A Next Step Option-Program Advisory Committee (NSO-PAC) reporting to the Director of the Virtual Laboratory for Technology was established in FY2000 to review and provide guidance on technical and programmatic issues for a Next Step Option in magnetic fusion. The NSO-PAC includes 15 senior scientists from 12 institutions in the U.S. as well as Europe and Japan.

An Advanced Burning Plasma Experiment

The FIRE is envisioned as an extension of the existing advanced tokamak program leading to an attractive magnetic fusion reactor. The configuration chosen for FIRE is similar to that of ARIES-RS (one of a series of Advanced Reactor Innovation Evaluation Studies), namely, a highly shaped plasma with double-null divertor and aspect ratio approximately equal to 4. The FIRE design activities have focused on the physics and engineering evaluation of a compact, high-field tokamak. The key "advanced tokamak" features are: strong plasma shaping, double-null poloidal divertors, low toroidal-field ripple (<0.3%), internal control coils, and space for wall stabilization capabilities. The magnets and structure are also capable of operation at toroidal magnetic field $B_t(R_o) \leq 12$ T and plasma current $I_p \leq 7.7$ MA with the parameters shown in Table 1.

Design Options

As a result of recommendations of the NSO-PAC and discussions within the fusion community, a system study and sensitivity analysis was undertaken to identify improved design points. An optimized

Table 1. Major Parameters of FIRE.

Plasma Parameter	Baseline	FIRE*
Major Radius, R_0	2.0 m	2.14 m
Minor Radius, a	0.525 m	0.595 m
Magnetic Field on Axis, B_0	10 T (12) T	10 T
Q	5 (20)	~10
Plasma Current, I_p	6.4 (7.7) MA	7.7 MA
Fusion Power	150 (200) MW	150 MW
Flattop Time, Coil Limit	20 (12) sec	20 sec
Triangularity, δ_{95}; δ_x	0.4; 0.7	0.4; 0.7
Elongation, κ_{95}; κ_ε	1.8; 2.0	1.8; 2.0
Tokamak Cost	~$0.3 B	~$0.3 B
Base Project Cost	~$1.2 B	~$1.2 B

(   ) Higher field capability.
FIRE* is an enhanced physics performance design.

physics performance design point, FIRE*, was identified with slightly lower aspect ratio (3.6 vs 3.81), major radius R_o = 2.14 m, minor radius a = 0.595 m, $B_t(R_o)$ = 10 T, and I_p = 7.7 MA with a flattop time of approximately 20 sec at 150 MW of fusion power. This design point is projected to achieve Q ≥ 10 using design guidelines similar to those employed by International Thermonuclear Experimental Reactor-FEAT (ITER-FEAT).

Burning Plasma Physics under Quasi-steady Conditions

The FIRE is being optimized to produce a burning plasma with a plasma duration (burn time) that is long enough to study the effect of self-heating on the evolution of plasma pressure, alpha ash accumulation, and the bootstrap current present in an advanced configuration. A Tokamak Simulation Code (TSC) simulation of this regime indicates that FIRE can access the high-confinement mode (H-mode) and sustain alpha-dominated plasmas, as shown in Figure 1. In addition, sufficient time is provided for plasma start-up and a controlled shutdown to avoid plasma disruptions. During the burn phase, plasma profile evolution, alpha ash accumulation, and techniques for burn control can be studied and initial investigation of plasma current evolution due to alpha heating started.

A longer-term goal for FIRE is to explore advanced tokamak regimes using pellet injection and current ramps to create reversed-shear plasmas for durations of 1 to 3 current redistribution times. This advanced tokamak capability is expected to produce modestly enhanced confinement and beta as observed in present large tokamak experiments, and would provide a continuous transition from H-mode operation to advanced tokamak operation. An important feature of the FIRE cryogenic copper alloy magnets (described below) is that the pulse length increases rapidly as the field is reduced with flattops of approximately 40 sec at 8 T and about 90 sec at 6 T. In this case, the copper toroidal-field magnets used in FIRE are not the limiting factor. Rather, the generic plasma technologies for driving and controlling the plasma current and plasma-facing components capable of exhausting particles and power for long pulses are the limiting factors. The development of these generic technologies and their testing in a fusion plasma environment would be a major contribution of the FIRE experiment.

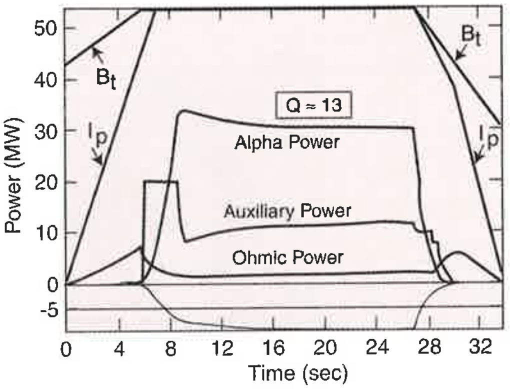


Figure 1. Evolution of a burning plasma in FIRE with major radius R = 2.14 m, aspect ratio A = 3.6, toroidal magnetic field B_t = 10 T, plasma current I_p = 7.7 MA, and an approximately 20 sec flattop.

Technology Considerations

The baseline magnetic fields and pulse lengths for FIRE can be provided with beryllium-copper and oxygen-free high-conductivity copper toroidal-field (TF) coils and oxygen-free high-conductivity copper poloidal-field (PF) coils that are precooled to 77 degrees K prior to the pulse and allowed to warm up to 373 degrees K at the end of the pulse. A sche-

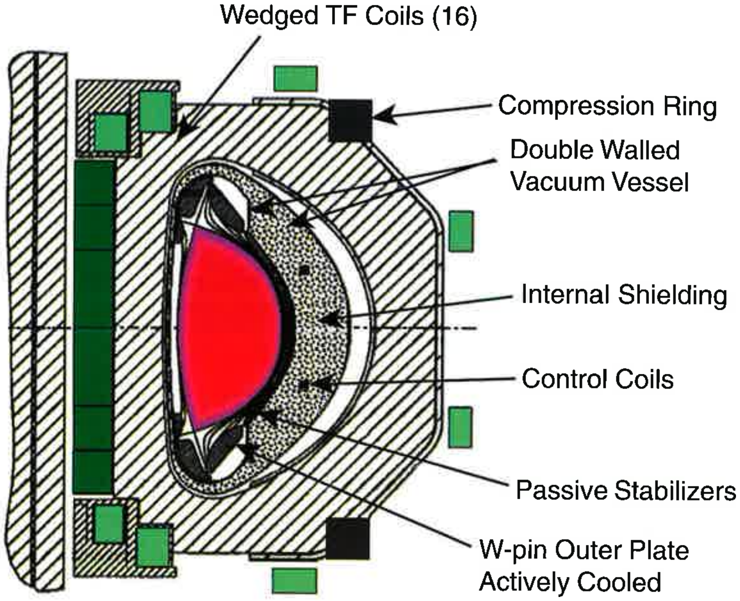


Figure 2. Cross section of the Fusion Ignition Research Experiment.

matic cross section of FIRE is shown in Figure 2. The 16 toroidal-field coil system is wedged, with a compression ring to resist de-wedging at the top and bottom of the inner TF leg. Shielding is added between the walls of a double-walled vacuum vessel to reduce nuclear heating of the coils, limit insulation dose, and allow hands-on maintenance outside the envelope of the TF coils within a few hours after a full power deuterium-tritium plasma. Large (1.3 m by 0.7 m) midplane ports provide access for heating, diagnostics, and remote manipulators, while 32 angled ports provide access to the divertor regions for utilities and diagnostics. The FIRE is being designed structurally to accommodate 3,000 full-field and 30,000 pulses at two-thirds field. The repetition time at full-field and full-power pulse length will be about 3 hours, with shorter times at reduced field or pulse length. The fusion energy production of 5.5 TJ produces a lifetime neutron dose to the TF insulating material at the inboard midplane of approximately 1.5×10^{10} Rads, which is consistent with the polyimide insulation being considered.

The power densities on the divertor plates are approximately 5 $\mathrm{MWm^{-2}}$ for detached operation, about 15 $\mathrm{MWm^{-2}}$ for semi-detached divertor operation, and approximately 25 $\mathrm{MWm^{-2}}$ for attached operation. Carbon is not allowed in the vacuum vessel due to tritium inventory build-up by co-deposition. The divertor plasma-facing components are tungsten "brush" targets mounted on copper backing plates, similar to a concept developed by the International Thermonuclear Experimental Reactor R&D activity. Prototype tungsten brush target plates have been tested successfully up to 25 $\mathrm{MWm^{-2}}$. The outer divertor plates and baffle are water-cooled, while the inner divertor targets and first wall are cooled by mechanical attachment to water-cooled copper plates inside the vacuum vessel. The first wall is comprised of beryllium plasma-sprayed onto copper tiles. The high neutron wall loading (~2 $\mathrm{MWm^{-2}}$) at fusion powers of 150 MW contributes significantly to first wall and vacuum vessel heating. The water-cooled copper plates inside the vessel alleviate excess heating of the stainless steel vessel due to neutrons. Sixteen cryo-pumps — closely coupled to the divertor chambers, but behind sufficient neutron shielding — provide pumping for deuterium-tritium and helium ash during the pulse. Pellet injection scenarios will help minimize tritium throughput. The in-device tritium inventory will be determined primarily by the cycle time of the divertor cryo-pumps, and can range from less than 2 grams for regeneration overnight to approximately 20 grams for monthly regeneration.

Outreach

Presentations on "Fusion, A Grand Challenge for Science and Technology" or "FIRE, A Next Step Option for Magnetic Fusion" were given at 19 U.S. and 3 international institutions during FY2000. In addition, "FIRE" was a major presence at the 18th IEEE/NPS Symposium on Fusion Engineering held in Albuquerque, NM, with 14 papers part of the program. Papers were also presented at American and European Physical Society meetings. The FIRE web site is a source and repository of information on fusion, as well as the Fusion Ignition Research Experiment.

Engineering and Technical Infrastructure

The Engineering and Technical Infrastructure Department is responsible for managing the engineering resources at the Princeton Plasma Physics Laboratory (PPPL). 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 upgrades to the National Spherical Torus Experiment (NSTX) led to 4.5-kG and 1-MA plasma operation during FY2000. The ohmic-heating power systems are now capable of 6-kV bipolar operation with four spare rectifiers in each leg, and the coaxial helicity injection (CHI) power supplies have been upgraded to support 50-kA, 24-pulse operation. To further protect the vacuum vessel ceramic insulators during CHI operations, the CHI power systems have been reconfigured with inductors and parallel diode snubbers for short-circuit current limiting and with output diodes for reverse-current blocking. Upgrades to power supplies and controls needed for NSTX High Harmonic Fast Wave operations have been done and that system has completed its 4-MW milestone. Boronization of internal surfaces of the vacuum vessel is now routinely accomplished through the use of the new trimethyl-boron injection system.

NSTX Neutral-beam Injection System

The two year, $6 million project to install and commission a 5-MW, 80-keV neutral-beam-injection system on NSTX was completed this year within budget and ahead of schedule. This system, which drew heavily on TFTR design, components, and operating experience, will enable tests of the efficiency with which a spherical torus plasma can retain its energy at high ratios of plasma pressure to magnetic field pressure. TFTR components in use on the NSTX neutral-beam-injection system include the test stand beamline and cryogenic panels, the cryogenic plant which provides liquid nitrogen and liquid helium, high-voltage power supplies, the control system, and parts of the cooling water system. The three U.S. Common Long-Pulse Ion Sources used on TFTR were dismantled, refurbished, and tested before use on NSTX.

Relocation of the TFTR beamline to the NSTX Test Cell necessitated modifications, including the redesign and relocation of coolant pipes, instrumentation and control systems, power and control cables, and vacuum systems. Protective armor was installed in the NSTX vacuum vessel. Power supply modifications included a new resistive divider for the gradient grid system, replacing the original divider and its freon bath. This improvement will reduce the cost of operation and eliminate the potential environmental impact associated with freon release.

FIRE Engineering

Engineering efforts in FY2000 on the Fusion Ignition Research Experiment (FIRE), focused on continued refinement of the design developed in FY1999 and coordination of cost estimates. In addition, a centralized computer-aided drawing-management system was introduced which significantly improves the sharing of design information between the FIRE participants. The engineering design details are shown in Figure 1.

A PPPL-Oak Ridge National Laboratory study was performed early in the year to determine the desirability of reducing the number of toroidal-field (TF) coils from 16 to 12. The larger spacing between the reduced number of TF coils would permit larger vessel ports and improved access for remote maintenance. The primary disadvantage would be higher toroidal-field ripple in the plasma, which could be reduced to acceptable levels by using ferromagnetic material for part of the vacuum vessel shielding. The ferromagnetic level would add significant complexity to magnetic analyses, plasma start-up and control, and diagnostics. Although fewer and larger ports would make maintenance of the internal components easier and provide a net increase in access area of 20%, it is still possible to maintain the internal components through the smaller ports of the 16 TF coil configuration. Consequently, it was concluded that the 16-coil design should be retained.

FIRE's design details were refined in concert with the cost estimating process. A PPPL/Stone and Webster study concluded that the TF coils stresses would be low enough to permit the elimination of the central tie rod and hub assembly. This change would eliminate these costly components while improving access to the central region of the solenoid, where cryogenic cooling lines and power bus connections would be located. A PPPL/Advanced En-

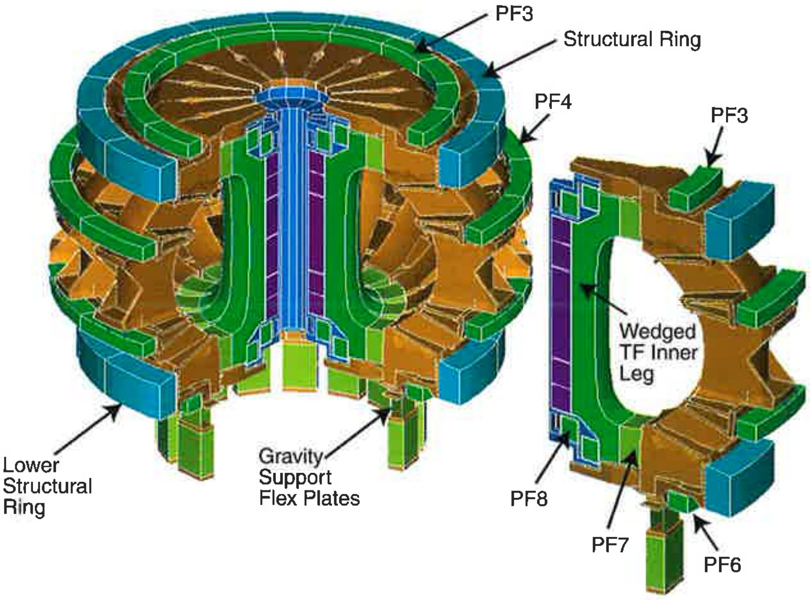


Figure 1. Engineering details of the Fusion Ignition Research Experiment.

ergy Systems study resulted in design changes to the stainless steel TF coil cases, permitting the use of lower cost castings rather than machined weldments.

Work also began on a study of a combined bucked and wedged TF coil configuration, in conjunction with new physics design point studies. This combined support configuration would reduce coil stresses and would permit the use of oxygen-free copper instead of beryllium-copper alloy. Besides being a lower cost material that is less costly to process, oxygen-free copper would greatly reduce power dissipation. The reduced power dissipation would reduce power supply and cryogenic systems costs and would permit longer pulse durations.

Cost estimates have now been developed for all of FIRE's project elements. These estimates were developed by the combined efforts of FIRE's laboratory and industrial participants. The total projected cost is $1.194 billion, including an average contingency of 24.7%. This estimate is based on a new, "greenfield" site with no significant site credits or significant equipment reuse.

NCSX Engineering

Joint engineering and physics efforts in FY2000 resulted in the development of an improved plasma configuration and a modular-coil-based design for the National Compact Stellarator Experiment (NCSX). The new design successfully addresses the shortcomings of the previous saddle-coil-based design: namely excessively high coil current density ($J_{cu} > 20$ kA/cm^2), poor plasma surface quality, and difficult access for diagnostics and neutral beams. The new design meets NCSX performance requirements.

New computational codes were developed which permit the design of practical modular coils that link the plasma and provide the toroidal field, as well as the helical fields, required by the stellarator. Compared to the highly conformal saddle coils, the modular coils are set back much farther from the plasma. This provides larger gaps between the windings, allowing for improved access to the stellarator core for diagnostics and heating. This "set back" location also improves magnetic field shaping flexibility. The modular coils will be pre-cooled to 80 °K prior to a pulse to substantially reduce power supply requirements and costs. With pre-cooling to 80 °K, operation at 1 T is achieved with the available complement of TFTR power supplies. The new NCSX design is based on a plasma configuration as shown in Figure 2. This configuration provides improved physics performance by using more smoothly shaped modular coils.

Figure 2. National Compact Stellarator Experiment coil design.

TFTR Decontamination and Decommissioning

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 Test Cell Basement. This is being done so the site can be downgraded to a general-use radiological facility and be ready for occupancy by another fusion device.

Technology from the nuclear fission industry is being utilized as appropriate to safely dismantle activated and contaminated systems. Disassembled components are being packaged for disposal in compliance with Department of Energy (DOE), 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.

At the start of FY2000, the TFTR D&D Project rapidly acquired the necessary staff by hiring more than fifty term-employees to supplement regular PPPL personnel. Term-staff included mechanical technicians, electricians, equipment operators, security personnel, mechanical and electrical engineers with D&D experience, health physics technicians, a construction safety engineer, and an industrial hygienist. By the end of FY2000 nearly 80 persons were working on the Project.

During FY2000, the D&D Engineering Group prepared more than 170 detailed procedures for rendering the equipment safe and for the removal of components and structures from the TFTR Test Cell and Test Cell Basement. All totaled, approximately 225 procedures will be required to complete the TFTR D&D Project. The underlying principles for these procedures are those of Integrated Safety Management. Another important feature of these procedures is the use of digital photos of the equipment to be worked on, with labels indicating key disconnection points. Once approved, these procedures are being incorporated into Engineering Work Packages which include a Job Hazard Analysis, necessary permits, and any drawings needed to complete the field activity. 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 and second quarters of FY2000, the primary focus of the field crews was to secure the safety of electrical systems and to open doorways so that large items could be removed from the Test Cell. The labyrinth at the northwest personnel door was the first to be opened. Next, shielding in front of the large northeastern Test Cell Door was removed and the door was opened for the first time since TFTR neutral-beam operations began in 1984. Space was cleared on the east side of the Test Cell for the staging and packaging for disposal of components removed from TFTR. This cleared area allowed 40-foot trailers to be brought into the Test Cell following the reopening of the northeast door.

In October 1999, a specialized team removed rows of in-vessel carbon tiles at Bay K, for analysis of tritium content. This information was needed to determine whether the tiles needed to be removed from the vacuum vessel to meet shipping and burial requirements for tritium. It was

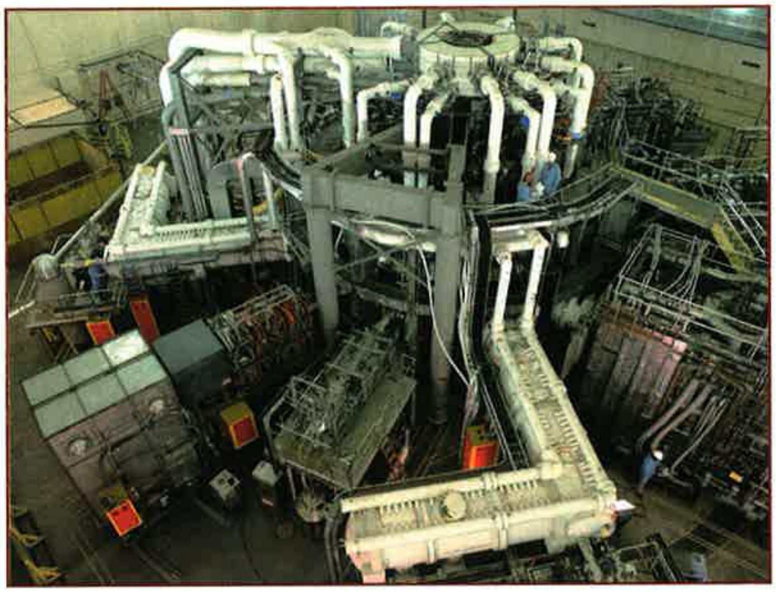


Figure 3. The Tokamak Fusion Test Reactor — March 1989.

determined that the tiles could stay inside the vessel.

During the second and third quarters of FY2000, diagnostic devices that could be reused within the DOE complex were removed from the Test Cell and Test Cell Basement. Crews removed noncontaminated piping and buswork from the top of the tokamak and cleared space around the tokamak for the removal of larger components. At first, concentration was placed on items which were not contaminated, so that removals would proceed as efficiently as possible. Floor space in the Test Cell and the Test Cell Basement was cleared significantly at this time.

Also during this period, a specialized team in bubblesuits entered the vacuum vessel to remove samples of the carbon tiles from around the vessel. This was done to

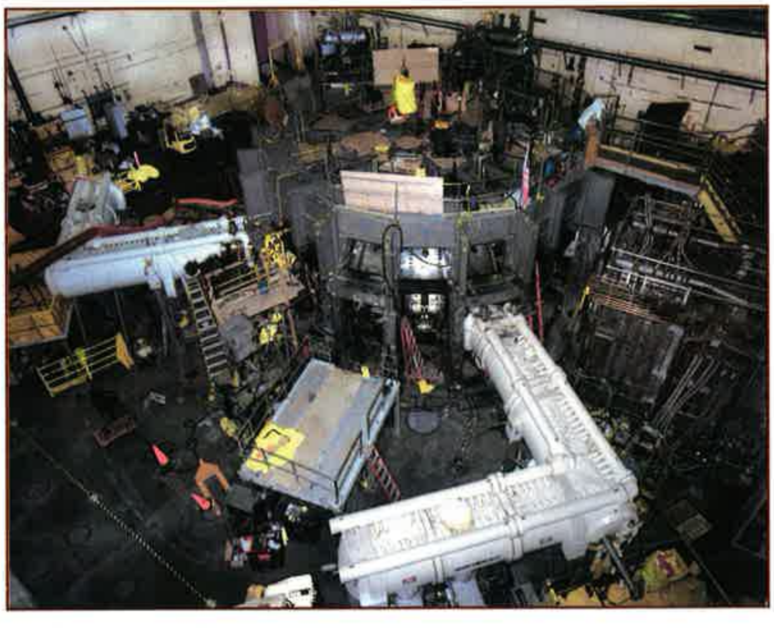


Figure 4. The Tokamak Fusion Test Reactor — September 2000.

determine the distribution of tritium so that vessel segmentation procedures could be established.

During the final quarter of FY2000, field crews cleared the top of TFTR, including diagnostic devices and a large amount of electrical cabling, in preparation for the removal of the umbrella structure and upper poloidal-field coils in early FY2001. This 92-ton lift will be the heaviest of the TFTR D&D Project. Removal of shear-compression panels that connect the toroidal field coils together was started. This proved to be quite challenging because of the tight tolerances involved and the loads applied to these components during assembly and operation of TFTR.

The D&D Engineering Group performed very successful full-scale trials of the diamond-wire-cutting technique that will be used to cut the vacuum vessel into segments for removal. These trials demonstrated that the best coolant for the diamond-wire rope is liquid nitrogen and the best fill material for the vacuum vessel is lightweight concrete. The training of technicians for this cutting will occur on full-scale mock-ups in FY2001.

Also during the final quarter of FY2000, tritium-contaminated tiles were removed from the areas where the vacuum vessel will be cut apart. This was done to reduce the airborne contamination during the vessel segmentation that will occur in late FY2001 and FY2002.

During FY2000, eleven truckloads (5,978 cubic feet) of radwaste were delivered to the DOE facility at Hanford, Washington for burial. Most of this material was sent as large pieces on flatbed trailers and in dump trailers. This minimized preparations for shipment, burial volume, and cost. More than 100,000 pounds of metal was released for reuse and 210,000 pounds of lead shielding was removed and put aside for reuse.

Overall, the TFTR D&D Project is off to a very good start. Department of Energy Cost and Schedule Reviews of the Project in December 1999 and again in July 2000 were very successful. By the end of the first year (September 30, 2000), the Project was under budget and about two months ahead of schedule. Although the more challenging work will be performed in the second and third years, a strong base has been established and the staff, equipment, and other resources are in place to allow the Project to be completed on-time and within budget.

D-Site Caretaking

The safety and radiological cleanliness of the D-Site facility was successfully maintained as TFTR D&D activities increased to planned levels and the NSTX completed a full and highly successful year of experiments. In addition, PPPL continued its collaboration with the Japanese Atomic Energy Research Institute, investigating the retention of tritium in carbon tiles during high-power deuterium-tritium plasma operations.

Modernization of the Engineering Shops

As part of a plan to modernize the PPPL engineering shops, two new computer-controlled machine tools were purchased. These devices allow parts to be fabricated from data files generated from computer-aided design (CAD) software. Cost savings are realized through faster and more accurate production. Payback of purchase costs is expected in less than two years.

The first machine, a water-jet machining center, (Figure 5) uses a 40,000 lb/in^2 stream of water and granulated garnet to cut through materials up to 2-inches thick. The water-jet cutter allows hard or soft materials such as ceramics, tungsten, stain-

Figure 5. PPPL's new water-jet machining center.

less steel, copper, or rubber to be precision machined to a 0.005-inch accuracy. The use of the computer-controlled water-jet allows intricate and precision parts to be cut without introducing residual stresses that would distort parts machined using conventional methods.

The second tool is a computerized numerically controlled (CNC) four-axis milling machine (Figure 6). In addition to being faster than a manual machine, computer control allows large arcs to be machined without rotating the part around a cutter. Plans for next fiscal year include the purchase of an additional milling machine, a CNC lathe and a new vacuum braze furnace for the braze shop.

Cyber Security

Computer security at PPPL has become an increasingly important issue. The explosive growth of the Internet has brought access to our site from an ever-increasing number of people. At the same time, the number of recorded attacks on our site has also increased. Much of the

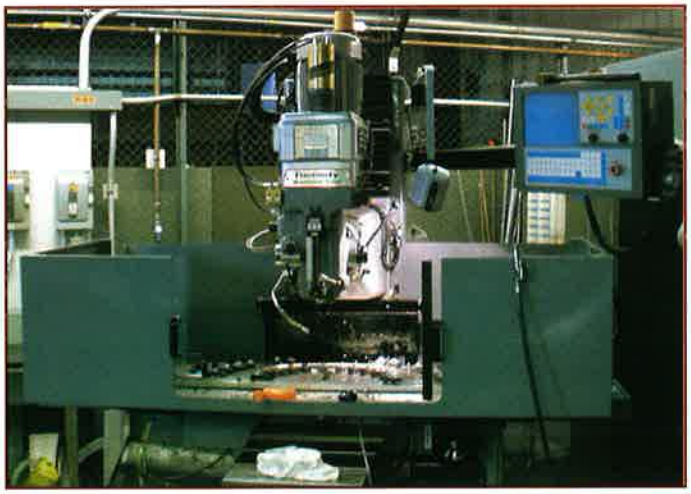


Figure 6. PPPL's new computerized numerically controlled four-axis milling machine.

effort in this area has addressed computer security alerts and installation of the latest patches. A separate important initiative this year was to modify the PPPL firewall to require authentication for access to all but our public resources.

Many other activities were undertaken this year to tighten computer security. An effort was started toward eliminating the use of reusable clear text passwords. Several systems were ordered to act as high-availability replacements for our current firewall and a firewall backup. A virus protection software has been implemented which will be used to protect incoming e-mail and ftp (file transfer protocol) transactions from computer viruses. Also started is an effort to examine our critical systems using the Computer Incident Advisory Capability's Internet Security Scanner tool. Additionally, the computer security staff participated in several DOE sponsored and privately conducted computer security courses.

In January 2000, PPPL submitted a comprehensive Cyber Security Program Plan to DOE for review and approval. Following on-site visits and presentations to DOE Chief Information Officer John Gilligan, and DOE Security Chief General Habiger, the plan was further reviewed and approved by the DOE in July.

Audio/Video Technologies

PPPL continues to collaborate heavily with a variety of other organizations. Laboratory groups currently make use of teleconferences, videoconferences, and Internet broadcasts of important meetings. During FY2000, additional conference rooms were configured for videoconferencing and teleconferencing. In particular, the Director's Conference Room, the DOE Conference Room, and room B318 now utilize the latest Polycom Teleconferencing equipment. The Director's Conference Room also has a dedicated LCD projector capability and meeting participants have laptop access to the internet.

Business Computing and Y2K

The two-year project to assure year 2000 (Y2K) readiness was completed and all systems successfully survived the transition into CY2000 with no impact on operational abilities. In late FY2000, the IBM compatible PC's were replaced with NT servers in order to establish a central NT Domain for the Laboratory and to provide better performance and high availability for the administrative applications.

During FY2000, an analysis to determine how the Laboratory will meet its financial and administrative computing system needs beyond FY2001 was begun. This effort identified two practical alternatives for the replacement of the Laboratory's remaining financial and administrative computing systems.

- Implementation of a commercial enterprise resource planning (ERP) product, such as the Peoplesoft package that was implemented by Princeton University.

- Continued use of a "legacy system" approach, preserving as much of the existing financial and administrative application systems functionality as possible. Software would be replaced with a supportable technology (e.g., JAVA). Critical functionality that is currently manual would be implemented in the General Ledger application. Web-based Graphical User Interfaces would be introduced to improve usability.

The effort to analyze these two alternatives to determine which provides the best value for the Laboratory will be completed in FY2001 and implementation will begin.

Network Systems

The deployment of switched Ethernet hubs throughout the Laboratory is well underway, and migration of critical data servers to 100-Mbps ports is complete. More than 1000 ports of switched Ethernet are in service and switched hubs have been installed in 6 of 7 primary hub locations. A new wiring design for high- performance Gigabit cabling and fiber-to-the-desktop was completed. An upgrade to the PPPL Theory Department infrastructure using this new design has been put in place. Wireless Ethernet segments were deployed in the NSTX Test Cell and in three conference rooms at PPPL.

Computer-aided Design and Drafting

Parametrics Technology Corporation (PTC) Pro/Engineer 3-D modeling design software is now the standard design tool at PPPL. Twelve sets of Pro/Engineer are available for use by PPPL draftspeople and mechanical engineers. The original five Alpha PC's purchased in 1997 for Pro/Engineer are being phased out and replaced with Intel platforms with high-speed video accelerators specifically designed for the computer-aided design and drafting (CADD) and scientific visualization market. A Pro/Intralink Distributed Drawing and Document management system is now in use by the Laboratory and Oak Ridge National Laboratory collaborators. A PTC Product View server has been installed and tested. This package allows web browsing of Pro/Engineer parts and assemblies. Part makeup, manipulation, and viewing (including parts lists) are easily accomplished within the browser. Product View is seen as an easy way to distribute the Pro/Engineer database to engineers and managers who are not Pro/Engineer users.

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 currently collaborating with a number of industrial partners in research and development. These collaborations, are either 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 Laboratory technology. The PPPL Technology Transfer Office implements the Laboratory's technology transfer efforts.

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 nonfederal 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 visit the industrial setting. In Technology Maturation Projects, Laboratory researchers work on technologies of interest to industry, but where 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 ORPA. The Laboratory works closely with the University for the patenting and protection of PPPL intellectual property.

The following projects were active in FY2000.

American Textile Partnership

Work continued on The American Textile Partnership (AMTEX), a multilaboratory master CRADA that spans the entire U.S. textile industry. AMTEX has a number of subtasks including the "Online Process Control Project." PPPL is collaborating with Dupont, BASF, and Wellman Incorporated through the Princeton Textile Research Institute to develop a noncontact diagnostic instrument that can be used by U.S. synthetic fiber manufacturers to assure that fibers

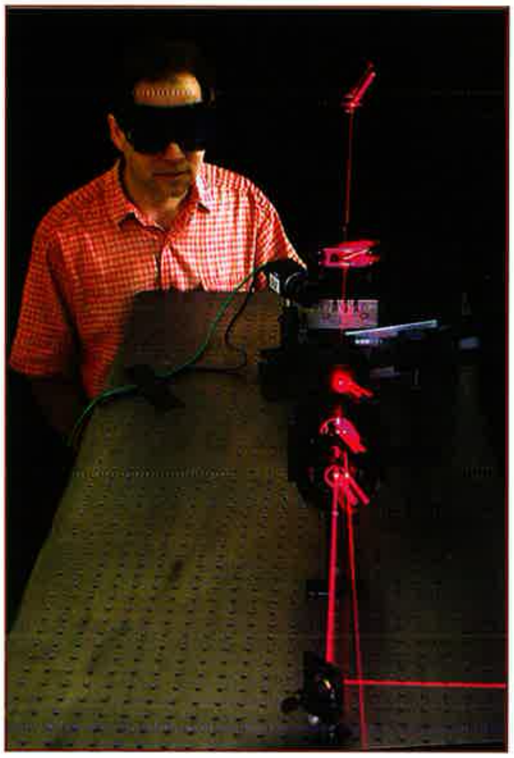


Figure 1. Analysis of helium-neon laser light scattered from a textile fiber is being investigated as a possible means of measuring important properties of these fibers, such as the birefringence and diameter. The goal is to develop a nearly real-time measurement that can be used by the textile industry.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

conform to specifications. The measurements will be made optically on the production line in real time. PPPL had completed the second year of this effort with a proof-of-principle demonstration at the facilities of several industrial partners. However, in FY1996 the program was suspended because of funding limitations.

In FY1997, the project was restarted, and a laboratory devoted to the study of laser-fiber interactions was established at PPPL. Since that time, computer modeling codes have been developed that successfully predict the relationship between fiber birefringence and the resultant pattern of laser light scattered from the fibers (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.

During FY2000, it was determined that a number of measurements of the refractive indices for the parallel and perpendicular directions were inconsistent with the accepted industry measurements. In particular, the refractive index measurement for the perpendicular direction had higher inconsistency than the parallel measurement. Part of the effort during FY2000 was devoted to understanding the reasons for the abnormal measurements. It was thought that one cause was distortion of the fiber, either by handling during the measurements, or by fibers having nonround cross sections during manufacture. Computer modeling was continued on nonround fibers and on fiber bundles. Also, two alternate methods for measuring the birefringence were employed. One used a charge-coupled device (CCD) imaging camera to detect the pattern, and the other used a single laser in which the wavelength is swept, rather then using a number of lasers, each with a single wavelength.

Plasma Sterilization

The sterilization of thermoplastic food containers is widespread in industry. However, limitations to existing techniques add to production costs. Consequently, improvements in sterilization processes will have a large economic impact. The aim of the PPPL Plasma Sterilization Project is to develop a method for quickly sterilizing food, beverage, and other thermoplastic containers using a plasma discharge. The goal is to sterilize thermoplastic containers with less than two seconds of treatment in a food production-line environment.

PPPL's innovative plasma sterilization technique uses energetic ions to destroy bacterial spores, which are the most difficult microorganisms to eliminate. However, the technique should be effective on other microorganisms as well. In early FY2000, an experimental plasma chamber for spore destruction was completed and the PPPL Engineering and Technical Infrastructure Department constructed a high-voltage pulse generator consistent with estimated requirements. Initial tests on the spore samples indicated need for greater current capability. Later in FY2000, a high-voltage pulse generator was constructed that should be adequate.

Exposure of spore samples will begin in FY2001, and the range of parameters for effective sterilization will be determined. Initial tests on the capability to destroy spores will be carried out on a small test surface. Hardware will then be adapted to the configuration of a beverage or food container. Additional experiments will be conducted to assess the effectiveness of plasma sterilization with different plastics and spore types. The evaluation will involve an analysis of the kill mechanism using scanning electron microscopy available on Princeton University's main campus. This work is supported by LPDA funding.

RF Pasteurization

In FY2000, PPPL and the U.S. Department of Agriculture (USDA) continued an interagency agreement to jointly develop new pasteurization methods that will use radio-frequency (rf) waves for pasteurizing raw liquid foods such as eggs, fruit juices, and milk. This Work-for-Others agreement between PPPL and the USDA came about when researchers at the USDA's Eastern Regional Research Center (ERRC) in Philadelphia identified the potential of rf radiation for pasteurization. Initial results and subsequent evaluation of microorganisms introduced into liquid foods indicated that rf radiation is an effective means for pasteurization

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

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

During FY2000, the USDA and PPPL determined that to achieve sterilization it may be necessary to provide a high-field environment at low frequencies. New equipment was assembled and operated at the ERRC with the help of PPPL engineers and technicians. The equipment has the capability of operating at a range of frequencies lower than the original equipment and at much higher field strengths. The fields are being applied across a gap of 0.20 cm between two parallel plates, between which the liquid flows. The equipment can run continuously, but field on and off times can be controlled to maintain a low liquid temperature. The new equipment is also capable of generating various waveforms that include sine wave, square wave, and exponential wave.

Imaging of Edge Plasma Turbulence in NSTX

Princeton Scientific Instruments, Inc. (PSI), Monmouth Junction, NJ, received a Small Business Innovative Research (Phase I) award to use their newly developed high-speed CCD imaging camera to measure plasma edge turbulence in the National Spherical Torus Experiment (NSTX). The PSI camera has a framing rate up to 1 million frames per second. Although edge plasma turbulence has been studied for many years, the high-speed dynamics of its two-dimensional structure is still highly uncertain due to a lack appropriate diagnostics. This CRADA project is providing, for the first time, the capability of making two-dimensional images of edge turbulence with a high enough framing rate to resolve the time evolution of the turbulence within one autocorrelation time, i.e., one "eddy turnover" time (≈10 μsec in NSTX).

Federally Supported WFO Projects

The following is a summary of federally supported Work For Others projects active at PPPL during FY2000.

Title: Kinetics Effects on MHD Phenomena in the Magnetosphere

Sponsor: National Science Foundation

Principal Investigator: C.Z. Cheng

Completion Date: March 31, 2001

Scope: The project deals with theory and data analysis related to kinetic effects on magnetohydrodynamic (MHD) phenomena in the magnetosphere. Kinetic-MHD phenomena are strongly affected by particle kinetic effects. Three areas are being studied: (1) kinetic effects on the stability properties of MHD modes, such as ballooning-mirror modes, and other resonant MHD instabilities, (2) correlation studies between the theoretical kinetic-MHD instability thresholds and the experimental instability thresholds computed from AMPTE/CCE and CRRES particle data during Pc 4-5 wave events, and (3) application of the kinetic-MHD analysis for studying the role of the ballooning mode as a possible substorm onset mechanism. These studies are being performed with realistic anisotropic plasma pressure magnetospheric equilibria and realistic particle distribution functions.

Title: MRX Experiment: Study of Fundamental Physics of Magnetic Reconnection in Laboratory Plasmas

Sponsor: National Science Foundation, National Aeronautics and Space Administration.

Principal Investigator: M. Yamada

Completion Date: March 31, 2001

Scope: Magnetic reconnection is an important manifestation of the interplay between plasma and magnetic fields. It is considered to be a key process in the evolution of solar flares and the earth's magnetosphere. Magnetic reconnection also occurs as one of the relaxation processes in fusion plasmas.

This study is investigating the coupling between microscale reconnection layers and global forcing and plasma topology evolution. PPPL's Magnetic Reconnection Experiment was utilized to address: (1) factors that determine the enhanced reconnection rate in the collisionless regime, (2) how magnetic energy is converted into flows and heat, (3) how magnetic helicity defines a global boundary, (4) the formation of global MHD forces in three-dimensional geometry, and (5) reconnection as a steady or burst process.

Results will impact the theories of three-dimensional reconnection of solar flares and the magnetosphere, as well as of laboratory plasmas. This study will impact concepts such as current sheets, flow patterns, and non-coplanar MHD flows.

Title: Low Frequency MHD Waves in the Magnetosheath-Magnetopause

Sponsor: National Science Foundation

Principal Investigators: C.Z. Cheng, J.R. Johnson

Completion Date: August 31, 2002

Scope: This study relates fluctuation levels of compressional waves found in the magnetosheath with wave activity and transport at the magnetopause. The goal is to identify an innovative basic plasma mechanism for understanding MHD waves in the magnetosheath-magnetopause. An extensive study of the correlation of theory and observation is being performed.

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

Sponsor: National Science Foundation

Principal Investigator: C.Z. Cheng

Completion Date: March 31, 2002

Scope: The project deals with computational studies of the realistic three-dimensional magnetospheric equilibrium structure of magnetic field, plasma currents, and plasma pressure by solving the force balance equations. The three-dimensional quasi-static magnetospheric equilibrium code for isotropic pressure, the MAG-3D code, will be improved to include the open field-line region in the computational domain, the effects of pressure anisotropy, and the magnetopause boundary condition. The MAG-3D code will be used to study: (1) the formation of the thin current sheet in the near-Earth plasma sheet region during the substorm growth phase and (2) the Earth's magnetospheric equilibrium for both quiet and disturbed times based on observed plasma pressure profiles. The studies will be made by imposing empirical magnetopause boundary conditions.

Title: Spherical Torus Propulsion by means of Coaxial Helicity Ejection

Sponsor: National Aeronautics and Space Administration

Principal Investigators: M. Ono, M. Peng

Completion Date: May 31, 2002

Scope: The direct extraction of fusion energy for propulsion has the potential to enable fast outer and middle solar system travel. This project involves an investigation of the physics of Coaxial Helicity Ejection which offers the possibility of extracting directly plasma kinetic energy for propulsion from a spherical torus (ST). An ST is a compact, reduced-weight magnetic confinement system presently under investigation at PPPL and other fusion research centers for its potential to deliver high fusion performance.

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

Sponsor: National Aeronautics and Space Administration

Principal Investigator: J.R. Johnson

Scope: Electromagnetic ion cyclotron waves are nearly always seen in the auroral ionosphere and are thought to be generated by electron-beam-driven instabilities. This project is developing a model describing how electron-beam sources of electromagnetic cyclotron waves feed sinks (ion cyclotron heating and Joule dissipation due to ionosphere collisions) giving rise to meso-scale magnetosphere/ionosphere coupling.

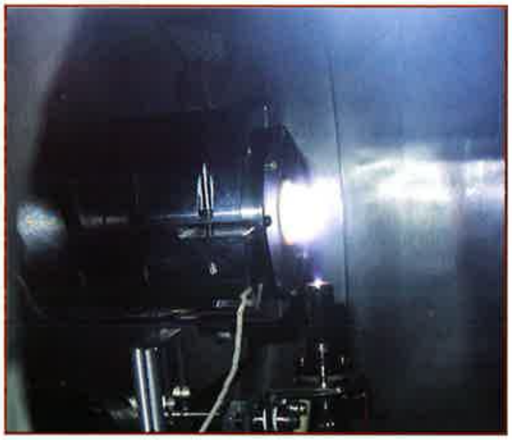


Figure 2. Princeton Plasma Physics Laboratory's 3-cm cylindrical Hall thruster operating at 160 W with xenon propellant.

Title: Hall Current Micro-thruster

Sponsor: U.S. Air Force

Principal Investigator: N. Fisch

Completion Date: September 30, 2001

Scope: To design, fabricate, and test a series of micro-thrusters (Figure 2) that are based on Hall current thruster principles but exhibit novel features that make scaling to the micro-propulsion regime attractive.

Title: Experimental and Theoretical Studies of Nonneutral Plasmas

Sponsor: Office of Naval Research

Principal Investigator: R. Davidson

Completion Date: September 30, 2001

Scope: This project is a vigorous experimental and theoretical program in critical problem areas related to the equilibrium, stability, and nonlinear properties of nonneutral plasma, including experimental studies on the Electron Diffusion Gauge facility of the interaction of a nonneutral electron plasma with background neutral gas.

Title: Raman Pulse Compression of Intense Lasers

Sponsor: Department of Defense Advanced Research Projects Agency

Principal Investigator: N. Fisch

Completion Date: September 30, 2001

Scope: This project entails several tasks to reduce the uncertainties associated with the effects of Raman backscatter processes in moderately intense, long laser pulses. Tasks include: (1) the development of the theory necessary to handle practical problems encountered in pump and pulse dispersion, (2) the development of numerical simulations of ionization, unwanted instabilities, and focusing processes, (3) the development of particle-in-cell simulations of signal amplification and noise reduction, (4) the experimental demonstration of the transient amplification regime, and (5) the evaluation of the potential for future intense pulse compression experiments.

Title: Extensions of Simulations Capability for Complex Three-Dimensional High Energy Density Systems Relevant to Science-based Stockpile Stewardship

Sponsor: Lawrence Livermore National Laboratory

Principal Investigator: E. Valeo

Completion Date: January 31, 2002

Scope: The goal of this effort is the development of a hybrid computational model of laser-plasma interactions that is both efficient and retains those wave-particle interactions that significantly affect collective plasma modes. To effectively increase our understanding and ultimately to design optimal target/laser configurations, the availability of an efficient model to simulate a large plasma volume, over hydrodynamic (nsec) timescales would be invaluable. The scope of this WFO project is complementary to major areas of research and code development at the Lawrence Livermore National Laboratory, which significantly impact the Science-based Stockpile Stewardship program and the Office of Fusion Energy Science's program in Inertial Fusion Energy.

Title: Development of Innovative Micro Air Vehicles

Sponsor: Naval Research Laboratory

Principle Investigators: R. Foch (NRL), D. Cylinder, L. Meixler

Completion Date: September 30, 2001

Scope: This work is being conducted in support of the Naval Research Laboratory's (NRL) Micro Air Vehicle (MAV) Program. MAVs (Figure 3) are aircraft that have a weight of less than one pound and have a payload of less than one ounce. The NRL MAV program involves fundamental research into unconventional aerodynamics of miniature air vehicles and exploratory development involving feasibility demonstrations of useful MAVs. This project is performing research in nonconventional aerodynamics, including flapping flight, hybrid fixed-wing/rotary-wing vehicles, and articulated-wing configurations.

Figure 3. PPPL researcher David Cylinder is creating innovative bird-like airframes for micro aircraft vehicles, which would carry sensors for intelligence gathering and radar jamming. He is shown here with his Samara model which looks like two winged seeds that counter rotate. The name comes from the samara seed — such as that of a maple tree — which has a wing like a single-bladed rotor.

Collaborations

Laboratories

A.F. Ioffe Physical-Technical Institute, St. Petersburg, Russian Federation

Argonne National Laboratory, Argonne, IL

Association Euratom-CEA, Cadarache, France

Association Euratom-CRPP-EPFL, Lausanne, Switzerland

Association Euratom-FOM, Nieuwegein, Netherlands

Associazione Euratom-ENEA, Frascati, Italy

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
The 2001 DOE Pollution Prevention Conference Committee, Albuquerque, NM
Textile Research Institute, Princeton, NJ
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

Patents and Invention Disclosures

Patents Issued

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

Method and System to Directly Produce Electrical Power Within the Lithium Blanket Region of a Magnetically Confined, Deuterium-Tritium (DT) Fueled Thermonuclear Fusion Reactor
— Robert D. Woolley

Provisional Patent Applications

Energetic Ions for Sterilization
— John A. Schmidt

Invention Disclosures

Method to Maintain Closed Flux Surfaces in FRC during RMF Experiments
— Samuel A. Cohen and Richard D. Milroy

Universal Nut Drive and Attachment Tool
— John Desandro, Bob Herskowitz, and Ken Lincoln

Ionization Enhancement in the Hall Thruster by Locating an Absorbing Electrode at the Sonic Transition
— A. Fruchtman, N.J. Fisch, and Y. Raitses

Visual Tritium Imaging System
— Charles A. Gentile, Stewart J. Zweben, and John Parker

AC Sweeping of Liquid Metals for High Power Density Target Applications
— Richard P. Majeski

High Throughput, High Field-of-view Imaging Lens
— Tobin Leo Munsat

Cylindrical Geometry Hall Thruster
— Yevgeny Raitses and Nathaniel Fisch

Stabilization of External Kink by a Conducting Wall in Compact Quasiaxially Symmetric Stellarators
— Martha Redi

Segmented Arc Furnace Cathode
— Stewart Zweben and Max Karasik

Graduate Education

Program in Plasma Physics graduate students for academic year 2000-2001. Seated (from left): Ethan Schartman, Barbara Sarfaty (Administrator), Sy Stange, Jef Spaleta, Seunghyeon Son and Kyle Morrison. Standing (from left): Josh Breslau, Dan Clark, Mark Boaz, Andrei Litvak, Sean Strasburg, Tom Kornack, Tom Jenkins, Jill Foley, Sorin Zaharia, Brent Jones, Sasha Landsman, and Adam Rosenberg.

The Princeton Plasma Physics Laboratory supports graduate education through the Program in Plasma Physics in the Department of Astrophysical Sciences of Princeton University. Students are admitted directly to the Program and are granted degrees through the Department of Astrophysical Sciences. With more than 200 graduates since 1959, the Program has had a significant impact on the field of plasma physics, providing many of today's leaders in 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 FY2000, there were 33 graduate students in residence in the Program in Plasma Physics, holding among them three Department of Energy Magnetic Fusion Science Fellowships, one Hertz Fellowship, and one NASA Graduate Student Researchers Program Fellowship.

Seven new students were admitted in FY2000 (Table 1), two from Russia, one from China, and four from the U.S. Four students graduated in FY2000 (Table 2), two receiving postdoctoral positions, one each at the Naval Research Laboratory (NRL) and at the California Institute of Technology. Two graduates took positions in private industry.

Program in Plasma Science and Technology

Applications of plasma science and technology meld several traditional scientific and engineering specialties. The purpose of the Program in Plasma Science and Technology (PPST) is to provide strong interdisciplinary support and training for graduate students working in these areas. The scope of interest includes fundamental studies of the plasmas, their interaction with surfaces and surroundings, and the technologies associated with their applications. Plasmas are essential to many high-technology applications, such as gaseous lasers, in which the lasing medium is plasma. X-ray laser research is prominent in the 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 microelectronic 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, and advanced-design particle accelerators.

The program 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. Departments in the program are Astrophysical Sciences, Chemical Engineering, Chemistry, Civil Engineering, Computer Science, Electrical Engineering,

Table 1. Students Admitted to the Plasma Physics Program in Fiscal Year 2000.

Student	Undergraduate Institution	Major Field
Mark Boaz	University of Illinois at Urbana-Champaign	Nuclear Engineering
Thomas Jenkins	Brigham Young University	Physics
Pavel Kolchin	Nizhny Novgorod University	Physics
Yang Ren	University of Science and Technology of China	Applied Physics
Ethan Schartman	Carnegie Mellon University	Physics
Artem Smirnov	Nizhny Novgorod University	Physics
Sy Stange	University of Oregon	Physics

Table 2. Recipients of Doctoral Degrees in Fiscal Year 2000.

Felice, GianMarco	
Thesis:	The Diffusion of Cosmic Rays Through the 90-Degree Pitch
Advisor:	Russell M. Kulsrud
Employment:	Private industry, Italy
Hsu, Scott C.	
Thesis:	Experimental Study of Ion Heating and Acceleration During Magnetic Reconnection
Advisor:	Masaaki Yamada
Employment:	California Institute of Technology
Karasik, Max	
Thesis:	Driven Motion and Instability of an Atmospheric Pressure Arc
Advisor:	Stewart Zweben
Employment:	Naval Research Laboratory
Leng, Lufeng	
Thesis:	High-Speed Fiber-Based Modules for TDM/WDM Soliton Systems
Advisor:	Keren Bergman
Employment:	Lucent Technologies

Mechanical and Aerospace Engineering, and Physics. In FY2000, 14 students received support from the PPST during the academic year and/or summer. They co-authored over a dozen refereed publications. Three PPST-supported students received PhD degrees.

In May, a new public lecture series was inaugurated, to display to the Princeton community the contributions of plasma science and technology to our society. The first distinguished lecturer was Dr. Franklin Chang-Diaz, the U.S. astronaut with the most space shuttle missions. Dr. Chang-Diaz, a pioneering researcher into the use of plasma rocket engines for missions to the remote planets, is also well know for his humanitarian efforts in both the U.S. and Central America.

To maintain this strong graduate program, increased efforts were made to develop appreciation for plasma physics in Princeton undergraduates. A sophomore seminar, entitled "All Plasmas Great and Small" was presented in Mathey College. Through a new internship program, five Princeton undergraduates worked on plasma-related projects during the summer. Two of those students have been nominated for the Pyne Prize, awarded to the Princeton senior with the highest academic standing.

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 programs 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. A marked increase in our science education outreach efforts occurred in FY2000. This is exemplified by the increased classroom visits and corresponding student participants (see Figure 1).

Teaching Science Matters

Started in FY1999, Teaching Science Matters is a three-year program of sustained, intensive, high-quality, professional development for teachers of grades 3 through 6. Princeton University's Teacher Preparation Program, the Invention Factory Science Center in Trenton, and PPPL work in partnership with the school districts of the cities of Trenton and Burlington, and the Florence Township Public Schools. Each partner institution has a specialized, clearly defined role in

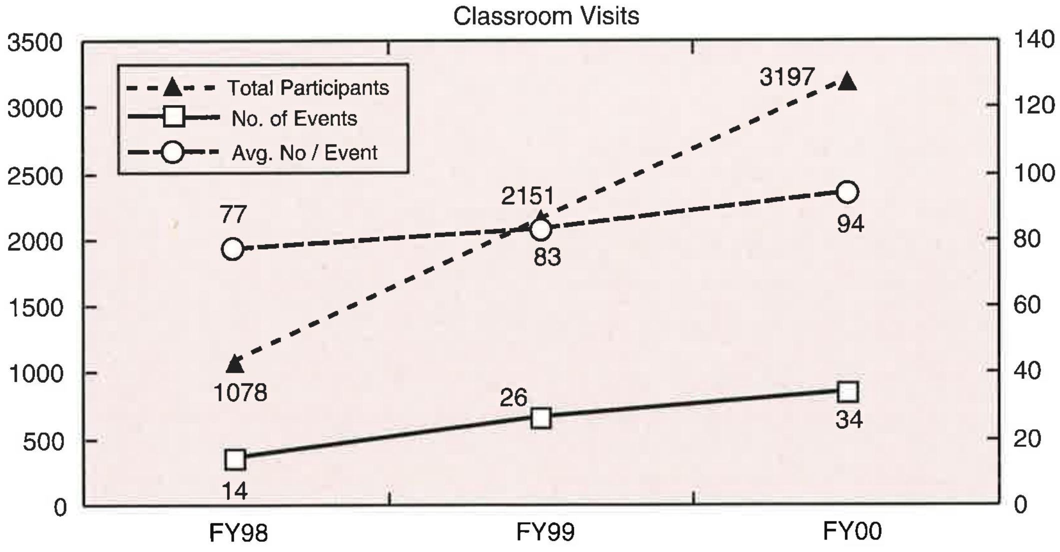


Figure 1. The number of classroom visits and student participants more than doubled between FY1998 and FY2000.

Figure 2. A classroom visitation by PPPL staff members.

the project that effectively uses its unique resources to enhance teacher professional development. Program activities are designed to further the implementation of the participating districts' vision, to strengthen the teaching of science, math, and technology, and to integrate these subjects with other core curriculum content areas. This should lead to an improved understanding and interest in science and math for the children in those districts. Results to date indicate that teachers:

- feel increasingly prepared to use inquiry-oriented teaching methods;
- use these methods more frequently; and
- feel increasingly prepared to teach science.

Teachers also report adopting reform-oriented practices such as:

- having their students engage more frequently in hands-on science activities;
- sharing ideas and solving problems in small groups; and
- having discussions which further students' science understanding.

Table 1 shows the growth of teachers participating in the collaboration who reported that their students take part in a series of reform-oriented science activities at least weekly. Overall, these results suggest that the Teaching Science Matters program has had a substantial influence on the attitudes, confidence, and practices of participating teachers.

Table 1. Percent of Teachers Reporting Growth in Specific Reform-oriented Activities.

	Fall 1998	Winter 2000
Work in cooperative learning groups	55	71
Engage in hands-on science activities	37	65
Participate in discussions with the teacher to further science understanding	46	62
Share ideas or solve problems in small groups	34	49
Participate in student-led discussions	28	34
Work on solving real-world problems	32	33
Record, represent, and/or analyze data	22	31
Write reflections in a notebook or journal	18	24
Design or implement their own investigations	10	17

Plasma Science Institute

The Plasma Science Institute, known as "Plasma Camp," is an intensive two-week program of lectures, lab work, and curriculum design for high school physics teachers. The program began in the summer of 1998 and participants are selected nationwide.

FY1999 Plasma Camp was the first time that teachers actually ran an experimental fusion device and conducted research the same way scientists do. Working with PPPL researchers, teachers from Kansas, Nebraska, and New Jersey operated The Current Drive Experiment-Upgrade (CDX-U), evaluating the temperature and density of the plasma, and analyzing plasma impurities recorded with a soft X-ray pinhole camera. The experiments involved changing the magnetic field level to gauge the effect on the plasma. In addition to participating in the CDX-U experiments, three returning teachers assisted in the Workshop and served as mentors to the new participants.

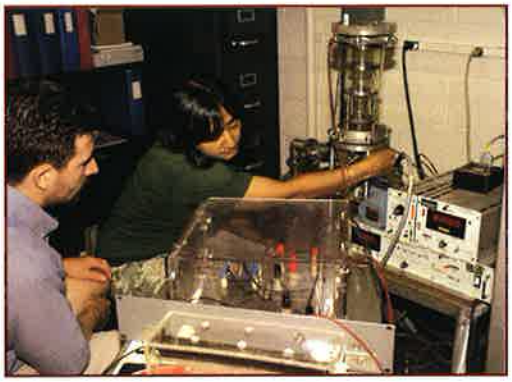


Figure 3. Teachers participating in PPPL's Plasma Science Institute.

The goal of Plasma Camp is to help teachers develop curricular materials for introductory physics teaching that make the subjects of plasma and fusion science accessible to high school students. One participant noted, "Plasma Camp has been the finest workshop I have attended. I had the opportunity to run an experiment on CDX-U. You just don't get that kind of extraordinary experience at workshops."

The benefits of Plasma Camp go far beyond the two weeks spent at PPPL. Participants submit proposals to receive grants of up to $2,000 to facilitate classroom use of knowledge gained from the experience.

Undergraduate Research Programs

During the summer of 2000, 32 students from colleges and universities throughout the United States participated in the National Undergraduate Fel-

Figure 4. Students who participated in the FY2000 National Undergraduate Fellowship and Energy Research Undergraduate Fellowship Laboratory Programs.

lowship and the Energy Research Undergraduate Laboratory Fellowship Programs. Students were selected competitively, based on their academic abilities, potential to do research work, and interest in graduate study.

In these programs, undergraduate science and engineering students are introduced to plasma science and technology in a one-week course, followed by participation in the ongoing research at the Laboratory for nine weeks. In addition to the research project, mentors provide guidance and support to the students in matters related to course selection, graduate programs, and career options.

Awards and Honors

Individual Awards

Diane Carroll

Special Award for Education and Outreach
Fusion Power Associates

Kai-Mei Fu

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

Zhihong Lin

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

Charles Neumeyer

Engineer of the Year Award
Professional Engineering Society of Mercer County

Masayuki Ono

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

Gennady Shvets

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

Thomas Stix

Distinguished Career Award
Fusion Power Associates

Arlene White

Presidential Achievement Award
Princeton University

Michael Williams
Excellence in Fusion Engineering Award
Fusion Power Associates

and

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

Laboratory Awards

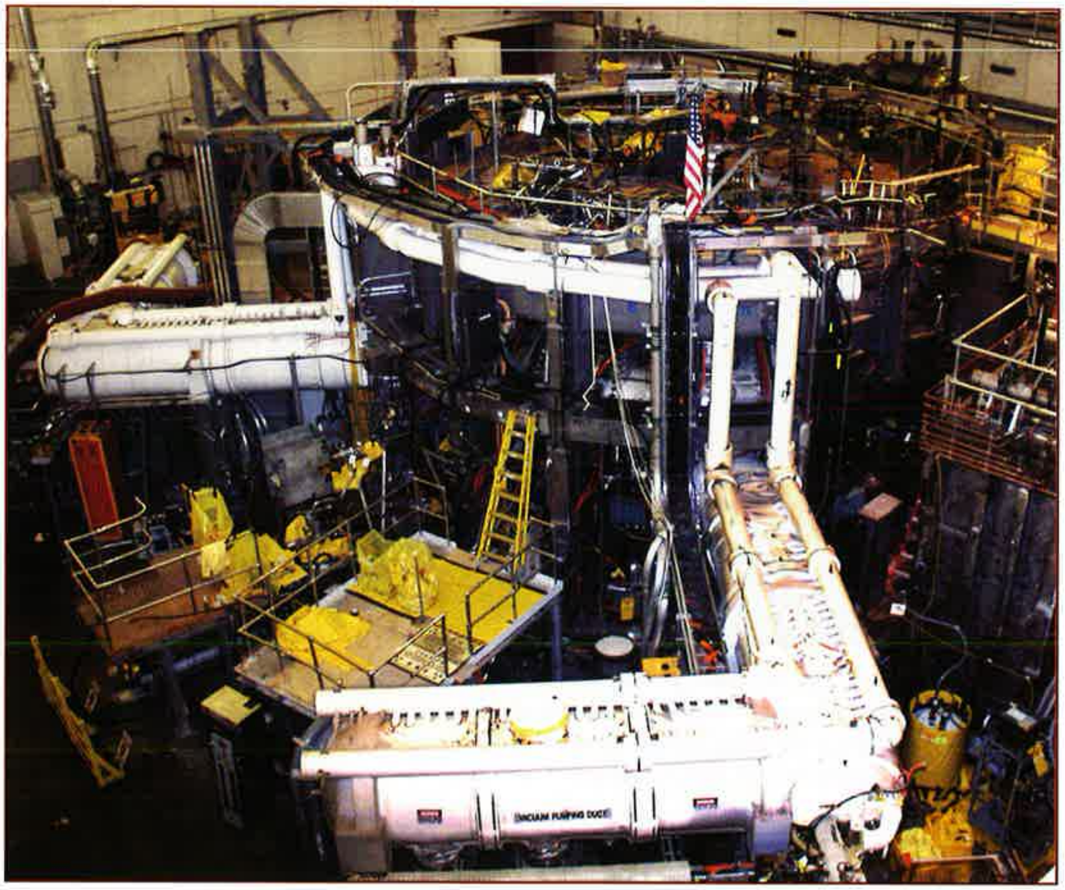
Regional Laboratory Award
Federal Laboratory Consortium for Technology Transfer
for the Princeton Plasma Physics Laboratory's
Extraordinary Efforts to further National
and Regional Technology Transfer Activities

PPPL Director Rob Goldston (left) and PPPL Technology Transfer Head Lewis Meixler hold the Regional Laboratory Award that PPPL received from the Federal Laboratory Consortium for Technology Transfer. The award recognizes PPPL for its extraordinary efforts to further national and regional technology transfer activities.

The Year in Pictures

On December 14, the National Spherical Torus Experiment at PPPL produced a one-million ampere plasma current — a new world record for a spherical torus device. Producing this plasma current set the stage for the Laboratory to create and study plasma conditions relevant to the production of fusion energy.

Al Planeta and his children Sarah, Brian, and Rachel tour the National Spherical Torus Experiment during the Lab's "Take Our Daughters to Work Day" program on April 27. The PPPL Director's Advisory Committee on Women hosted 28 children of employees for the day, which included a talk, "How Fusion Will Protect Our Natural Resources," by PPPL Director Rob Goldston; a tour; and mentoring sessions with staff members and parents.



Progress on the disassembly and removal of the Tokamak Fusion Test Reactor (TFTR) at PPPL continued throughout the year. The project began in October, 1999, and is expected to be completed in three years at a cost of $47.9 million. Shown is a view of the TFTR Test Cell in March.

PPPL's June 3 Open House was a smash, drawing approximately 2,500 people. The Lab's visitors, ranging from tots to seniors, walked around the National Spherical Torus Experiment, toured other experimental areas, learned about the physics behind sports, crawled into a portable planetarium, and participated in safety activities, as well as tabletop demonstrations about electromagnetism, thermodynamics, and common plasmas. Above, PPPL's Marianne Tyrrell has a "hair raising" experience while trying out the Van de Graaff generator during the event's hands-on science demonstrations. The generator develops an electrostatic charge, making the hair of anyone who touches it stand on end. At Tyrrell's right is her husband, PPPL's Mike Viola (wearing white T-shirt), and across from her is PPPL's Bob Simmons (in cap).

The Laboratory honored thirty-five inventors for FY1999 during the annual Patent Recognition Dinner in June at Princeton University's Prospect House. Those attending the dinner and receiving awards were, from left, Martin Peng, Nathaniel Fisch, Joel Hosea, John Schmidt, Allen Boozer, Hyeon Park, Elizabeth Foley, Nevell Greenough, Yevgeny Raitses, Leonid Zakharov, Keith Rule, Gennady Shvets, Robert Woolley, and Geoff Gettelfinger.

During the summer and fall, PPPL Director Rob Goldston and his wife, Ruth, hosted four staff picnics at their home. More than 200 employees enjoyed the soirees, which included dips in the pool, grilled hot dogs, refreshments, and plenty of conversation.

In July and August, 45 elementary and middle school teachers from New Jersey participated in one-week "Sizzling Summer Science" workshops that were organized, in part, by PPPL's Science Education Program staff. During the workshops, teachers conducted experiments and developed inquiry-based teaching skills. From left around the table are Trenton teacher Denise Mylowe, Burlington teacher Ed Alfaro, and Trenton teacher Brenda Koonce making parachutes. First, they constructed parachutes from instructions and then designed their own and developed experiments. These exercises were to show the differences between "cookbook" science and inquiry-based science.

During the summer, Pamela Lucas was named Head of PPPL's Science Education Program. Lucas, who joined the Laboratory's Science Education staff six years ago, had been Acting Head for eight months prior to being named Head.

PPPL Financial Summary by Fiscal Year
(Thousands of Dollars)

	FY96	FY97	FY98	FY99	FY00
Operating Costs					
Fusion Energy Sciences					
TFTR Physics/Data Analysis	$13,004	$13,607	$4,955	$317	$ —
TFTR Operations	33,792	13,497	—	—	—
TFTR Shutdown/Caretaking	8	12,368	3,292	2,952	3,125
TFTR D&D	—	—	—	371	8,976
Subtotal TFTR	$46,804	$39,472	$8,247	$3,640	$12,101
NSTX	$1,163	$1,441	$3,241	$13,737	$18,248
NCSX	1,073	702	2,524	2,840	3,644
Theory and Computation	2,683	2,929	4,003	5,161	5,823
Off-site Collaborations	1,253	4,028	9,241	9,281	8,342
Off-site University Research Support	—	—	985	697	719
CDX-U	699	479	802	680	876
MRX	125	39	165	221	600
Heavy Ion Fusion	162	210	238	415	513
Science Education Programs	301	440	691	652	515
ITER	2,981	3,546	3,677	488	—
TPX	(1,255)	(1,062)	(224)	(116)	—
Other Fusion	954	1,220	1,982	2,300	1,973
Change in Inventories*	(90)	(35)	(50)	(35)	4
Total Fusion Energy Sciences	$56,853	$53,409	$35,522	$39,961	$53,358
Environmental Restoration and Waste Mgt	$3,581	$4,066	$3,735	$3,564	$3,036
Computational and Technology Research	391	157	101	92	21
Basic Energy Sciences	—	—	302	534	608
High Energy Physics	—	—	73	80	98
University and Science Education	279	92	—	—	—
Energy Management Studies	136	13	3	58	34
Total DOE Operating	$61,240	$57,737	$39,736	$44,289	$57,155
Work for Others					
Korea Basic Science Institute	$186	$1,837	$2,039	$871	$81
All Other	693	1,199	2,218	1,755	1,180
TOTAL OPERATING COSTS	$62,119	$60,773	$43,993	$46,915	$58,416
Capital Equipment Costs					
TFTR	$546	$241	$ —	$ —	$1,273
NSTX	—	3,412	12,268	8,503	5,532
All Other Fusion	71	32	—	970	897
Environmental Restoration and Waste Mgt	125	75	(1)	58	1
TOTAL CAPITAL EQUIPMENT COSTS	$742	$3,760	$12,267	$9,531	$7,703
Construction Costs					
General Plant Projects - Fusion	$2,158	$473	$454	$798	$2,070
General Plant Projects - ERWM	—	—	—	—	7
Safety and Fire Protection Improvements	332	34	—	—	—
Radioactive Waste Handling Facility	560	1	—	—	—
Energy Management Projects	66	255	45	15	110
Tokamak Fusion Test Reactor	—	—	—	(2)	—
TOTAL CONSTRUCTION COSTS	$3,116	$763	$499	$811	$2,187
TOTAL PPPL	$65,977	$65,296	$56,759	$57,257	$68,306

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

PPPL Organization

Directorate

Robert J. Goldston
Director

Richard J. Hawryluk
Deputy Director

William M. Tang
Chief Scientist

Nathaniel J. Fisch
Associate Director for Academic Affairs

John W. DeLooper
Associate Director for External Affairs

Steven M. Iverson
Head, Human Resources

Susan E. Murphy-LaMarche
Deputy Head, Human Resources

PPPL Director's Cabinet

Robert J. Goldston
Director

Richard J. Hawryluk
Deputy Director

William M. Tang
Chief Scientist

William Happer
Chair, Princeton University Research Board

Departments

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

Off-Site Research
Ned R. Sauthoff

Plasma Science and Technology
Stewart J. Zweben

National Spherical Torus Experiment
Martin Peng, Program Director*
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

	FY96	FY97	FY98	FY99	FY00
Faculty	7	6	6	3	3
Physicists	89	88	87	89	91
Engineers	105	76	74	74	85
Technicians	198	137	136	139	197
Administrative	81	66	68	69	77
Office and Clerical Support	28	19	18	19	21
Total	508	392	389	393	474

PPPL Advisory Council

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

Dr. Norman R. Augustine
Princeton University

Dr. David E. Baldwin
General Atomics

Professor D. Allan Bromley
Yale University

Dr. Andrea Dupree
Harvard University

Professor Edward A. Frieman
Scripps Institution of Oceanography

Professor Robert A. Gross
Chapel Hill, North Carolina

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

*§Bakos, J.S., Djotyan, G., Sörlei, Zuszsa, Szigeti, J., Mansfield, D.K., and Sarkozi, J., "Broadening and Shifting of the Methanol 119 mm Gain Line of Linear and Circular Polarization by Collision with Chiral Molecules," Phys. Rev. A **63** (January 2001) 012507-012511; Princeton Plasma Physics Laboratory Report PPPL-3457 (June 2000) 10 pp.

Bell, M.G. for the NSTX Research Team, "Physics Results from the National Spherical Torus Experiment," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 101-104 (or_027.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001). Princeton Plasma Physics Laboratory Report PPPL-3459 (June 2000) 4 pp.

Bell, R.E. and Synakowski, E.J., "New Understanding of Poloidal Rotation Measurements in a Tokamak Plasma," AIP Conference Proceedings **547** (December 2000) edited by Roberto C. Mancini and Ronald A. Phaneuf (AIP, Melville, New York, 2000). [Paper presented at the *12th American Physical Society Topical Conference on Atomic Processes in Plasmas* (Reno, Nevada, March 19-23, 2000)]; Princeton Plasma Physics Laboratory Report PPPL-3447 (May 2000) 14 pp.

Belova, E.V., Jardin, S.C., Ji, H., Yamada, M., and Kulsrud, R., "Numerical Study of Tilt Stability of Prolate Field-reversed Configurations," Phys. Plasmas **7** (December 2000) 4996-5006; Princeton Plasma Physics Laboratory Report PPPL-3456 (June 2000) 31 pp.

*Bertschinger, Ahmad, I., G., Biel, W., Bitter, M., Weinheimer, J., and Kunze,H.-J., "Analysis of ArXVII Spectra during Sawtooth Crashes in TEXTOR-94 Discharges with a High-resolution X-ray Polarimeter," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 1228-1231 (P3_112.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001).

*Biskamp, D., Diamond, P.H., Garbet, X., Lin, Z., Nührenberg, J., and Rogers, R.N., "Conference Report: First Principles Based Transport Theory," (Report on the International Atomic Energy Agency Technical Committee Meeting held at Kloster Seeon, Germany, 21-23 June 1999), Nucl. Fusion **40** (April 2000) 873-878.

---

*First author is from another institution. PPPL co-authors are underlined.

†Paper presented at conference in fiscal year 2000; proceedings to be published.

§Submitted for publication in fiscal year 2000.

Bitter, M., Bertschinger, G., Biel, W., Jaspers, R., Weinheimer, J., and Kunze, H.-J., "A New Method for Absolute Measurements of the Toroidal Plasma Rotation Velocity at TEXTOR-94," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 840-843 (P2_119.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001).

Boldyrev, Stanislav A. and Schekochihin, Alexander A., "Geometric Properties of Passive Random Advection," Phys. Rev. E **62** (July 2000) 545-552.

*Bonoli, P.T., Parker, R.R., Porkolab, M., Ramos, J.J., Wukitch, S.J., Takase, Y., Bernabei, S., Hosea, J.C., Schiling, G., and Wilson, J.R., "Modelling of Advanced Tokamak Scenarios with LHCD in Alcator C-Mod," Nucl. Fusion **40** (June 2000) 1251-1256.

*Borba, D., Alper, B., Budny, R.V., Fasoli, A., Heeter, R.F., Kerner, W., Sharapov, S.E., and Smeulders, P., "Beam Driven Alfvén Eigenmodes and Fishbones in JET," Nucl. Fusion **40** (April 2000) 775-783.

Brown, T., "Fusion Ignition Research Experiment System Integration," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 172-175 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050); Princeton Plasma Physics Laboratory Report PPPL-3382 (November 1999) 4 pp.

Brunkhorst, C., Ciotti, D., Fredd, E., Wilson, J.R., Geveke, D.J., and Kozempel, M., "Development of Process Equipment to Separate Nonthermal and Thermal Effects of RF Energy on Microorganisms," J. Microwave Power E.E. **35** (January 2000) 44-50.

Brunner, S., Valeo, E., and Krommes, J.A., "Collisional Delta-f Scheme with Evolving Background for Transport Time Scale Simulations," Phys. Plasmas **6** (December 1999) 4504-4521.

Brunner, S., Valeo, E., and Krommes, J.A., "Linear Delta-f Simulations of Nonlocal Electron Heat Transport," Phys. Plasmas **7** (July 2000) 2810-2823; Princeton Plasma Physics Laboratory Report PPPL-3427 (January 2000) 36 pp.

Budny, R.V., Ernst, D.R, Hahm, T.-S., McCune, D.C., Christiansen, J.P., Cordey, J.G., Gowers, C.G., Guenther, K., Hawkes, N., Jarvis, O.N., Stubberfield, P.M., Zastrow, K.-D., Horton, L.D., Saibene, G., Sartori, R., Thomsen, K., and, von Hellermann, M.G., "Local Transport in Joint European Tokamak Edge-localized, High-confinement Mode Plasmas with H, D, DT, and T Isotopes," Phys. Plasmas 7 (December 2000) 5038-5050.

*Burgess, T., Brown, T., Chesser, J., Dilling, D., Heitzenroeder, P., and Nelson, B., "Remote Maintenance Requirements and Approach for the FIRE Project," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 484-487 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050).

Chao, E.H., Davidson, R.C., Paul, S.F., and Morrison, K.A. "Effects of Background Gas Pressure on the Dynamics of a Nonneutral Electron Plasma Confined in a Malmberg-Penning-Trap," Phys. Plasmas 7 (March 2000) 831-838.

*Chen, L., Lin, Z.H., and White, R., "Excitation of Zonal Flow by Drift Waves in Toroidal Plasmas," Phys. Plasmas 7 (August 2000)

3129-3132; Princeton Plasma Physics Laboratory Report PPPL-3378 (November 1999) 10 pp.

*Chen, Liu; Lin, Zhihong; and White, Roscoe, "Zonal Flow Excitation by Drift Waves in Toroidal Plasmas," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 1557-1560 (P4_080.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001).

†Cheng, C.Z., "Kinetic Ballooning Instability as a Substorm Onset Mechanism," presented at *The Structure Formation and Functions of Gaseous, Strongly Coupled, and Biological Plasmas Conference* (Japan, July 14-16, 1999); Princeton Plasma Physics Laboratory Report PPPL-3369 (October 1999) 13 pp.

§Cheng, C.Z. and Choe, G.S., "Solar Flare Mechanism Based on Magnetic Arcade Reconnection and Island Merging," Princeton Plasma Physics Laboratory Report PPPL-3450 (June 2000) 13 pp; submitted to Earth, Planets and Space.

Choe, G.S. and Cheng, C.Z., "A Model of Solar Flares and Their Homologous Behavior," Astrophys. J. **541** (September 2000) 449-467; Princeton Plasma Physics Laboratory Report PPPL-3428 (January 2000) 44 pp.

Chrzanowski, J.H., Neumeyer, C., Heitzenroeder, P., Barnes, G., Viola, M., Nelson, B., Gorenson, P., and the NSTX Group, "National Spherical Torus Experiment (NSTX) Torus Design, Fabrication and Assembly," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 59-62 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050); Princeton Plasma Physics Laboratory Report PPPL-3396 (November 1999) 4 pp.

§Chu, T.K., "Symmetries-imposed Configurational Limit and Configurational Limit-induced Change of Symmetry in a Driven, Dissipative Tokamak Plasma," submitted to Physics of Plasmas.

Chu, T.K. "Turbulent Steady-state Configuration of an Inductively Driven, Dissipative Tokamak Plasma," Phys. Plasmas 7 (September 2000) 3537-3541.

Clark, Daniel S. and Fisch, Nathaniel J, "The Possibility of High Amplitude Driven Contained Modes During TFTR IBW Experiments," Phys. Plasmas 7 (July 2000) 2923-2932.

Cohen, S.A. and Milroy, R.D., "Maintaining the Closed Magnetic-field-line Topology of a Field-reversed Configuration with the Addition of Static Transverse Magnetic Fields," Phys. Plasmas 7 (June 2000) 2539-2545; Princeton Plasma Physics Laboratory Report PPPL-3418 (January 2000) 23 pp.

Cohen, S.A. and Glasser, A.H., "Ion Heating in the Field-reversed Configuration by Rotating Magnetic Fields Near the Ion-cyclotron Resonance," Phys. Rev. Lett. **85** (December 2000) 5114-5117; Princeton Plasma Physics Laboratory Report PPPL-3475 (July 2000) 8 pp.

§Darrow, D.S., Bell, R., Johnson, D.W., Kugel, H., Wilson, J.R., Cecil, F.E., Maingi, R., Krasilnikov, A., and Alekseyev, A., "Fast Ion Loss Diagnostic Plans for the National Spherical Torus Experiment," presented at the *13th Topical Conference on High Temperature Diagnostics Plasma* (Tucson, Arizona, June 18-22, 2000), conference proceedings to be published in Review of Scientific Instruments; Princeton Plasma Physics Laboratory Report PPPL-3452 (June 2000) 12 pp.

Davidson, R.C., Qin, H., and Shvets, G., "A Paul Trap Configuration to Simulate Intense Non-neutral Beam Propagation over Large Distances through a Periodic Focusing Quadrupole Magnetic Field," Phys. Plasmas 7 (March 2000) 1020-1025.

Davidson, R.C. and Qin, H., "Effects of Axial Momentum Spread on the Electron-ion Two-stream Instability in High-intensity Ion Beams," Phys. Lett. A **270** (May 2000) 177-185; Princeton Plasma Physics Laboratory Report PPPL-3449 (June 2000) 17 pp.

Davidson, R.C. and Strasburg, S., "Warm-fluid Stability Properties of Intense Non-neutral Charged Particle Beams with Pressure Anisotrophy," Phys. Plasmas 7 (June 2000) 2657-2670.

*DeBoo, J.C., Kinsey, J.E., Bravenec, R., Fredrickson, E., Greenfield, C.M., Lin-Liu, Y.R., Lohr, J., Luce, T.C., McKee, G.R., Prater, R., Rettig, C.L., Schissel, D.P., Staebler, G.M., and Waltz, R.E., "Experimental Tests of Transport Models using Modulated Electron Cyclotron Heating," Nucl. Fusion **39**, Yokohama Special Issue 2 (November 1999) 1935-1940.

*Dimits, A.M., Bateman, G., Beer, M.A., Cohen, B.I., Dorland, W., Hammett, G.W., Kim, C., Kinsey, J.E., Kotschenreuther, M., Kritz, A.H., Lao, L.L., Mandrekas, J., Nevins, W.M., Parker, S.E., Redd, A.J., Shumaker, D.E., Sydora, R., and Weiland, J., "Comparisons and Physics Basis of Tokamak Transport Models and Turbulence Simulations," Phys. Plasmas 7 (March 2000) 969-983.

Dorf, L., Raitses, Y., and Fisch, N.J., "Using Emissive and Nonemissive Segmented Electrodes to Control Beam Divergence in Hall Thrusters," IEEE Publication **4A04** (2000) 186 (IEEE, Piscataway, NJ, 2000). [Paper presented at the *27th IEEE International Conference on Plasma Science* (ICOPS-2000, New Orleans, LA, June 4-7, 2000).]

Dudek, L.E., Blanchard, W., Kalish, M., Gernhardt, R., and Parsells, R.F., "Design and Construction of the NSTX Bakeout, Cooling and Vacuum Systems," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 277-280 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050); Princeton Plasma Physics Laboratory Report PPPL-3386 (November 1999) 4 pp.

Ernst, D.R., Bell, R.E., Bell, M.G., Budny, R.V., Coppi, B., Hammett, G.W., Hawryluk, R.J., Hill, K.W., Mansfield, D.K., Mikkelsen, D.R., Park, H.K., Porkolab, M., Scott, S.D., Schmidt, G.L., Synakowski, E.J., and Zarnstorff, M.C., "Transitionless Enhanced Confinement and the Role of Radial Electric Field Shear," Phys. Plasmas 7 (February 2000) 615-625; Princeton Plasma Physics Laboratory Report PPPL-3375 (October 1999) 24 pp.

§Felice, G.M. and Kulsrud, R.M., "Cosmic Ray Pitch Angle Scattering Through 90°," Princeton Plasma Physics Laboratory Report PPPL-3488 (September 2000) 45 pp; submitted to Astrophysical Journal.

*Ferron, J.R., Baylor, L.R., Chance, M.S., Chu, M.S., Jackson, G.L., Lao, L.L., Murakami, M., Osborne, T.H., Synder, P.B., Strait, E.J., Turnbull, A.D., and Wade, M.R., "H-mode Edge-driven Instabilities as Low-n Kink/Ballooning Modes," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 548-551 (P2_023.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001).

Finley, Virginia L., "Princeton Plasma Physics Laboratory Annual Site Environmental Report for Calendar Year 1998," Princeton Plasma Physics Laboratory Report PPPL-3440 (March 2000) 88 pp.

Fisch, N.J. "Physics of Alpha Channeling and Related TFTR Experiments," Nucl. Fusion **40** (June 2000) 1095-1100.

§Fisch, N.J., Raitses, Y., Dorf, L.A., and Litvak, A.A., "Design and Operations of Hall Thruster with Segmented Electrodes," Princeton Plasma Physics Laboratory Report PPPL-3405 (December 1999) 11 pp; submitted to Journal of Propulsion and Power.

§Fisch, N.J., Raitses, Y., Dorf, L.A., and Litvak, A.A., "Variable Operation of Hall Thruster with Multiple Segmented Electrodes," J. Appl. Phys. **89** (February 2001) 2040-2046; Princeton Plasma Physics Laboratory Report PPPL-3432 (February 2000) 18 pp.

*Fisher, P.W., Gouge, M.J., Foster, C.A., Nelson, B.E., and Gentile, C.A., "Plasma Fueling, Pumping, and Tritium Handling Considerations for FIRE," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 463-466 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050).

§Fredrickson, E.D., Austin, M.E., Groebner, R., Manickam, J., Rice, B., Schmidt, G., and Snider, R., "Heatpulse Propagation Studies on DIII-D and the Tokamak Fusion Test Reactor," Phys Plasmas 7 (December 2000) 5051-5063; Princeton Plasma Physics Laboratory Report PPPL-3443 (April 2000) 41 pp.

§Fredrickson, E., Bell, M., Budny, R.V., and Synakowski, E., "Nonlinear Evolution of Double Tearing Modes in Tokamaks," Phys. Plasmas 7 (October 2000) 4112-4120; Princeton Plasma Physics Laboratory Report PPPL-3411 (December 1999) 30 pp.

Fredrickson, E.D., Bialek, J., Garofalo, A.M., Johnson, L.C., LaHaye, R.J., Lazarus, E.A., Manickam, J., Navratil, G.A., Okabayashi, M., Strait, E.J., and Scoville, J.T., "Closed Loop Feedback of MHD Instabilities on DIII-D," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 1453-1456 (P4_050.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001).

Fredrickson, E., Van Dam, J.W., Budny, R.V., Darrow, D., Fu, G.Y., Hosea, J., Phillips, C.K., and Wilson, J.R., "Observation of Modes at Frequencies Near the Second Alfvén Gap in the Tokamak Fusion Test Reactor," Phys. Plasmas 7 (October 2000) 4121-4125; Princeton Plasma Physics Laboratory Report PPPL-3444 (April 2000) 18 pp.

*§Fruchtman, A. and Fisch, N.J., "Abrupt Sonic Transition in the Hall Thruster," submitted to Journal of Propulsion and Power.

*§Fruchtman, A. and Fisch, N.J., "Variational Principle for Optimal Accelerated Neutralized Flow," Phys. Plasmas **8** (January 2001) 56-58.

*§Fruchtman, A., Fisch, N.J., and Raitses, Y., "Control of the Electric Field Profile in the Hall Thruster," submitted to Physics of Plasmas.

Fu, G.Y., "Vertical Stability in a Current-carrying Stellarator," Phys. Plasmas 7 (April 2000) 1079-1080; Princeton Plasma Physics Laboratory Report PPPL-3368 (October 1999) 6 pp.

Fu, G.Y., Ku, L.P., Cooper, W.A., Hirshman, S.H., Monticello, D.A., Redi, M.H., Reiman, A., Sanchez, R., and Spong, D.A., "Magnetohydrodynamics Stability of Compact Stellarators," Phys. Plasmas 7 (May 2000) 1809-1815; Princeton Plasma Physics Laboratory Report PPPL-3412 (January 2000) 21 pp.

Fu, G.-Y., , Ku, L.P., Monticello, D.A., Redi, M.H., Reiman, A., and Cooper, W.A., "MHD Stability Calculations of Current-carrying Quasi-symmetric Stellarators," presented at the *12th International Stellarator Workshop* (Madison, Wisconsin, September 27 - October 1, 1999). The workshop paper is available in pdf format at the following web site: http://hsxa.ece.wisc.edu/Stell_workshop/Papers-pdf/Fu_MHD-stability-calculations-of-current-carrying-quasi-axisymmetric-stellarators.pdf (active as of July 8, 2001).

*§Gao, Qingdi; Budny, R.V.; a Zhang, Jinhu; Li, Fangzhu; and Jiao, Yiming, "Sustained Reversed Magnetic Shear Mode of Operation in the HL-2A Tokamak," submitted to Nuclear Fusion.

Gates, D., Bell, M., Ferron, J., Kaye, S., Menard, J., Mueller, D., Neumeyer, C., and Sabbagh, S., "Initial Operation of NSTX with Plasma Control," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 1433-1436 (P4_045.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001). Princeton Plasma Physics Laboratory Report PPPL-3453 (June 2000) 4 pp.

Gates, D.A., Mueller, D., Neumeyer, C., and Ferron, J.R., "Control System Development Plan for the National Spherical Torus Experiment," IEEE Transactions on Nuclear Science 47 (April 2000) 222-224. [Paper presented at the *11th IEEE/NPSS Conference on Real-Time Computer Applications in Nuclear, Particle and Plasma Physics* (Santa Fe, New Mexico, June 14-18, 1999).]

Gentile, C.A., Skinner, C.H., Young, K.M., Ciebiera, L., Langish, S.W., von Halle, A., Kennedy, C.W., O'hira, S., and Shu, W.M., "Tritium Decontamination of TFTR D-T Graphite Tiles Employing Ultra Violet Light and a Nd:YAG Laser," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 321-322 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050); Princeton Plasma Physics Laboratory Report PPPL-3372 (October 1999) 3 pp.

Gentile, C.A., Zweben, S.J., Skinner, C.H., Young, K.M., Langish, S.W., Nishi, M.F., Shu, W.M., Parker, J., and Isobe, K., "Visual Tritium Imaging of In-vessel Surfaces," presented at the *14th International Conference on Plasma Surface Interaction in Controlled Fusion Devices* (Rosenheim, Germany, May 26-30, 2000); Princeton Plasma Physics Laboratory Report PPPL-3458 (June 2000) 6 pp.

Gentile, C.A., Zweben, S.J., Skinner, C.H., Young, K.M., Parker, J., Ciebiera, L., Langish, S.W., von Halle, A., Kennedy, C.W., and Isobe, K., "A Visual Detection System for Determining Tritium Surface Deposition Employing Phosphor Coated Materials," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 319-320 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050); Princeton Plasma Physics Laboratory Report PPPL-3371 (October 1999) 4 pp.

*Geveke, D.J., Kozempel, M., and Brunkhorst, C., "Development of Equipment to Separate Nonthermal and Thermal Effects of Radio Frequency Energy on Microorganisms," presented at the *Annual Meeting of the American Institute of Chemical Engineers* (Dallas, Texas, October 31 through November 5, 1999), to be published in conference proceedings.

*Goranson, P., Barnes, G., Chrzanowski, J., Heitzenroeder, P., Nelson, B., Neumeyer, C., and Ping, J., "Design of the Plasma Facing Components for the National Spherical Tokamak Experiment (NSTX)," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 67-70 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050).

*Goranson, P., Brooks, A., Brown, T., Cole, M., Fan, H-M., Heitzenroeder, P., Reiersen, W., Nelson, B., and Williamson, D., "Design of the Vacuum Liner for the National Compact Stellarator Experiment (NCSX)," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 235-238 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050).

Gorelenkov, N.N., Bernabei, S., Cheng, C.Z., Hill, K., Nazikian, R., Kaye, S., Kusama, Y., Kramer, G.J., Shinohara, K., Ozeki, T., and Gorelenkova, M.V., "Stability Properties of Toroidal Alfvén Modes Driven by Fast Particles," Nucl. Fusion **40** (July 2000) 1311-1323; Princeton Plasma Physics Laboratory Report PPPL-3391 (November 1999) 22 pp.

Gorelenkov, N.N., Cheng, C.Z., Fu, G.Y., Kaye, S., White, R., and Gorelenkova, M.V., "Fast Particle Destabilization of Toroidicity-induced Alfvén Eigenmodes in the National Spherical Torus Experiment," Phys. Plasmas 7 (May 2000) 1433-1436; Princeton Plasma Physics Laboratory Report PPPL-3402 (December 1999) 13 pp.

Gorelenkov, N.N., Nave, M.F.F., Budny, R., Cheng, C.Z., Fu, G.Y., Hastie, J., Manickam, J., and Park, W., "Effect of Plasma Rotation on Sawtooth Stabilization by Beam Ions," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 1553-1556 (P4_079.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001). Princeton Plasma Physics Laboratory Report PPPL-3463 (June 2000) 4 pp.

*Greenfield, C.M., Burrell, K.H., Casper, T.A., DeBoo, J.C., Doyle, E.J., Gohil, P., Groebner, R.J., Kinsey, J.E., Pinsker, R.I., Prater, R., Rettig, C.L., Staebler, G.M., Stallard, B.W., Synakowski, E.J., Thomas, D.M., and the DIII-D Team, "Improvement of Core Barriers with ECH and Counter-NBI in DIII-D," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 544-547 (P2_022.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001).

*Greenfield, C.M., Rettig, C.L., Staebler, G.M., Stallard, B.W., Austin, M.E., Burrell, K.H., DeBoo, J.C., DeGrassie, J.S., Doyle, E.J., Gohil, P., Groebner, R.J., Lohr, J., McKee, G.R., Peebles, W.A., Petty, C.C., Pinsker, R.I., Rice, B.W., Rhodes, T.L., Synakowski, E.J., Waltz, R.E., and Zeng, L., "Behavior of Electron and Ion Transport in Discharges with an Internal Transport Barrier in the DIII-D Tokamak," Nucl. Fusion **39**, Yokohama Special Issue 2 (November 1999) 1723-1732.

Hahm, T.S., Burrell, K.H., Lin, Z., Nazikian, R., and Synakowski, E.J., "Theory, Simulation, and Experimental Studies of Zonal Flows," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö,

T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 1561-1564 (P4_081.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001). Princeton Plasma Physics Laboratory Report PPPL-3468 (July 2000) 4 pp.

Hahm, T.S., Burrell, K.H., Lin, Z., Nazikian, R., and Synakowski, E.J., "Zonal Flow Measurements Concept I," Plasma Phys. Control. Fusion **42** (May 2000) A205-A210 [presented at the *7th International Atomic Energy Agency (IAEA) Technical Committee Meeting on H-Mode and Transport Barrier Physics* (Oxford, United Kingdom, September 27-29, 1999)]; Princeton Plasma Physics Laboratory Report PPPL-3361 (October 1999) 12 pp.

Hammett, G.W., Dorland, W., Beer, M.A., and Kotschenreuther, M., "Potential Methods for Improving Pedestal Temperatures and Fusion Performance," presented at the *Workshop on Opportunities and Directions in Fusion Energy Science for the Next Decade* (Snowmass, Colorado, July 11-23, 1999), Workshop proceedings published on CD ROM. The conference proceedings is available in pdf format at the following web site: http://www.ap.columbia.edu/SMproceedings/ (active as of October 2000). Princeton Plasma Physics Laboratory Report PPPL-3360 (October 1999) 7 pp.

*Hawkes, N.C., Stratton, B.C., Alper, B., Budny, B., Challis, C.D., Reyes-Cortes, S., Drozdov, V., Günther, K., Mazon, D., Hender, T.C., Testa, D., Zastrow, K-D., and Zwingmann, W., "Current Profile and E_r Results with MSE Measurement in JET Optimised Shear Plasmas," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 249-252 (P1_049.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001).

*Heidbrink, W.W., Fredrickson, E.D., Mau, T.K., Petty, C.C., Pinsker, R.I., Porkolab, M., and Rice, B.W., "High Harmonic Ion Cyclotron Heating in DIII-D: Beam Ion Absorption and Sawtooth Stabilization," Nucl. Fusion **39** (October 1999) 1369-1389.

Heitzenroeder, Philip J. and the FIRE Engineering Team, "Development of a Cost-Effective Design for the Fusion Ignition Research Experiment," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 447-450 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050); Princeton Plasma Physics Laboratory Report PPPL-3399 (December 1999) 4 pp.

Heitzenroeder, Philip; Chrzanowski, James; Neumeyer, Charles; Fan, Horng-Ming; and the NSTX Team, "Chosen Solutions to the Engineering Challenges of the National Spherical Torus Experiment Magnets," IEEE Transactions on Applied Superconductivity **10** (March 2000) 618-623. [Paper presented at the *16 International Conference on Magnet Technology* (Ponte Vedra Beach, Florida, September 26-October 1, 1999)]; Princeton Plasma Physics Laboratory Report PPPL-3364 (October 1999) 6 pp.

*Hoang, G.T., Bourdelle, C., Garbet, X., Antar, G., Budny, R.V., Aniel, T., Basiuk, V., Becoulet, A., Devynck, P., Lasalle, J., Martin, G., Saint-Laurent, F., and the Tore Supra Team, "Internal Transport Barrier with Ion-cyclotron-resonance Minority Heating on Tore Supra," Phys. Rev. Lett. **84** (May 2000) 4593-4596.

*Hoang, G.T., Monier-Garbet, P., Aniel, T., Bourdelle, C., Budny, R.V., Clairet, F., Eriksson, L.G., Garbet, X., Grisolia, C., Platz,

P., and Vallet. J.C., "A H-minority Heating Regime in Tore Supra Showing Improved L-mode Confinement," Nucl Fusion **40** (May 2000) 913-921.

Hsu, Scott C., "Experimental Study of Ion Heating and Acceleration during Magnetic Reconnection," Ph.D. Thesis (2000), Princeton University, Princeton, New Jersey; Princeton Plasma Physics Laboratory Report PPPL-3430 (January 2000) 142 pp.

Hsu, S.C., Fiksel, G., Carter, T.A., Ji, H., Kulsrud, R.M., and Yamada M., "Local Measurement of Nonclassical Ion Heating during Magnetic Reconnection," Phys. Rev. Lett. **84** (April 2000) 3859-3862; Princeton Plasma Physics Laboratory Report PPPL-3389 (November 1999) 12.

*Hwang, D.Q., McLean, H.S., Baker, K.L. Evans, R.W., Horton, R.D., Terry, S.D., Howard, S., and Schmidt, G.L., "Interaction of a Spheromak-like Compact Toroid with a High Beta Spherical Tokamak Plasma," Nucl. Fusion **40** (May 2000) 897-905.

Jardin, S.C., "Timescales for Non-inductive Current Buildup in Low-aspect-ratio Toroidal Geometry," Nucl. Fusion **40** (June 2000) 1101-1112; Princeton Plasma Physics Laboratory Report PPPL-3393 (November 1999) 31 pp.

§Jardin, S.C., Bathke, C.G., Ehst, D.A., Kaye, S.M., Kessel, Jr. C.E., Lee, B.J., Mau, T.K., Menard, J., Miller, R., and Najmabadi, F., "Physics Basis for a Tokamak Fusion Power Plant," submitted to Fusion Engineering and Design.

Jardin, S.C., Kaye, S., Kessel, C., and Glasser, A.H., "Tokamak Simulation Code Modeling of NSTX," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 1549-1552 (P4_078.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001). Princeton Plasma Physics Laboratory Report PPPL-3472 (July 2000) 4 pp.

§Jardin, S.C., Kessel, C.E., Menard, J., Mau, T.K., Miller, R., Najmabadi, F., Chan, V., Lao, L., Linliu, Y.R., Miller, R.L., Petrie, T., Politzer, P., and Turnbull, A.D., "Physics Basis for a Spherical Torus Power Plant," Princeton Plasma Physics Laboratory Report PPPL-3392 (November 1999) 71 pp; submitted to Fusion Engineering and Design.

Jardin, S.C., Schmidt, G.L., Fredrickson, E.D., Hill, K.W., Hyun, J., Merrill, B.J., and Sayer, R., "A Fast Shutdown Technique for Large Tokamaks," Nucl. Fusion **40** (May 2000) 923-933; Princeton Plasma Physics Laboratory Report PPPL-3356 (September 1999) 20 pp.

§Jassby, D.L. and Schmidt, J.A., "Electrical Energy Requirements for ATW and Fusion," Princeton Plasma Physics Laboratory Report PPPL-3438 (February 2000) 11 pp; submitted as a Technical Note for Fusion Technology.

Johnson, D., Kaita, R., Roquemore, A.L., and the NSTX Team, "Diagnostic Development on NSTX," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 81-86 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050); Princeton Plasma Physics Laboratory Report PPPL-3406 (December 19999) 6 pp.

†Johnson, D.W., LeBlanc, B.P., Long, D.L., and Renda, G., "APD Detector Electronics for the NSTX Thomson Scattering System," presented at the *13th Topical Conference on High Temperature Diagnostics Plasma* (Tucson, Arizona, June 18-22, 2000), conference proceedings to be published in Review of Scientific

Instruments; Princeton Plasma Physics Laboratory Report PPPL-3480 (August 2000) 13 pp.

§Johnson, Jay R. and C.Z. Cheng, "Signatures of Mode Conversion and Kinetic Alfvén Waves at the Magnetopause," Princeton Plasma Physics Laboratory Report PPPL-3477 (July 2000) 7 pp; submitted to Geophysical Research Letters.

Kaita, R., Efthimion, P., Hoffman, D., Jones, B., Kugel, H., Majeski, R., Munsat, T., Raftopoulos, S., Taylor, G., Timberlake, J., Soukhanovskii, V., Stutman, D., Iovea, M., Finkenthal, M., Doerner, R., Luckhardt, S., Maingi, R., and Causey, R., "Diagnostics for Liquid Lithium Experiments in CDX-U," Princeton Plasma Physics Laboratory Report PPPL-3455 (June 2000) 9 pp; submitted to Review of Scientific Instrument.

Kaita, R., Majeski, R., Luckhardt, S., Doerner, R., Finkenthal, M., Ji, H., Kugel, H., Mansfield, D., Stutman, D., Woolley, R., Zakharov, S., and Zweben, S., "Liquid Lithium Wall Experiments in CDX-U," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 127-130 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050); Princeton Plasma Physics Laboratory Report PPPL-3373 (October 1999) 4 pp.

Karasik, Max, "Driven Motion and Instability of an Atmospheric Pressure Arc," Ph.D. Thesis (1999), Princeton University, Princeton, New Jersey; Princeton Plasma Physics Laboratory Report PPPL-3398 (December 1999) 167 pp.

Karasik, M., Roquemore, A.L., and Zweben, S.J., "Experiment and Modeling of an Atmospheric Pressure Arc in an Applied Oscillating Magnetic Field," Phys. Plasmas 7 (June 2000) 2715-2727.

§Karasik, M. and Zweben, S.J., "Experiments and Modeling of an Instability of an Atmospheric Pressure Arc," Phys. Plasmas 7 (October 2000) 4326-4340.

Kaye, S.M., Bell, M.G., Bell, R.E., Gates, D., Maingi, R., Mazzucato, E., Menard, J., Mueller, D., Park, W., Paul, S., Sabbagh, S., and Stutman, D., "Operational Limits in the National Spherical Torus Experiment," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 1437-1440 (P4_046.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001). Princeton Plasma Physics Laboratory Report PPPL-3454 (June 2000) 4 pp.

*Kelliher, D.J., McCarthy, P.J., Baranov, Y., Christiansen, J.P., Hawkes, N.C., Stratton, B.C., and Stubberfield, P., "Consistency of Current Profile Recovery on JET using TRANSP and EFIT Codes," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 1489-1492 (P4_062.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001).

Kessel, C.E. and Bulmer, R.H., "Poloidal Field Design and Plasma Scenarios for FIRE," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 176-179 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050); Princeton Plasma Physics Laboratory Report PPPL-3370 (October 1999) 8 pp.

*Kolesnichenko, Ya.I., Lutsenko, V.V., White, R.B., and Yakovenko, Yu.V., "Effect of Sawtooth Oscillations on Energetic Ions," Nucl. Fusion **40** (July 2000) 1325-1341 {presented at the *6th International Atomic Energy Agency (IAEA) Technical Committee Meeting on Energetic Particles in Magnetic Confinement Systems* [Japan Atomic Energy Research Institute (JAERI), Naka, Japan, October, 12-14, 1999]}; Princeton Plasma Physics Laboratory Report PPPL-3404 (December 1999) 36 pp.

*Kolesnichenko, Ya.I., Lutsenko, V.V., White, R.B., and Yakovenko, Yu.V., "Expulsion of Energetic Ions from the Plasma Core in the Presence of Sawtooth Oscillations in Spherical Tokamaks," presented at the *International Atomic Energy Agency (IAEA) Coordinated Research Project "Comparison of Compact Toroid Configuration"* (IAEA Headquarters, Vienna, July, 10-14, 2000); Princeton Plasma Physics Laboratory Report PPPL-3484 (August 2000) 6 pp.

*Kolesnichenko, Ya.I., Lutsenko, V.V., White, R.B., and Yakovenko, Yu.V., "Small-action Particles in a Tokamak in the Presence of an n=1 Mode," Phys. Rev. Lett. **84** (Mar 2000) 2152-2155; Princeton Plasma Physics Laboratory Report PPPL-3376 (November 1999) 7 pp.

*Kondo, T., Isobe, M., Sasao, M., Darrow, D.S., Toi, K., Takechi, M., Matsunaga, G., Osakabe, M., Yoshimura, Y., Takahashi, C., Nishimura, S., Okamura, S., Matsuoka, K., and CHS Group, "Observation of MHD-induced Fast Ion Losses on the CHS Heliotron/Torsatron," Nucl. Fusion **40** (September 2000) 1575-1586.

*Kotschenreuther, M., Dorland, W., Liu, Q.P., Zarnstorff, M.C., Miller, R.L., Lin-Liu, Y.R., "Attaining Neoclassical Transport in Ignited Tokamaks," Nucl. Fusion **40**, Yokohama Special Issue 3 (March 2000) 677-684.

*Kramer, G.J., Iwase, M., Kusama, Y., Morioka, A., Nemoto, M., Nishitani, T., Shinohara, K., Takeji, S., Tobita, K., Ozeki, T., Cheng, C.Z., Fu, G.-Y., and Nazikian, R., "Fast Particle Experiments in JT-60U," Nucl. Fusion **40** (July 2000) 1383-1396.

§Krommes, John A., "Recent Results on Analytical Plasma Turbulence Theory: Realizability, Intermittency, Submarginal Turbulence, and Self-organized Criticality," Princeton Plasma Physics Laboratory Report PPPL-3420 (January 2000) 14 pp; submitted to Plasma Physics and Controlled Fusion.

Krommes, John A., "Renormalized Dissipation in the Nonconservatively Forced Burgers Equation," Phys. Plasmas 7 (March 2000) 1064-1067; Princeton Plasma Physics Laboratory Report PPPL-3422 (January 2000) 4 pp.

Krommes, John A., "Self-organized Criticality, Long-time Correlations, and the Standard Transport Paradigm," Phys. Plasmas 7 (May 2000) 1752-1758; Princeton Plasma Physics Laboratory Report PPPL-3435 (February 2000) 8 pp.

Krommes, John A., "The Roles of Shear and Cross-correlations on the Fluctuation Levels in Simple Stochastic Models," Phys. Plasmas 7 (April 2000) 1148-1157; Princeton Plasma Physics Laboratory Report PPPL-3377 (November 1999; Revised February 2000) 12 pp.

§Krommes, John A. and Kim, Chang-Bae, "Interactions of Disparate Scales in Drift-wave Turbulence," Phys. Rev. E **62** (December 2000) 8508-8539.

§Krommes, John A. and Ottaviani, Maurizio, "Long-time Tails Do Not Necessarily Imply Self-organized Criticality or the Breakdown of the Standard Transport Paradigm," Princeton Plasma Physics Laboratory Report PPPL-3421 (January 2000) 4 pp; submitted to Physics of Plasmas.

Ku, L.P., Fu, G.Y., Monticello, D., and Reiman, A., "Properties of High-Beta, Quasi-

Axisymmetric NCSX Stellarator Configurations," presented at the *12th International Stellarator Workshop* (Madison, Wisconsin, September 27 - October 1, 1999). The workshop paper is available in pdf format at the following web site: http://hsxa.ece.wisc.edu/Stell_workshop/Papers-pdf/Ku_properties-of-high-beta-QAS-NCSX-configurations.pdf (active as of July 8, 2001); Princeton Plasma Physics Laboratory Report PPPL-3484 (November 1999) 11 pp.

Kugel, H.W., Blanchard, W., D'Amico, G., Gernhardt, R., and Provost, T., "NSTX Filament Preionization and Glow Discharge Cleaning Systems," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 296-299 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050); Princeton Plasma Physics Laboratory Report PPPL-3381 (November 1999) 4 pp.

†Kugel, H.W., Loesser, D., Roquemore, A.L., Menon, M.M., and Barry, R.E., "Precision Metrology of NSTX Surfaces using Coherent Laser Radar Ranging," presented at the *13th Topical Conference on High Temperature Diagnostics Plasma* (Tucson, Arizona, June 18-22, 2000), conference proceedings to be published in Review of Scientific Instruments; Princeton Plasma Physics Laboratory Report PPPL-3467 (July 2000) 14 pp.

Kugel, H.W., Maingi, R., Wampler, W., Berry, R.E., Bell, M., Blanchard, W., Gates, D., Johnson, D., Kaita, R., Kaye, S., Maqueda, R., Menard, J., Menon, M.M., Mueller, D., Ono, M., Paul, S., Peng, Y-K M., Raman, R., Roquemore, A., Skinner, C.H., Sabbagh, S., Stratton, B., Stutman, D., Wilson, J.R., Zweben, S., and the NSTX National Research Team, "Overview of Impurity Control and Wall Conditioning in NSTX," presented at the *14th International Conference on Plasma Surface Interaction in Controlled Fusion Devices* (Rosenheim, Germany, May 26-30, 2000); Princeton Plasma Physics Laboratory Report PPPL-3469 (July 2000) 19 pp.

Kugel, H.W., McCormack, B., Kaita, R., Goranson, P., Guttadora, L., Hatcher, R., Holoman, T., Johnson, D., Nelson, B., Neumeyer, C., and Roquemore, A.L., "NSTX High Temperature Sensor Systems," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 300-305 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050); Princeton Plasma Physics Laboratory Report PPPL-3380 (November 1999) 6 pp.

Kulsrud, Russell M., "The Origin of Galactic Magnetic Fields," in **Plasmas in the Universe**, the proceedings of the *International School of Physics "Enrico Fermi"* (Varenna on Lake Como, Villa Monastero, July 6-16, 1999) edited by B. Coppi, A. Ferrari, and E. Sindoni (IOS Press, Washington, DC, 2000) 107-125.

*Kusama, Y., Kramer, G.J., Kimura, H., Saigusa, M., Ozeki, T., Tobita, K., Oikawa, T., Shinohara, K., Kondoh, T., Moriyama, M., Tchernychev, F.V., Nemoto, M., Morioka, A., Iwase, M., Isei, N., Fujita, T., Takeji, S., Kuriyama, M., Nazikian, R., Fu, G.Y., Hill, K.W., and Cheng, C.Z., "Characteristics of Alfvén Eigenmodes, Burst Modes and Chirping Modes in the Alfvén Frequency Range Driven by Negative Ion Based Neutral Beam Injection in JT-60U," Nucl. Fusion **39**, Yokohama Special Issue 2 (November 1999) 1837-1843.

Leng, Lufeng, "High-Speed Fiber-Based Modules for TDM/WDM Soliton Systems," Ph.D. Thesis (1999), Princeton University, Princeton, New Jersey.

Lewandowski, J.L.V., "Drift Wave Simulations in Stellarator Geometry," Phys. Plasmas 7 (August 2000) 3360-3368; "Drift Waves in General Toroidal Geometry," Princeton Plasma Physics Laboratory Report PPPL-3433 (February 2000) 29 pp.

Lewandowski, J.L.V., "Drift Wave Simulations with Reduced Stellarator Equilibria," Phys. Plasmas **6** (December 1999) 4788-4790; Princeton Plasma Physics Laboratory Report PPPL-3400 (December 1999) 12 pp.

Lewandowski, J.L.V., "Hybrid Model for Drift Waves in Fully Three-dimensional Plasmas: Theory and Applications," Aust. J. Phys. **53** (2000) 259-287.

Lewandowski, J.L.V., "Visualization of Magnetically Confined Plasmas," Princeton Plasma Physics Laboratory Report PPPL-3401 (December 1999) 36 pp; submitted to Computing and Visualization in Science.

Lewandowski, J.L.V., Lin, Z., Lee, W.W., and Hahm, T.S., "Sheared-flow Modes in Toroidal Geometry," Phys. Plasmas 7 (February 2000) 588-595; Princeton Plasma Physics Laboratory Report PPPL-3374 (October 1999) 21 pp.

Lin, Z., Hahm, T.S., Lee, W.W., Tang, W.M., and White, R.B., "Gyrokinetic Simulations in General Geometry and Applications to Collisional Damping of Zonal Flows," Phys. Plasmas 7 (May 2000) 1857-1862; Princeton Plasma Physics Laboratory Report PPPL-3437 (February 2000) 7 pp.

*Maingi, R., Kugel, H., Gates, D., Johnson, D., Kaita, R., Kaye, S., Macqueda, R., Mazzucato, E., Menard, J., Mueller, D., Paul, S., Roquemore, L., Sabbagh, S., and Skinner, C., "Initial Wall Conditioning and Impurity Control Techniques in NSTX," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 1605-1608 (P4_098.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001).

*Malkin, V.M., Shvets, G., and Fisch, N.J., "Detuned Raman Amplification of Short Laser Pulses in Plasma," Phys. Rev. Lett. **84** (February 2000) 1208-1211.

*Malkin, V.M., Shvets, G., and Fisch, N.J., "Ultra-powerful Compact Amplifiers for Short Laser Pulses," Phys. Plasmas 7 (May 2000) 2232-2240.

*Malyshkin, L., and Kulsrud, R., "Effect of Coulomb Collisions on Time Variations of the Solar Neutrino Flux," Mon. Not. R. Astron. Soc. **316** (August 2000) 249-266.

*§Malyshkin, Leonid and Kulsrud, Russell, "Transport Phenomena in Stochastic Magnetic Mirrors," Princeton Plasma Physics Laboratory Report PPPL-3486 (August 2000) 25 pp; submitted to Astrophysical Journal.

Manuilskiy, Igor and Lee, W.W., "The Split-weight Particle Simulation Scheme for Plasmas," Phys. Plasmas 7 (May 2000) 1381-1385; Princeton Plasma Physics Laboratory Report PPPL-3390 (November 1999) 13 pp.

*Mau, T.K., Jardin, S.C., Kessel, C.E., Menard, J.E., Miller, R.L., Najmabadi, F., Chan, V.S., Lao, L.L., Petrie, T.W., Politzer, P.A., and Turnbull, A.D., "Physics Basis for the AIRES-ST Power Plant," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 45-48 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050).

$Mazzucato, E., "Microwave Imaging Reflectometry for the Visualization of Turbulence in Tokamaks," Nucl. Fusion **40** (February 2001) 203-213; Princeton Plasma Physics Laboratory Report PPPL-3408 (December 1999) 22 pp.

Mazzucato, E., "High Field Tokamaks for Burning Plasma Experiments," J. Fusion Energy **18** (March 1999) 47-50; "The Importance of the Toroidal Magnetic Field for the Feasibility of a Tokamak Burning Plasma Experiment," Princeton Plasma Physics Laboratory Report PPPL-3442 (March 2000) 10 pp.

*McClements, K.G., Akers, R., Appel, L.C., Gryaznevich, M.P., Gorelenkov, N.N., and Gorelenkova, M.V., "Alfvén Eigenmodes in a Beam-assisted Ohmic START Discharge," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 1509-1512 (P4_067.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001).

McCormack, B., Kaita, R., Kugel, H., and Hatcher, R., "Rogowski Loop Designs for NSTX," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 306-309 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050); Princeton Plasma Physics Laboratory Report PPPL-3415 (January 2000) 5 pp.

Meade, D.M., Thome, R.J., Sauthoff, N.R., Heitzenroeder, P.J., Nelson, B.E., Ulrickson, M.A., Kessel, C.E., Schultz, J.H., Rutherford, P.H., Wesley, J.C., Young, K.M., Nevins, W.M., Uckan, N.A., and Schmidt J.A., "Physics Basis for the Fusion Ignition Research Experiment (FIRE)," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 1449-1452 (P4_049.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001). Princeton Plasma Physics Laboratory Report PPPL-3466 (July 2000) 4 pp.

Meade, Dale, "Fusion Ignition Research Experiment," Comments on Modern Phys. **2** (February 2000) C81-C97; Princeton Plasma Physics Laboratory Report PPPL-3471 (July 2000) 11 pp.

Menard, J., Fredrickson, E., Gates, D., Goldston, R., Kaye, S., Kugel, H., Maingi, R., Maqueda, R., Mueller, D., Paul, S., Sabbagh, S.A., and Stutman, D., "Flux Consumption Optimization and the Achievement of 1 MA Discharges on NSTX," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 1441-1444 (P4_047.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001).

*Menon, M.M., Barry, R.E., Skinner, C.H., and Gentile, C., "Study of the Surface Features on the TFTR Inner Limiter using a Frequency Modulated Coherent Laser Radar Device Developed for ITER," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 261-263 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050).

Monticello, D., Hirshman, S., and Reiman, A., "PIES Applications to NCSX," presented at the *12th International Stellarator Workshop* (Madison, Wisconsin, September 27 - October 1, 1999). The workshop paper is available in pdf format at the following web site: http://hsxa.ece.wisc.edu/Stell_workshop/Papers-pdf/Monticello_PIES-applications-to-NCSX.pdf (active as of July 8, 2001); Princeton Plasma Physics Laboratory Report PPPL-3359 (October 1999) 15 pp.

Munsat, T. and Majeski, R., "An Inexpensive Ohmic Transformer Firing Circuit for the CDX-U Spherical Torus," Princeton Plasma

Physics Laboratory Report PPPL-3367 (October 1999) 13 pp; submitted to Review of Scientific Instruments.

§Munsat, Tobin, "High-temperature Carbon-irradiation Issues for the Sombrero ICF Reactor," Fusion Engineering and Design 54 (February 2001) 249-262; Princeton Plasma Physics Laboratory Report PPPL-3366 (October 1999) 30 pp.

Mynick, H.E. and Pomphrey, N., "Control-Matrix Approach to NCSX Design," paper presented at the *12th International Stellarator Workshop* (Madison, Wisconsin, September 27 - October 1, 1999). The workshop paper is available in pdf format at the following web site: http://hsxa.ece.wisc.edu/Stell_workshop/Papers-pdf/Mynick_Control-matrix-approach-to-NCSX-design.pdf (active as of July 8, 2001); Princeton Plasma Physics Laboratory Report PPPL-3365 (October 1999) 15 pp.

§Mynick, H.E. and Pomphrey, N., "Control-Matrix Approach to Stellarator Design and Control," Phys. Plasmas 7 (December 2000) 4960-4971; Princeton Plasma Physics Laboratory Report PPPL-3434 (February 2000) 35 pp.

Nazikian, R., Gorelenkov, N.N., Budny, R.V., Cheng, C.Z., and Fu, G-Y., "Resonant Toroidal Alfvén Eigenmodes (RTAEs) in Neutral Beam Heated Reverse Magnetic Shear Plasmas on TFTR," presented at the *6th International Atomic Energy Agency (IAEA) Technical Committee Meeting on Energetic Particles in Magnetic Confinement Systems* [Japan Atomic Energy Research Institute (JAERI), Naka, Japan, October, 12-14, 1999] and to be published in the conference proceedings; Princeton Plasma Physics Laboratory Report PPPL-3387 (November 1999) 4 pp.

Neilson, G.H., Reiman, A.H., Zarnstorff, M.C., Brooks, A., Fu, G.-Y., Goldston, R.J., Ku, L.-P., Lin, Z., Majeski, R., Monticello, D.A., Mynick, H., Pomphrey, N., Redi, M.H., Reiersen, W.T., Schmidt, J.A., Boozer, A.H., Miner, Jr., W.H., Valanju, P.M., Cooper, W.A., Drevlak, M., Merkel, P., and Nuehrenberg, C., "Physics Issues in the Design of High-beta, Low-aspect-ratio Stellarator Experiments," Phys. Plasmas 7 (May 2000) 1911-1918; "Physics Basis for High-Beta, Low-Aspect-Ratio Stellarator Experiments," Princeton Plasma Physics Laboratory Report PPPL-3397 (November 1999) 21 pp.

*Nelson, B., Burgess, T., Brown, T., Fan, H., and Heitzenroeder, P., "Fusion Ignition Research Experiment Vacuum Vessel Design and Configuration," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 459-462 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050).

Neumeyer, C. and the NSTX Team, "National Spherical Torus Experiment (NSTX) Construction, Commissioning, and Initial Operations," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 63-66 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050); Princeton Plasma Physics Laboratory Report PPPL-3414 (December 2000) 4 pp.

Neumeyer, C., Hatcher, R., Marsala, R., and Ramakrishnan, S., "National Spherical Torus Experiment (NSTX) Power Supply Real Time Controller," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 285-288 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050); Princeton Plasma Physics Laboratory Report PPPL-3413 (January 2000) 5 pp.

§Neumeyer, C., Heitzenroeder, P., Spitzer, J., Chrzanowski, J., Brooks, A., Bialek, J., Fan, H.M., Barnes, G., Viola, M., Nelson, B., Goranson, P., Wilson, R., Fredd, E., Dudek, L., Parsells, R., Kalish, M., Blanchard, W., Kaita, R., Kugel, H., McCormack, B., Ramakrishnan, S., Hatcher, R., Oliaro, G., Perry, E., Egebo, T., von Halle, A., Williams, M., and Ono, M., "Engineering Design of the National Spherical Torus Experiment," Fusion Engineering Design **54** (February 2001) 275-319; Princeton Plasma Physics Laboratory Report PPPL-3446 (May 2000) 78 pp.

Ono, Masayuki and the NSTX Team, "National Spherical Torus Experiment (NSTX)," Princeton Plasma Physics Laboratory Report PPPL-3445 (May 2000) 8 pp; submitted to Journal of Plasma and Fusion Research.

Ono, M., Kaye, S.M., Neumeyer, C., Peng, Y-K.M., Williams, M., Barnes, G., Bell, M., Bialek, J., Bigelow, T., Blanchard, W., and 50 other coauthors plus the NSTX Team, "Making of the NSTX Facility," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 53-38 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050); Princeton Plasma Physics Laboratory Report PPPL-3385 (November 1999) 6 pp.

Park, H., Edwards, S., Guttadora, L., Deng, B., Domier, C.W., Lee, K.C., Johnson, M., and Luhmann, Jr., N.C., "Status of Far Infrared Tangential Interferometry/Polarimetry (FIReTIP) on NSTX," presented at the *24th International Infrared and Millimeter Waves (IR&M) Conference* (Beijing, China, September 11-15, 2000); Princeton Plasma Physics Laboratory Report PPPL-3485 (August 2000) 6 pp.

Park, W., Belova, E.V., Fu, G.Y., Tang, X.Z., Strauss, H.R., and Sugiyama, L.E., "Plasma Simulation Studies using Multilevel Physics Models," Phys. Plasmas **6** (May 1999) 1796-1803; Princeton Plasma Physics Laboratory Report PPPL- 3423 (January 2000) 8 pp.

Parsells, R.F., Bretz, N., Dalghren, F., Dudek, L., Johnson, D., LeBlanc, B., Steill, G., Palladino, D., and Simon, D., "Multipulse Thomson Scattering System for the National Spherical Torus," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 310-312 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050).

Paul, Stephen F.; Chao, Edward H.; Davidson, Ronald C.; and Phillips, Cynthia K., "Confinement of Pure Ion Plasma in a Cylindrical Current Sheet," AIP Conference Proceedings **498** (1999) 435-444 [presented at the *1999 Workshop on Nonneutral Plasmas Physics* (Princeton, New Jersey, August 2-5, 1999)]; Princeton Plasma Physics Laboratory Report PPPL-3403 (December 1999) 10 pp.

Perkins, F.W., White, R.B., and Bonoli, P., "Generation of Plasma Rotation in a Tokamak by Ion-cyclotron Absorption of Fast Alfvén Waves," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 1-4 (or_001.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001).

Perry, E., Chrzanowski, J., Rule, K., Strykowsky, R., Viola, M., and Williams, M., "Decontamination and Decommissioning of the Tokamak Fusion Test Reactor," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 97-100 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050); Princeton Plasma Physics Laboratory Report PPPL-3395 (November 1999) 4 pp.

*Persson, M., Nadeem, M., Lewandowski, J.L.V., and Gardner, H.J., "Drift Waves in Stellarator Geometry," Plasma Phys. Control. Fusion **42** (February 2000) 203-216; Princeton Plasma Physics Laboratory Report PPPL-3431 (February 2000) 14 pp.

*Petty, C.C. and 49 other coauthors including Fredrickson, E.D., Gorelov, I., Johnson, L.C., Okabayashi, M. and Wong, K.-L., "Advanced Tokamak Physics in DIII-D," Plasma Phys. Control. Fusion **42** (December 2000) B75-B85. Invited paper from the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000).

*§Ping, Y., Geltner, I., Fisch, N.J., Shvets, G., and Suckewer, S., "Demonstration of Ultrashort Laser Pulse Amplification in Plasmas by a Counterpropagating Pumping Beam," Phys. Rev. E **62** (October 2000) R4532-R4535.

§Qin, H., Tang, W.M., and Lee, W.W., "Gyrocenter-Gauge Kinetic Theory," Phys. Plasmas **7** (November 2000) 4433-4445; Princeton Plasma Physics Laboratory Report PPPL-3482 (August 2000) 36 pp.

Qin, H., Tang, W.M., Rewoldt, G., and Lee, W.W., "On the Gyrokinetic Equilibrium," Phys. Plasmas **7** (March 2000) 991-1000.

Qin, H., Davidson, R.C., and Lee, W.W.-L., "3D Nonlinear Perturbative Particle Simulations of Two-stream Collective Processes in Intense Particle Beams," Phys. Lett. A **272** (August 2000) 389-394.

Qin, Hong; Davidson, Ronald C.; and Lee, W. Wei-li, "3D Multispecies Nonlinear Perturbative Particle Simulations of Collective Instabilities in Intense Particle Beams," presented at the *Workshop on Instabilities of High Intensity Hadron Beams in Rings* (Upton, New York, June/July 1999) and published in the conference proceedings.

*Rafikov, R.R., and Kulsrud, R.M., "Magnetic Flux Expulsion in Powerful Superbubble Explosions and the Alpha-omega Dynamo," Mon. Not. R. Astron. Soc. **314** (June 2000) 839-848.

Raitses, Y., Dorf, L.A., Litvak, A.A., and Fisch, N.J., "Plume Reduction in Segmented Electrode Hall Thruster," J. Appl. Phys. **88** (August 2000) 1263-1270; Princeton Plasma Physics Laboratory Report PPPL-3426 (January 2000) 28 pp.

Raitses, Y., Fisch, N.J., Ertmer, K.M., and C.A. Burlingame, "A Study of Cylindrical Hall Thruster for Low Power Space Applications," presented at the *36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, (Huntsville, Alabama, July 16-19, 2000) and submitted for publication in the Journal of Propulsion and Power; Princeton Plasma Physics Laboratory Report PPPL-3479 (July 2000) 10 pp.

Ramakrishnan, S., Neumeyer, C., Baker, E., Hatcher, R., Ilic, A., Marsala, R., O'Neill, D., and von Halle, A., "NSTX Electrical Power Systems," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 281-284 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050); Princeton Plasma Physics Laboratory Report PPPL-3407 (December 1999) 4 pp.

*Raman, R., Jarboe, T.R., Mueller, D., Schaffer, M.J., Maqueda, R., Nelson, B.A., Sabbagh, S., Bell, M., Ewig, R., Fredrickson, E., Gates, D., Hosea, J., Ji, H., Kaita, R., Kaye, S.M., Kugel, H., Maingi, R., Menard, J., Ono, M., Orvis, D., Paul, S., Peng, M., Skinner, C.H., Wilgen, J.B., Zweben, S., and the NSTX Research Team, "Coaxial Helicity Injection for the Generation of Non-inductive Current in NSTX," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Buda-

pest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 636-639 (P2_050.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001).

Redi, M.H., Cooper, W.A., Diallo, A., Fu, G-Y., Nuhrenberg, C., Reiman, A.H., White, R.B., Zarnstorff, M.C., and the NCSX Team, "Stability and Transport in Compact Quasi-Axisymmetric Stellarators," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 1445-1448 (P4_048.dpf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001). Princeton Plasma Physics Laboratory Report PPPL-3465 (July 2000) 4 pp.

Redi, M.H., Diallo, A., Cooper, W.A., Fu, G.Y., Johnson, J.L., Nührenberg, C., Pomphrey, N., Reiman, A.H., White, R.B., Zarnstorff, M.C., and the NCSX Team, "Robustness and Flexibility in NCSX: Global Ideal MHD Stability and Energetic Particle Transport," presented at the *12th International Stellarator Workshop* (Madison, Wisconsin, September 27 - October 1, 1999). The workshop abstract is available in pdf format at the following web site: http://hsxa.ece.wisc.edu/Stell_workshop/Papers-pdf/Redi_Robustness-and-flexibility-in-NCSX_Global-ideal-MHD-stability-and-energetic-particle-transport.pdf (active as of July 8, 2001); Princeton Plasma Physics Laboratory Report PPPL-3358 (October 1999) 5 pp.

Redi, M.H., Diallo, A., Cooper, W.A., Fu, G.Y., Johnson, J.L., Nührenberg, C., Pomphrey, N., Reiman, A.H., White, R.B., Zarnstorff, M.C., and the NCSX Team, "Robustness and Flexibility in Compact Quasi-axial Stellarators: Global Ideal MHD Stability and Energetic Particle Transport," Phys. Plasmas 7 (June 2000) 2508-2526; Princeton Plasma Physics Laboratory Report PPPL-3429 (January 2000) 40 pp. — PPPL-3429 is an expanded version of PPPL-3351 (July 1999) 5 pp and PPPL-3358 (October 1999) 5 pp.

Reiersen, W., Dahlgren, F., Fan, H-M., Neumeyer, C., and Zata, I., "The Toroidal Field Coil Design for ARIES-ST," Princeton Plasma Physics Laboratory Report PPPL-3424 (January 2000) 4 pp.

Reiersen, W.T., Brooks, A., Brown, T., Cole, M., Fan, H-M., Goranson, P., Heitzenroeder, P., Nelson, B., and Williamson, D., "Progress in the Engineering Design of the National Compact Stellarator Experiment (NCSX)," Princeton Plasma Physics Laboratory Report PPPL-3425 (January 2000) 4 pp.

Reiman, A., Fu, G., Hirshman, S., Ku, L., Monticello, D., Mynick, H., Redi, M., and 28 additional coauthors, "Physics Design of a High Beta Quasi-Axisymmetric Stellarator," presented at the *12th International Stellarator Workshop* (Madison, Wisconsin, September 27 - October 1, 1999). The workshop paper is available in pdf format at the following web site: http://hsxa.ece.wisc.edu/Stell_workshop/Papers-pdf/Reiman_Physics-design-of-a-high-beta-quasi-axisymmetric-stellarator.pdf (active as of July 8, 2001).

Rewoldt, G., Ku, L.-P., Tang, W.M., and Cooper, W.A., "Drift Mode Calculations in Nonaxisymmetric Geometry," Phys. Plasmas **6** (December 1999) 4705-4713.

§Rewoldt, G., Ku, L.-P., Tang, W.M., Sugama, H., Nakajima, N., Watanabe, K.Y., Murakami, S., Yamada, H., and Cooper, W.A., "Drift Mode Calculations for the Large Helical Device," Phys. Plasmas 7 (December 2000) 4942-4947; Princeton Plasma Physics Laboratory Report PPPL-3451 (June 2000) 17 pp.

*Rice, B.W., Burrell, K.H., Ferron, J.R., Greenfield, C.M., Jackson, G.L., Lao, L.L., La Haye, R.J., Luce, T.C., Stallard, B.W., Strait, E.J., Synakowski, E.J., Taylor, T.S., Turnbull, A.D., and Wade, M.R., “Progress Towards Sustainment of Advanced Tokamak Modes in DIII-D,” Nucl. Fusion **39**, Yokohama Special Issue 2 (November 1999) 1855-1864.

Rule, Keith; Perry, Erik; Larson, S.; Viola, M.; Madaris, Susan; Rose, Robert; and Jenkins, Nicholas, “Demonstrating Diamond Wire Cutting of the TFTR,” presented at the *Waste Management Symposium 2000* (Tuscon, Arizona, February 27 - March 2, 2000); Princeton Plasma Physics Laboratory Report PPPL-3439 (February 2000) 13 pp.

*Sabbagh, S.A., Bell, M., Bitter, M., Gates, D., Kaye, S.M., Lao, L.L., Maingi, R., Maqueda, R., Menard, J., Mueller, D., Paoletti, F., Stutman, D., and Wurden, G.A., “Investigation of Experimental Equilibrium Domain in NSTX Ohmic Plasmas,” in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 229-232 (P1_043.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001).

Schekochihin, Alexander A. and Kulsrud, Russell M., “Finite Correlation Time Effects in Kinematic Dynamo Problem,” presented at the *Sherwood International Fusion Theory Conference* (Los Angeles, California, March 27-29, 2000); Princeton Plasma Physics Laboratory Report PPPL-3436 (February 2000) 4 pp.

*Scoville, J.T., Kellman, D.H., Pronko, S.G.E., Nerem, A., Hatcher, R., O’Neill, D., Rossi, G., and Bolha, M., “The Resistive Wall Mode Feedback Control System on DIII-D,” in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 198-201 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050).

*Shirai, H., Kikuchi, M., Takizuka, T., Fujita, T., Koide, Y., Rewoldt, G., Mikkelsen, D., Budny, R., Tang, W.M., Kishimoto, Y., Kamada, Y., Oikawa, T., Naito, O., Fukuda, T., Isei, N., Kawano, Y., Azumi, M., and the JT-60 Team,“ Reduced Transport and E_r Shearing in Improved Confinement Regimes in JT-60U,” Nucl. Fusion **39**, Yokohama Special Issue 2 (November 1999) 1713-1722.

†Shvets, G., Fisch, N.J., Pukhov, A., and Meyer-ter-Vehn, J., “Pulse Compression in Plasma: Generation of Femtosecond Pulses Without CPA,” presented at the *12th International Conference on Ultra-fast Phenomena*, (Charleston, South Carolina, July, 9-13 2000) and to be published in the conference proceedings; Princeton Plasma Physics Laboratory Report PPPL-3474 (July 2000) 3 pp.

†Shvets, G., Fisch, N.J., Pukhov, A., and Meyer-ter-Vehn, J., “Superradiant Pulse Compression using Free-carrier Plasma,” to be presented at *IEEE Lasers and Electro-optics Society 2000* (Rio Grande, Puerto Rico, 13-16 November 13-16, 2000) and to be published in the conference proceedings; Princeton Plasma Physics Laboratory Report PPPL-3473 (July 2000) 3 pp.

Sichta, P. and Dong, J., “Startup of the Experimental Physics Industrial Control System at NSTX,” in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 289-291 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050); Princeton Plasma Physics Laboratory Report PPPL-3410 (December 1999) 3 pp.

Sichta, P., Dong, J., Oliaro, G., and Tindall, K., "The NSTX Central Instrumentation and Control System," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 292-295 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050); Princeton Plasma Physics Laboratory Report PPPL-3409 (December 1999) 4 pp.

Simon, D.I., Bretz, N.L., Marmar, E., Bravenec, R., and Parsells, R.F., "Optical and Mechanical Design of C-Mod Motional Stark Effect Diagnostic," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 349-351 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050); Princeton Plasma Physics Laboratory Report PPPL-3383 (November 1999) 3 pp.

Skinner, C.H., Gentile, C.A., Ascione, G., Carpe, A., Causey, R.A., Hayashi, T., Hogan, J., Langish, S., Nishi, M., Shu, W.M., Wampler, W.R., and Young, K.M., "Studies of Tritiated Co-deposited Layers in TFTR," presented at the *14th International Conference on Plasma Surface Interaction in Controlled Fusion Devices* (Rosenheim, Germany, May 26-30, 2000); Princeton Plasma Physics Laboratory Report PPPL-3462 (June 2000) 15 pp.

Skinner, C.H., Gentile, C.A., and Young, K.M., "Observations of Flaking of Co-deposited Layers in TFTR," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 89-92 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050); Princeton Plasma Physics Laboratory Report PPPL-3379 (November 1999) 4 pp.

*Snyder, P.B., Wilson, H.R., Xu, X.Q., Chance, M.S., Chu, M.S., Ferron, J.R., Lao, L.L., Strait, E.J., and Turnbull, A.D., "Full Spectrum Stability Analysis of the Tokamak Edge Region," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 324-327 (P1_080.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001).

*Spong, D.A., Hirshman, S.P., Whitson, J.C., Batchelor, D.B., Sanchez, R., Carreras, B.A., Lynch, V.E., Lyon, J.F., Valanju, P.M., Miner, W.H., Moroz, P.E., Zarnstorff, M.C., Monticello, D.A., Ware, A.S., and Garcia, L., "Design Studies of Low Aspect Ratio Quasi-omnigenous Stellarators," Nucl. Fusion **40**, Yokohama Special Issue 3 (March 2000) 563-567.

*Starostin, A.N., Savchenko, V.I., and Fisch, N.J., "Effect of Quantum Uncertainty on the Rate of Nuclear Reactions in the Sun," Phys. Lett. A **274** (September 2000) 64-68.

§Strachan, J.D., Erents, K., Fundamenski, V., von Hellermann, M., Horton, L., Lawson, K., McCracken, G., Spence, J., Stamp, M., and Zastrow K-D., "JET Methane Screeing Experiments," submitted to Journal of Nuclear Materials.

Strasburg, Sean and Davidson, Ronald C., "Macroscopic Description of Pressure-anisotropy-driven Collective Instability in Intense Charged Particle Beams," Phys. Lett. A **269** (April 2000) 40-49; Princeton Plasma Physics Laboratory Report PPPL-3448 (June 2000) 23 pp.

Strasburg, Sean and Davidson, Ronald C., "Production of Halo Particles by Excitation of Collective Modes in High-intensity Charged Particle Beams," Phys. Rev. E **61** (May 2000) 5753-5766.

*Strait, E.J., Garofalo, A.M., Austin, M.E., Bialek, J.M., Chu, M.S., Fredrickson, E.D., Lao, L.L., LaHaye, R.J., Lazarus, E.A., McKee, G., Navratil, G.A., Okabayashi, M., Rice, B.W., Sabbagh, S.A., Scoville, J.T., Taylor, T.S., Turnbull, A.D., Walker, M.L., and the DIII-D Team, "Observation and Control of Resistive Wall Modes," Nucl. Fusion **39**, Yokohama Special Issue 2 (November 1999) 1977-1982.

*Swain, D.W., Carter, M.D., and Majeski, R.P., "Plasma Heating and Current Drive Systems for the Fusion Ignition Research Experiment (FIRE)," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 467-470 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050).

*Swain, D.W., Wilson, J.R., Ryan, P.M., Pinsker, R.I., Carter, M.D., Gates, D., Hosea, J.C., Maqueda, R., Menard, J.E., Mueller, D., Sabbagh, S.A., Stutman, D., and Wilgen, J.B., "Results of High-harmonic Fast Wave Experiments on NSTX," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 808-811 (P2_108.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001).

Tang, W.M., "IAEA Theory Summary for the 1998 IAEA Meeting, Yokohama, Japan — October 17-24, 1998," in the proceedings of the *17*th International Atomic Energy Agency (IAEA) Conference on *Fusion Energy 1998* (Yokohama, Japan, October 19-24, 1998) Vol. 4 (IAEA, Vienna, 1999) 1655-1663; Princeton Plasma Physics Laboratory Report PPPL-3481 (August 2000) 9 pp.

Tang, X.Z. and Boozer, A.H., "Anisotropies in Magnetic Field Evolution and Local Lyapunov Exponents," Phys. Plasmas 7 (April 2000) 1113-1124; Princeton Plasma Physics Laboratory Report PPPL-3417 (January 2000) 35 pp.

†Taylor, G., Efthimion, P., Jones, B., Munsat, T., Spaleta, J., Hosea, J., Kaita, R., Majeski, R., and Menard, J., "Electron Bernstein Wave Electron Temperature Profile Diagnostic (invited)," presented at the *13th Topical Conference on High Temperature Diagnostics Plasma* (Tucson, Arizona, June 18-22, 2000), conference proceedings to be published in Review of Scientific Instruments; Princeton Plasma Physics Laboratory Report PPPL-3476 (July 2000) 27 pp.

*Toi, K., and 46 named authors including Darrow, D.S., and the LHD Experimental Groups, "Energetic Ion Driven MHD Instabilities Observed in the Heliotron/Torsatron Devices Compact Helical System and Large Helical Device," Nucl. Fusion **40** (July 2000) 1349-1362.

§Uzdensky, D.A. and Kulsrud, R.M., "Two-dimensional Numerical Simulation of the Resistive Reconnection Layer," Phys. Plasmas 7 (October 2000) 4018-4030; Princeton Plasma Physics Laboratory Report PPPL-3478 (July 2000) 32 pp.

*Wampler, W.R., Skinner, C.H., Pitcher, C.S., LaBombard, B., Lipschultz, B., and Fiore, C., "Long Term Retention of Deuterium and Tritium in Alcator C-Mod," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 267-270 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050).

*Werner, Andreas; Weller, Arthur; and Darrow, Douglass S., "Fast Ion Losses in the W7-AS," in the proceedings of the *27th Eu-*

ropean Physical Society Conference on Controlled Fusion and Plasma Physics (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 998-992 (P3_038.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001).

White, R.B., Perkins, F.W., and Bonoli, P., "Generation of Plasma Rotation in a Tokamak by Ion-Cyclotron Absorption of Fast Alfvén Waves," submitted to Physical Review Letters.

White, R.B., Perkins, F.W., Garbet, X., Bourdelle, C., Basiuk, V., and Eriksson, L.G., "Rotation and Particle Loss in Tore Supra," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 1457-1460 (P4_051.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001). Princeton Plasma Physics Laboratory Report PPPL-3460 (June 2000) 4 pp.

*Williamson, D., Brooks, A., Brown, T., Cole, M., Fan, H.-M., Goranson, P., Hechler, M., Heitzenroeder, P., Nelson, B., and Reiersen, W.T., "Design Description of the Saddle Coils for the National Compact Stellarator Experiment (NCSX)," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 441-444 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050).

Wong, K.L., Chu, M.S., Luce, T.C., Petty, C.C., Politzer, P.A., Prater, R., Chen, L., Harvey, R.W., Austin, M.E., Johnson, L.C., LaHaye, R.J., and Snider, R.T., "Excitation of Internal Kink Instability during Off-axis Electron Cyclotron Heating in the DIII-D Tokamak," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 408-411 (P1_108.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001).

§Wong, K.L., Itoh, K., Itoh, S.-I., Fukuyama, A., and Yagi, M., "Short Wavelength Fluctuations and Electron Transport in TFTR," Phys. Lett. A **276** (November 2000) 5-6; Princeton Plasma Physics Laboratory Report PPPL-3487 (September 2000) 11 pp.

Woolley, Robert D., "PF and TF Power Systems for the Fusion Ignition Research Experiment (FIRE)," in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (Albuquerque, New Mexico, October 25-29, 1999) 455-458 (IEEE, Piscataway, New Jersey, USA, 1999, Catalog No. 99CH37050).

*Wukitch, S.J., Bonoli, P.T., Boivin, R., Goetz, J.A., Mazurenko, A., Nelson-Melby, E., Lee, W.D., Porkolab, M., Fiore, C., Hosea, J., Hubbard, A., Hutchinson, I.H., Marmar, E., Rice, J., Schilling, G., Taylor, G., Wilson, J.R., Wolfe, S.M., and the Alcator C-Mod Group, "Initial Results from Upgraded ICRF System on Alcator C-Mod," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 1212-1215 (P3_105.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001).

Yamada, Masaaki; Ji, Hantao; Hsu, Scott; Carter, Troy; Kulsrud, Russell; and Trintchouk, Fedor, "Experimental Investigation of the Neutral Sheet Profile during Magnetic Reconnection," Phys. Plasmas 7 (May 2000) 1781-1787; Princeton Plasma Physics Laboratory Report PPPL-3394 (November 1999) 20 pp.

Zaharia, S., Cheng, C.Z., and Johnson, J.R., "Particle Transport and Energization Associated with Substorms," J. Geophys. Res. – Space Physics **105** (August 2000) 18741-18752; Princeton Plasma Physics Laboratory Report PPPL-3388 (November 1999) 30 pp.

Zakharov, L.E., "Stabilization of Tokamak Plasma by Lithium Streams," Princeton Plasma Physics Laboratory Report PPPL-3483 (August 2000) 9 pp; submitted to Physical Review Letters.

Zakharov, L.E. and Pletzer, A., "Theory of Perturbed Equilibria for Solving the Grad-Shafranov Equation," Phys. Plasmas **6** (December 1999) 4693-4704.

Zweben, S., Maqueda, R., Hill, K., Johnson, D., Kaye, S., Kugel, H., Levinton, F., Maingi, R., Roquemore, L., Sabbagh, S., and Wurden, G., "Visible Imaging of Edge Turbulence in NSTX," in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Budapest, Hungary, June 12-16, 2000), edited by K. Szegö, T.N. Todd, and S. Zoletnik, Europhysics Conference Abstracts (ECA) Vol. **24B** (European Physical Society, 2000) 836-839 (P2_118.pdf). The conference proceedings is available in pdf format at http://www.eps2000.kfki.hu (active as of July 13, 2001). Princeton Plasma Physics Laboratory Report PPPL-3464 (June 2000) 5 pp.

Zweben, S.J., Caird, J., Davis, W., Johnson, D.W., and LeBlanc, B., "Plasma Turbulence Imaging using High-Power Laser Thomson Scattering," Princeton Plasma Physics Laboratory Report PPPL-3461 (June 2000) 19 pp; submitted to Review of Scientific Instruments.

Zweben, Stewart and Karasik, Max, "Laboratory Experiments on Arc Deflection and Instability" Princeton Plasma Physics Laboratory Report PPPL-3441 (March 2000) 31 pp; submitted for publication in Iron and Steelmaker Magazine.

Princeton Plasma Physics Laboratory scientists collaborated with other national and international fusion institutions in fiscal year 2000. Their names were included in the author list of papers published by these institutions. A number of collaborative papers not listed in this publication list can be found in the proceedings of the *27th European Physical Society Conference on Controlled Fusion and Plasma Physics* (the proceedings of this conference is available in pdf format at http://www.eps2000.kfki.hu — active as of July 13, 2001) and in the proceedings of the *18th IEEE/NPSS Symposium on Fusion Engineering — SOFE99* (published by IEEE, Piscataway, NJ, USA, 1999, Catalog No. 99CH37050).

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)
ARIES	Advanced Reactor Innovation Evaluation Studies
ASDEX	Axially Symmetric Divertor Experiment (at the Max-Planck-Institut für Plasmaphysik, Garching, Germany)
B_t	Toroidal Magnetic Field
BEST	Beam Equilibrium Stability and Transport Code
CAD	Computer-aided Design
CADD	Computer-aided Design and Drafting
CCD	Charge-coupled Device
CDX-U	Current Drive Experiment-Upgrade at the Princeton Plasma Physics Laboratory
CHI	Coaxial Helicity Injection
CIC	Charge Injection Corporation
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-DI 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
EFIT	An equilibrium code
ELMy	Edge Localized Modes
EPM	Energetic Particle Mode
ER/WM	Environmental Restoration and Waste Management
eV	Electron Volt
FAC	Field-aligned Current
FESAC	Fusion Energy Sciences Advisory Committee
FIRE	Fusion Ignition Research Experiment (a national design study collaboration)
FPT	Fusion Physics and Technology, Inc.
FRC	Field-reversed Configuration
FTP	File Transfer Protocol
FY	Fiscal Year
GA	General Atomics in San Diego, California
GDC	Glow Discharge Cleaning
HCX	High Current Experiment at the Princeton Plasma Physics Laboratory
H-mode	High Confinement Mode

HHFW	High Harmonic Fast Waves
I_p	Plasma Current
ICRF	Ion Cyclotron Range of Frequencies
IDSP	Ion Dynamic Spectroscopy Probe; an optical probe used to measure local ion temperature and flows during magnetic reconnection
IMF	Interplanetary Magnetic Field
IRE	Integrated Research Experiment at the Princeton Plasma Physics Laboratory
IRE	Internal Reconnection Event
IRE	Internal Reconnection Event
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
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
OFES	Office of Fusion Energy Sciences (at the U.S. Department of Energy)
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
PPPL	Princeton Plasma Physics Laboratory in Princeton, New Jersey
PSACI	Plasma Science Advanced Scientific Computing Initiative
Q	The ratio of the fusion power produced to the power used to heat a plasma
QA	Quality Assurance
QA	Quasi-axisymmetry
QAS	Quasi-axisymmetry Stellarator
QDB	Quiescent Double Barrier
REs	Reconnection Event(s)
rf	Radio-frequency (Heating)
RI	Radiative-improved Confinement Mode
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
W7-AS	An operating stellarator in Germany
W7-X	A stellarator being built in Germany
WFOs	Work For Others
Y2K	Year 2000

July 2001

Editors: Anthony R. DeMeo and Carol A. Phillips

Contributors: M.G. Bell, T. Carter, S.A. Cohen, C.Z. Cheng, R.C. Davidson, A.R. DeMeo, P.C. Efthimion, N.J. Fisch, L.R. Grisham, R.J. Goldston, R.J. Hawryluk, M.T. Iseicz, H. Ji, D.W. Johnson, J.R. Johnson, R. Kaita, D.V. Lawson, P.R. Lucas, R.P. Majeski, D.M. Meade, L.D. Meixler, G.H. Neilson, M. Ono, M. Peng, C.A. Phillips, G. Rewoldt, N.R. Sauthoff, G. Schilling, W.M. Tang, P. Wieser, M.D. Williams, M. Yamada, and K.M. Young.

Cover Design: Gregory J. Czechowicz

Photography: Elle Starkman

Design and Layout: Gregory J. Czechowicz

The Princeton Plasma Physics Laboratory is funded by the U.S. Department of Energy under contract DE-AC02-76CH03073 and managed by Princeton University.

For additional information contact:

Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: (609) 243-2750
Fax: (609) 243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov/