Princeton Plasma Physics Laboratory
Highlights for Fiscal Year 2005

Office of Science
U.S. DEPARTMENT OF ENERGY

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

About PPPL

The Princeton Plasma Physics Laboratory (PPPL) is dedicated to developing the scientific and technological knowledge base for fusion energy as a safe, economical, and environmentally attractive energy source for the world's long-term energy requirements.

Princeton University manages PPPL under contract with the U.S. Department of Energy. The fiscal year 2005 budget was approximately $81 million. The number of full-time regular employees at the end of the fiscal year was 395, not including approximately 20 subcontractors and limited-duration employees, 38 graduate students, and visiting research staff. The Laboratory is sited on 88 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.

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

A photograph of a dust cloud of silica microspheres illuminated by laser light and suspended in a plasma. Titled "Plasma Table," it won first prize at Princeton University's "Art of Science Competition" in 2005. More than 200 entries were entered in the competition whose images came directly from research in science and engineering or were works by artists incorporating tools and concepts from science. The photograph was taken by PPPL photographer Elle Starkman in collaboration with Science Education Program Head Andrew Post-Zwicker.

This publication highlights activities at the Princeton Plasma Physics Laboratory for fiscal year 2005 — 1 October 2004 through 30 September 2005.

Mission

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

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

Vision

Deepening the understanding of plasmas and creating key innovations to make fusion power a practical reality.

Advantages of Fusion Energy

- Worldwide availability of inexhaustible low-cost fuel.
- No chemical combustion products and therefore no contribution to acid rain or global warming.
- No runaway reaction or meltdown possible.
- Materials and by-products unsuitable for weapons production.
- Radiological hazards thousands of times less than from fission.
- Compact, steady energy source without need for large-area land use, large-scale energy storage, very long-distance transmission, or local carbon dioxide sequestration.
- Fusion complements other nearer-term energy technologies.

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From the Director

Fiscal year 2005 (October 2004 — September 2005) was another year of excellent progress towards the Laboratory's goal of practical fusion energy. New diagnostics, a new coil configuration, and new control systems were brought on line for the National Spherical Torus Experiment (NSTX). These upgrades have permitted both deeper understanding and improved performance. The plasma discharge duration in NSTX was increased through improved shaping leading to the control of Edge-localized Modes. Plasma current generation without an internal transformer was dramatically demonstrated. Plasma stability was enhanced using new field-error control capabilities. The role of magnetic shear in improving electron thermal transport was studied in detail. Lithium coating was shown to be useful for density control for the first time in a diverted plasma. And last, but certainly not least, detailed measurements were made of fast-ion losses due to the excitation of a "Sea of Alfvén Modes," which are anticipated to play a role on ITER as well.

The National Compact Stellarator Experiment (NCSX) moved into the construction phase, completed key R&D, and began to receive high-quality components from industry. The R&D performed on the "twisted race-track" test winding coil paid off handsomely in allowing the coil winding team at the Princeton Plasma Physics Laboratory (PPPL) to step out confidently in our own in-house efforts.

An 18-month negotiation between Europe and Japan resulted in a win-win solution for the hosting of ITER, and Cadarache, France, near Aix-en-Provence, was selected as the site. Indicative of the importance which Europe and Japan attach to fusion, the successful offer from Europe included provision of 8% of the value of ITER for "broader approach" fusion facilities in Japan, as well as a commitment to expend 20% of Europe's investment for the construction of ITER in Japanese industry. Detailed multi-national negotiations on the ITER Joint Implementing Agreement recommenced, and PPPL played an important role in these. In parallel, in the U.S., we began R&D on the components that are anticipated to be within our area of responsibility.

Robert J. Goldston

PPPL's Theory and Advanced Simulations effort was crowned with success in a number of areas. The earlier discovery of the importance of non-local turbulence spreading provided insight into the role of edge turbulence in causing enhanced fluctuations in the core of the plasma, and studies of energetic particles have elucidated the effects of Alfvén eigenmodes both in present experiments and those expected in ITER. The PPPL Computational

Plasma Physics Group continued to expand the range of algorithms used in our codes, our access to large off-site computers, and international sharing of our advanced data analysis tools. The tools and techniques developed in fusion plasma physics continue to be prized for the understanding of space physics, in particular storms in the magnetosphere and coronal mass ejections.

Our Off-Site Research activities paid high dividends. Teaming with Columbia University and General Atomics, PPPL played a leadership role in studies of Resistive Wall Mode control on the DIII-D tokamak. This effort, coupled with the studies on NSTX, is providing the physics basis for similar capabilities to be considered for ITER. We also participated strongly in the understanding of a different "Sea of Alfvén Modes" observed in the core of specially prepared "reversed shear" plasmas in DIII-D and the Joint European Torus (JET). Our efforts at C-MOD have resulted in a deeper understanding of the atomic physics behind the Motional Stark Effect. Our collaboration on the W7-AS stellarator in Germany has revealed the remarkable stability properties of this magnetic confinement configuration. W7-AS routinely violates linear ideal-MHD stability criteria and is limited in the pressure that it can hold by the onset of magnetic stochasiticity in the plasma edge. This bodes very well for the anticipated performance of NCSX.

The small Lithium Tokamak Experiment demonstrated improved energy confinement with extensive lithium coating. It also demonstrated the remarkable result that a thin layer of lithium can spread heat dramatically over a large area. With proper engineering this technique may be applicable to large-scale fusion systems, where concentration of heat flux in space and time can be the factor limiting the power capability of devices such as ITER and beyond.

The Hall Thruster Experiment is successfully broadening its study to microthrusters. The Field-reversed Configuration (FRC), a speculative but attractive fusion configuration, has been the subject of considerable theoretical study, suggesting means of sustainment and stabilization of these systems. Our small FRC experiment has been upgraded. A strong effort in nonneutral plasmas is strengthening the understanding of the physics of high-intensity accelerators for high-energy physics, for high-energy-density physics, and for inertial fusion energy. An experiment to test the physics of the Magnetorotational Instability, believed to be the mechanism by which accretion disks feed their central massive bodies, has operated successfully with water, establishing the regime needed for study with a conducting fluid. Indeed even these results have contributed to the debate as to whether subcritical shear instabilities can occur in Keplerian flows. New diagnostic tools, of high relevance both to NSTX and to other devices, have been successfully demonstrated.

The PPPL Engineering and Technical Infrastructure Department continues to support the operation of NSTX, the construction of NCSX, as well as the flotilla of smaller experiments and computational facilities at the Laboratory. Safe operation is of the highest importance in these activities. Our Environment, Safety and Health track record is very good, but this is an area that requires continuous attention. Internal self-assessments, external reviews, careful evaluation of lessons-learned from PPPL and elsewhere, and constant attention to our motto "Safely, Safely, Safely" are high priorities.

The effort to develop fusion is a long-term one, so we are proud of the applications of our science and technology to other fields of endeavor. We have worked with the Picatinny Arsenal to develop a Miniature Integrated Nuclear Detection System (MINDS), which is now being deployed to identify specific radionuclides for homeland security applications. We also have a strong collaboration with the Naval Research Laboratory on the development of Micro Air Vehicles, in addition to the space plasma physics and thruster applications discussed earlier.

In summary, fiscal year 2005 was a very satisfying time for PPPL, with many major accomplishments across a broad frontier. The lesson to be drawn is that the combination of a vigorous domestic fusion research program with the international ITER project can position the U.S. well to lead in the development and in the ultimate deployment of fusion energy.

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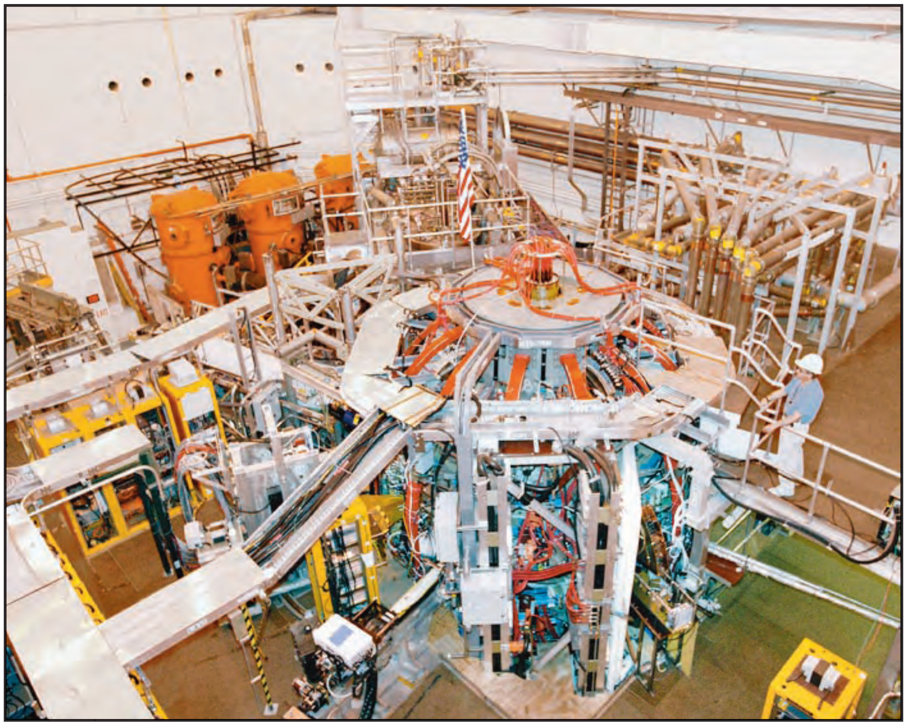
National Spherical Torus Experiment



National Spherical Torus Experiment

The National Spherical Torus Experiment (NSTX) is designed to investigate the physics of tokamak-like plasmas at very low aspect ratio, resulting in a small hole in the center of the plasma "doughnut." Theoretically and experimentally this allows the study of plasmas at very high beta, which is relevant to the design of cost-effective fusion systems. It also allows an alternative perspective of special value in assessing physics issues of relevance to ITER, both by permitting tests of physics concepts in a closely related, but different, overall configuration, but also in some cases, such as toroidicity-induced Alfvén eigenmodes, allowing direct access to ITER-relevant regimes not accessible elsewhere.

In FY05, the NSTX completed 18 weeks of operation, meeting its primary facility milestone for the year and providing data for some 38 separate experiments. Prior to FY05 experiments, the two innermost poloidal-field coils at the upper and lower ends of the central solenoid were replaced with an axially shorter pair further from the midplane. This led to improvements in plasma shaping capability and effects on plasma stability discussed in detail below.

During FY05, measurements of the internal poloidal field at eight points simultaneously along the plasma minor radius became available using the motional Stark effect (MSE) diagnostic on collisionally excited emission from deuterium neutral-beam injection (NBI). The successful application of the MSE technique in the low magnetic field typical of NSTX is a major achievement. The MSE data are used as constraints in the analysis of the plasma equilibrium with the EFIT code, which can also include kinetic profiles, including the electron pressure measured by multi-pulse Thomson-scattering (MPTS) and the thermal ion pressure and toroidal rotation measured by charge-exchange tecombination spectroscopy (CHERS).

The FY05 experiments benefited from several new capabilities introduced during the year. An additional ten spatial channels for the MPTS diagnostic were installed and commissioned in June; these channels, which are concentrated in the edge pedestal region of typical plasmas, took data through the latter half of the experimental campaign. The system was fully calibrated at the conclusion of the experiments and analysis of the data is underway.

The toroidal-field coil, which had undergone refurbishment of its bolted joints at the conclusion of the FY04 experiments, operated for about 2,500 pulses. At the end of the operating period, the coil was run up to 95% of its design rating of 0.6 T, although the majority of experiments were conducted with fields up to 0.45 T. Throughout the FY05 operation, the measured resistances of the 72 joints in the coil remained well within specifications and did not show significant deterioration.

Improvements in Plasma Shaping Capability and the Effects on Plasma Stability

Prior to the FY05 experiments, the two innermost poloidal-field coils at the upper and lower ends of the central solenoid, known as the PF1A coils, were replaced by an axially shorter pair further from the midplane to increase the plasma shaping, in particular the capability to produce simultaneously high elongation κ and triangularity δ of the plasma cross section. The changes in the coils and representative plasma shapes are shown in Figure 1. Plasmas with $\kappa = 2.7$ and $\delta_{av} = 0.8$ (where δ_{av} is the average of the upper and lower triangularity) have now been produced at an aspect ratio $A = 1.5$.

Comparisons of the values of κ and δ_{av} achieved in FY04 and FY05 are shown in Figure 2. The highest value of the "shaping factor" $q_{95}I_p/aB_T$ (where q_{95} is the safety factor at the 95% normalized flux

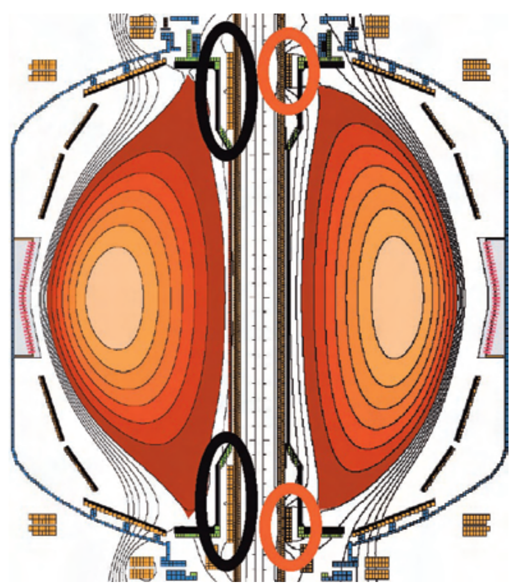


Figure 1. Cross section through the NSTX showing the PF1A coils (circled) and typical plasma configurations available in FY04 (left) and FY05 (right).

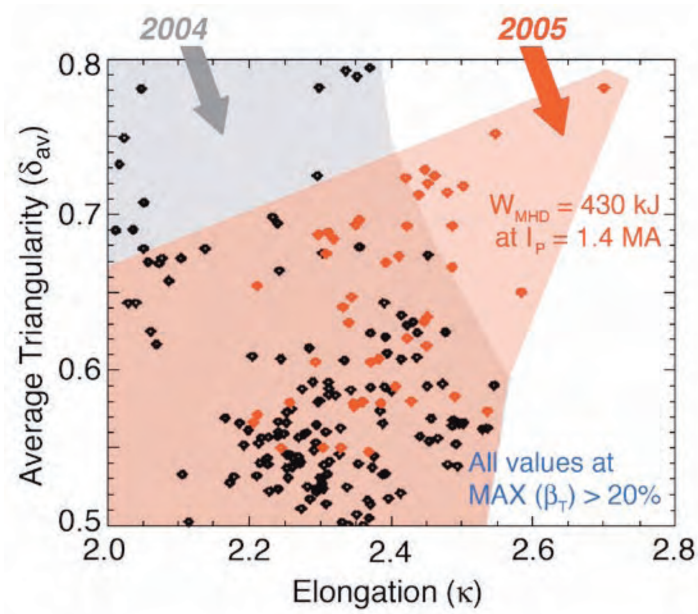


Figure 2. Values of the plasma cross-section elongation κ and the triangularity δ averaged between the upper and lower X-points at the time of maximum toroidal beta β_T for discharges in which β_T exceeded 20%. Data from FY05 with the modified inner poloidal-field coils and from FY04 are distinguished.

surface, I_p the plasma current, a the mid-plane half-width of the cross section, and B_T the vacuum toroidal magnetic field at the plasma geometric center) reached 37 MA/m·T at a slightly lower aspect ratio A = 1.35 with κ = 2.3, δ_{av} = 0.6. Plasma currents I_p up to 1.5 MA have now been achieved. At an applied toroidal field of 0.45 T, the plasma stored energy reached 430 kJ, a record for NSTX, for a NBI-heating power of 7.3 MW. At lower field, 0.34 T, the toroidal beta β_T reached 35%, although maximizing β_T was not a major focus of the experiments in FY05. By ramping down the plasma current during neutral-beam injection, poloidal-beta β_p up to 2.1 and Troyon-normalized beta $\beta_N = \beta_T/(I_p/aB_T)$ up to 7.2 %·m·T/MA have been produced, which significantly exceed the ideal stability limit calculated without wall stabilization.

One result of operating with higher κ and δ simultaneously was the reemergence of small, high-frequency edge-localized modes (ELMs) in high-confinement mode (H-mode) plasmas. Previously, operating at κ > 2.2 with lower triangularity produced large ELMs which caused significant drops in the plasma energy. The small ELMs do not perturb the plasma energy significantly but they do slow the rate of density rise. This regime has provided a significant extension in the pulse length achievable at moderate plasma currents, 0.7–1.0 MA. Figure 3 shows basic waveforms for a lower single-null divertor discharge which extended to 1.5 s at 0.7 MA; the current was constant for about four current-relaxation times.

Calculations have been made with the TRANSP code of the noninductively driven current in this plasma, assuming classical thermalization of the energetic ions introduced by NBI; this assumption provides a good match between the measured and predicted deuterium-deuteri-

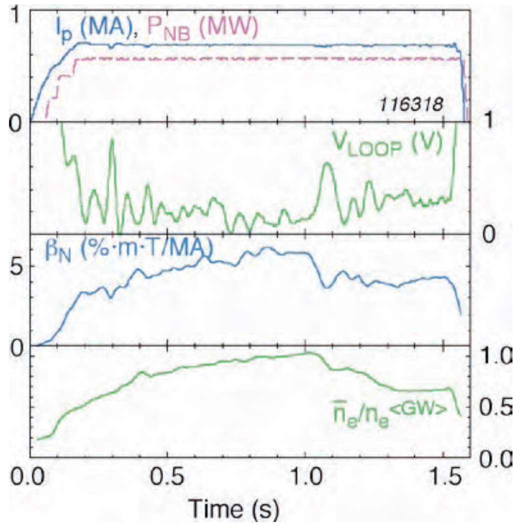


Figure 3. Waveforms of plasma discharge parameters for the longest duration 0.7 MA plasma.

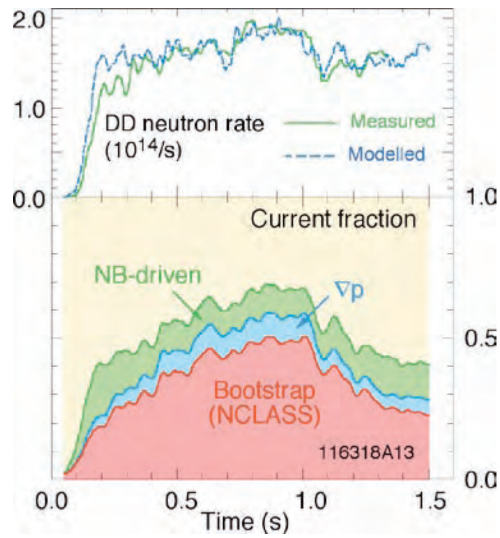


Figure 4. Results of TRANSP code analysis for the plasma in Figure 3 showing the time evolution of the components of the total current and the measured and modeled deuterium-deuterium (D-D) neutron rate.

um (D-D) fusion neutron rates during MHD-quiescent periods. As seen in Figure 4, the calculation shows that the non-inductive components, including the neoclassical bootstrap current, other ∇p terms, and the beam-driven current, provide up to 70% of the total current at peak beta. Despite the beneficial effect of the ELMs in slowing the density rise, this plasma discharge reached the nominal density limit predicted by Greenwald scaling. This roughly coincided with a drop in the central rotation of the plasma, the development of a persistent saturated n = 1 mode, and a drop in beta. While this coincidence does not show causality, it does suggest that density control will be important for the development of even longer H-mode discharges in NSTX. During the period of MHD activity, it was necessary to introduce an anomalous diffusivity of 5 m^2/s for energetic ions in the TRANSP model to match the measured neutron rate. This indicates the importance of non-classical effects on beam heating and current drive.

Generation of Persistent Toroidal Current by Coaxial Helicity Injection

Coaxial Helicity Injection (CHI) has the potential to initiate toroidal plasma current in a spherical torus by creating a plasma discharge and injecting poloidal current from electrodes coaxial with the major axis in the presence of applied toroidal and appropriate poloidal magnetic fields. Recent experiments in NSTX have aimed to exploit the technique of "transient CHI" originally developed in the Helicity Injected Torus (HIT-II) device at the University of Washington, Seattle.

The NSTX experiments in FY05 benefited from several upgrades, including the capability to inject both the gas and the electron-cyclotron-resonant microwave power (18-GHz) for initiating the discharge directly into the chamber below the CHI electrodes. This reduced the amount of gas needed to create the discharge, thereby increasing the energy input per plasma particle and thus the possible temperature of the CHI discharge in its high-current phase. A fast "crowbar" switch was also provided for the capacitor bank supply (10–50 mF, 2-kV rated) so that the injected current could be reduced rapidly once the CHI plasma discharge had expanded to fill the region available for plasma inside the vacuum vessel. With these changes, a clear demonstration was obtained of toroidal plasma current which persisted on closed magnetic surfaces beyond the end of the injector current pulse.

Figure 5 shows examples of the discharge waveforms for a plasma discharge obtained with a 15-mF capacitor bank charged to 1.5 kV, in which a peak toroidal plasma current of 120 kA was generated for an injected current of 1.9 kA, representing a current multiplication factor greater than 60. When the injector current had decayed to zero (t ≈ 11 ms), approximately 6.5 kJ of electrical energy had been dissipated in the plasma circuit. At this time, a toroidal plasma current of 50 kA was still flowing, which subsequently decayed on a timescale of about 7 ms. Images of the visible light emission during this phase showed the formation of a plasma ring detached from the injector and close to the center column. Future experiments will attempt to maximize the CHI-initiated current and to couple these discharges both to inductive and noninductive current drive.

Effects of Applied Radial Field Perturbations on Plasma Stability and Rotation

The NSTX routinely operates with normalized-beta above the stability limit calculated without the stabilizing effect of the conducting wall, so plasmas are susceptible to the growth of resistive wall modes (RWM) unless sufficient plasma rotation can be maintained. Nonaxisymmetric field perturbations, both intrinsic and induced by the modes themselves, can act to slow the rotation induced by the NBI heating in NSTX and thereby contribute to mode growth. To allow extended operation near the ideal-wall limits, three pairs of nearly rectangular coils have been installed on the midplane outside the vacuum vessel to produce radial

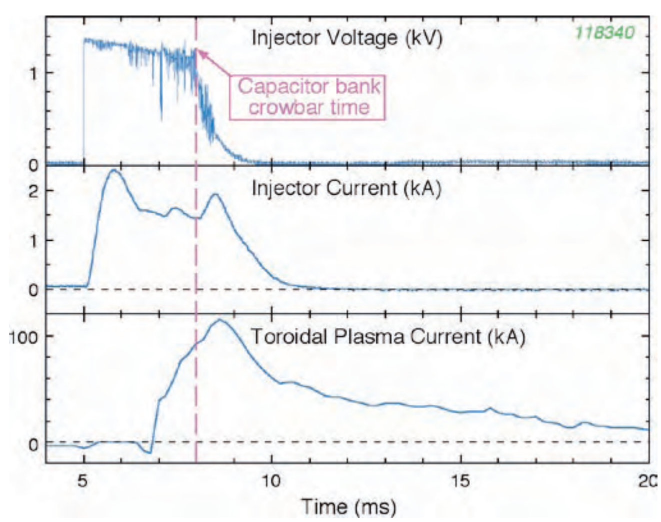


Figure 5. Waveforms for a coaxial helicity injection (CHI) plasma discharge which produced a toroidal current of about 50 kA as the injector current returned to zero. The toroidal current persisted for a further 10 ms.

magnetic field perturbations. These coils are referred to as the error field correction and resistive wall mode (EFC/RWM) coils. Each coil has an area of about 1.6 m^2 and contains two turns. The diametrically opposite coil pairs are powered by three switching power amplifiers, which can drive currents up to 3 kA at frequencies up to several kHz.

The effect of DC perturbations generated by the EFC/RWM coils with toroidal mode number n = 1 on the development of locked modes was investigated first; the results are summarized in Figure 6. In a series of otherwise similar ohmically heated, low-density, deuterium, lower single-null divertor plasmas, the amplitude of the applied perturbation needed to trigger a locked mode as a function of its direction, traced out a circle, suggesting that there is an intrinsic radial error field perturbation corresponding to the vector from the center of the circle to the origin, i.e., about 1.3 G in the conditions of these discharges.

The response to stationary perturbations with toroidal mode numbers n = 1 or 3 has also been investigated in initially rapidly rotating plasmas heated by 6 MW of NBI to $\beta_N \approx 5$. It was found that in these conditions, the apparent n = 1 error field was in the opposite direction to that observed in the low-β ohmic-heating discharges. Analysis indicates that this error field is proportional to the product of the ohmic-heating solenoid and toroidal-field coil currents, suggesting that some small motion of the toroidal-field coil inner bundle is involved. As seen in Figure 7, when a small n = 1 perturbation was applied in the direction to augment the intrinsic error field, the plasma toroidal rotation (measured by CHERS) collapsed, starting near the edge but then extending across the profile. A locked mode then developed and the discharge terminated earlier than a reference discharge with no perturbation. Conversely, when the applied perturbation counteracted the intrinsic error field, the rotation collapse was avoided and the high-β_N phase was extended. When a 50-ms long, n = 3 perturbation pulse was applied to a similar NBI-heated discharge, the plasma

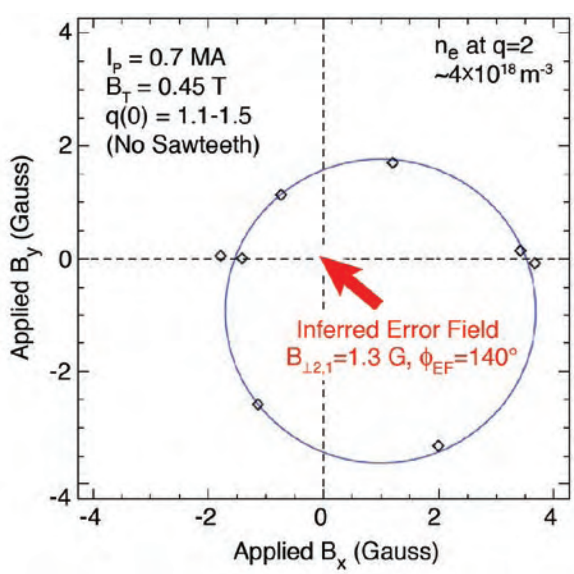


Figure 6. Measurements of the threshold in the applied n = 1 error field to generate a locked mode in otherwise similar plasmas as the direction of the applied field was varied.

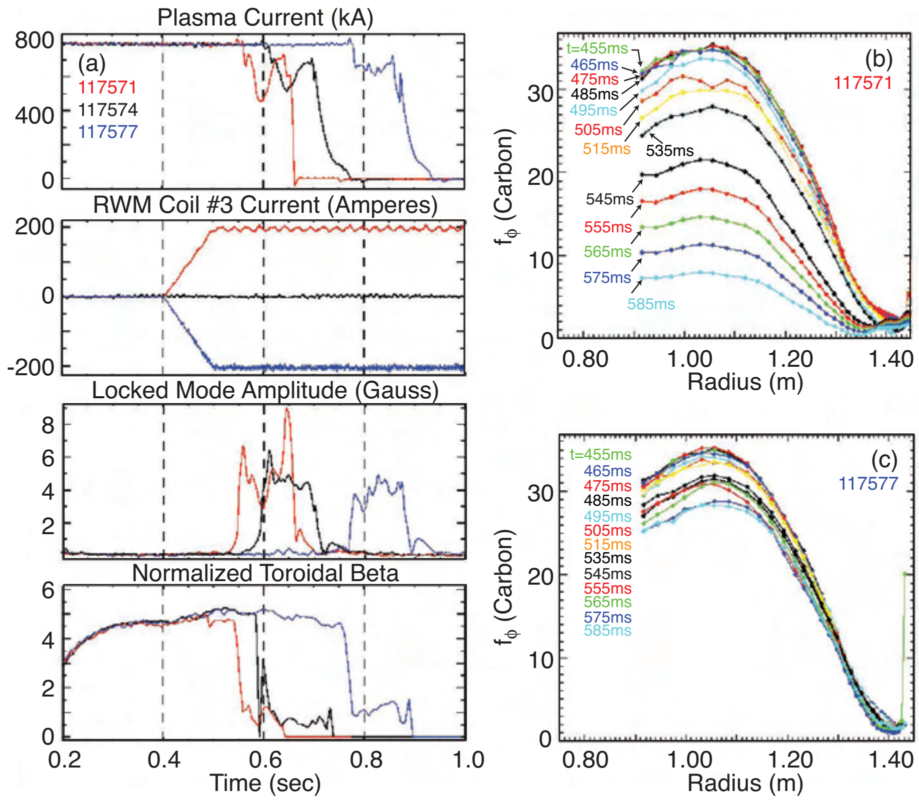


Figure 7. (a) Waveforms for three plasma discharges with an n = 1 error field applied in the canceling and augmenting directions with respect to the intrinsic field and without any applied correction. (b, c) Profiles of the toroidal rotation frequency (=$v_\phi/2\pi R$ measured by CHERS) at various times as the n = 1 error field is applied in the augmenting (b) and canceling (c) directions.

rotation at the edge stopped temporarily and, provided that a locked mode not develop while the plasma edge was stationary, resumed after the perturbation was removed. In this case, the perturbation of toroidal rotation in the plasma center, which did not contain q-surfaces resonant with the applied n = 3 perturbation, appeared to be damped by neoclassical toroidal viscosity.

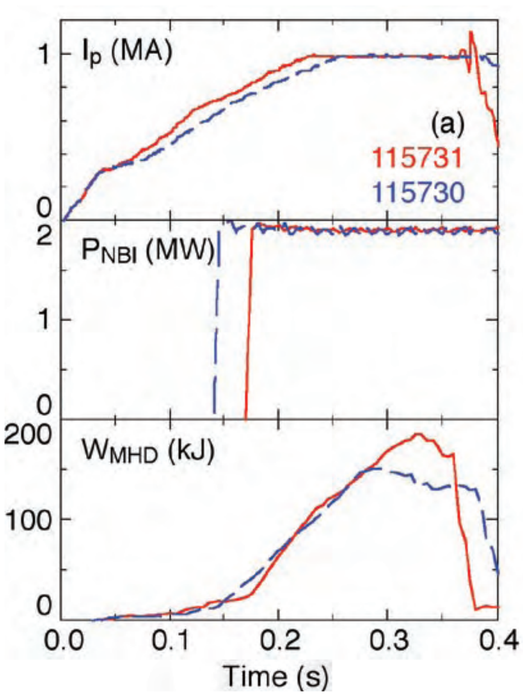
The EFC/RWM coils were also used to probe the response of the system to a rotating n = 1 field perturbation in plasmas where a slowly rotating RWM had already developed. The rotating perturbation was generated by programming the currents in the three pairs of coils with sinusoidal waveforms successively phase shifted by 120°. Depending on the frequency of rotation of the applied perturbation, the plasma was found to increase or decrease the applied field, a phenomenon referred to as resonant field amplification. In the conditions of this experiment, the greatest resonant field amplification occurred when the applied n = 1 perturbation was rotating at a frequency of about 30 Hz in the same direction as the intrinsic plasma toroidal flow.

Effect of Modifying the Magnetic Shear on Electron Thermal Transport

As previously reported, with NBI heating, the confinement of both the thermal and unthermalized ions is extremely good in NSTX and, in most operating regimes, the dominant thermal loss is through the electron channel. However, in plasmas with a fast initial current ramp, which develop a region of reversed magnetic shear in the core, improved electron confinement has also been observed. The creation of reversed shear in these discharges was previously inferred from the behavior of perturbations on the soft X-ray emission profiles, supported by TRANSP code modeling of the current diffusion assuming neoclassical plasma resistivity. The motional Stark effect (MSE) measurements of the q-profile made this year have confirmed the inference of reversed shear and also guided the development of a scenario for obtaining strongly reversed magnetic shear reliably.

Figure 8(a) shows the waveforms for two successive discharges with a flattop current of 1 MA but slightly different initial current ramps and timing of the NBI, while Figure 8(b) shows the resultant q-profiles at time t = 0.31 s as determined by the LRDFIT code using the MSE pitch-angle data as a constraint on the fit. The production of strongly reversed shear through a fast current ramp is very sensitive to the MHD mode activity in the ramp-up phase of the discharge: quite small bursts of activity detected by the Mirnov coils can cause a rapid drop in the central q and result in a profile with positive or near-zero shear in the center. However, once established, the reversed-shear profile can be maintained for up to 0.2 s.

A comparison of the profiles of the plasma temperatures and density is shown in Figure 9(a). Although the ion temperature is very similar in the two discharges, the electron temperature is significantly higher in the reversed-shear case, suggesting a reduction in electron thermal transport. This has been confirmed by TRANSP code analysis based on classical thermalization of the fast ions from neutral-beam injection but including a modest anomalous fast-ion diffusivity of 0.5–1.5 m^2/s to bring the measured and calculated D-D neutron rates into agreement. The electron thermal diffusivities calculated by TRANSP for the two discharges are shown in Figure 9(b); a re-



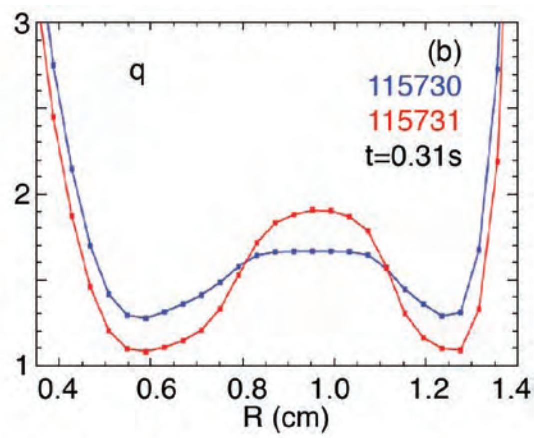


Figure 8. (a) Comparison of discharge waveforms for successive plasmas, the first developing a region of weakly, the second of strongly reversed shear. (b) q-profiles for the two discharges at time t = 0.31 s from analysis of the motional Stark effect (MSE) data with the LRDFIT code.

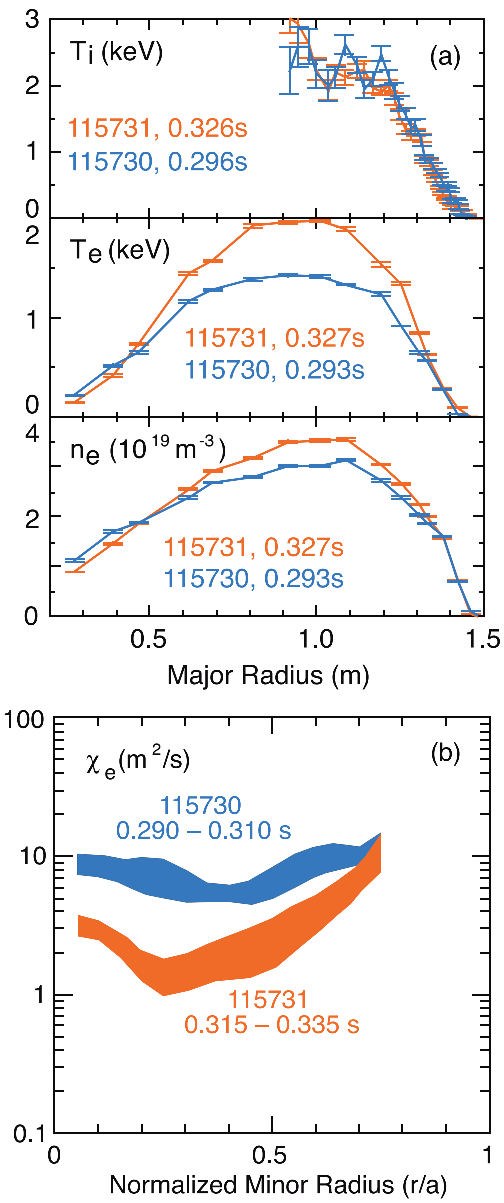


Figure 9. (a) Profiles of the plasma temperatures and density for the two discharges in Figure 8 at the times of peak plasma energy. (b) Profiles of the electron thermal diffusivity calculated by TRANSP (the bands indicate the variability of the diffusivity over the time interval indicated).

duction of electron thermal diffusivity by a factor 2 to 4 over the inner 70% of the minor radius is evident.

Adding a modest amount of high-harmonic fast-wave radio-frequency (rf) heating power, ~0.7 MW, launched with balanced parallel wavenumber $k_{||} \approx \pm 7\ m^{-1}$, produced electron heating in the central region of a reversed-shear plasma established with 2 MW of neutral-beam injection. The region where the heating was observed roughly coincided with the region of shear reversal inferred from the equilibrium analysis.

Use of Lithium Coating to Control Recycling from Plasma Facing Surfaces

The Lithium Pellet Injector, first introduced in FY04, was used to produce changes in the recycling of hydrogenic species from the plasma contact surfaces, which contributes to the secular density rise observed in most NBI-heated plasmas in NSTX. The experiments involved both plasmas limited on the central column and lower single-null divertor plasmas; both these contact areas are covered by carbon tiles. For each configuration, the surface layers of the plasma contact area were first depleted of deuterium by a series (about 10) of low-density, ohmically heated, helium discharges. These were followed by a reference deuterium discharge with 2 MW of NBI heating. One or two lithium pellets with masses 1.7–5 mg were then injected into each of a series (10–20) of helium discharges, to introduce a total of 24–30 mg of lithium.

Spectroscopic data indicated that the injected lithium was deposited primarily on the surfaces surrounding the plasma contact area. In both the limiter and divertor configurations, the first subsequent deuterium NBI-heated plasma showed a reduction in the volume-average plasma density during the neutral-beam-injection heating by a factor of about two compared to the respective reference discharge before the lithium deposition. This is illustrated for the divertor configuration plasmas in Figure 10. The saturation of the apparent wall pumping can be understood if the effect occurs through the formation of lithium deuteride on the surface: the amount of lithium introduced could react with about 6–9 mg of deuterium and about 3.5 mg of deuterium was injected on each discharge. The lithium deposition was repeated for the plasmas limited on the central column, without any preceding helium-only sequence, and a similar reduction in density was observed on the first subsequent NBI-heated discharge. The results for the limiter plasmas are similar to the experience with lithium coating in the Tokamak Fusion Test Reactor (TFTR) and with a liquid-lithium limiter in the Current Drive Experiment-Upgrade (CDX-U), but these NSTX experiments extend the potential benefits of lithium surface coating for plasma density control to divertor plasmas.

H-mode Pedestal, Edge-localized Modes, and Boundary Physics

The dependence of the power threshold for the H-mode transition on the plasma configuration was investigated in an experiment conducted jointly with the Mega-Ampere Spherical Tokamak (MAST) group at the Culham Laboratory, United Kingdom, and the Alcator C-Mod group at the Massachusetts Institute of Technology. Similar to MAST experiments with neutral-beam injection, it was found that in NSTX the minimum threshold power with either NBI or high-harmonic fast-wave (HHFW) heating occurred for a symmetric double-null divertor configuration, as defined by $\delta r_{sep} < \rho_i$, where δr_{sep} is the radial separation of the inner and outer separatrices at the outer midplane, as calculated by the EFIT code, and ρ_i is the local ion gyro-radius, typically 0.5 cm. The NSTX experiment, however, produced the first example of an H-mode in an spherical torus for the upper single-null divertor configuration with the ion ∇B-drift away from the divertor X-point; the threshold power in this case was between two and four times higher than for the complementary lower single-null configuration. This experiment also demonstrated that the low- to high-confinement mode (L-H) transition power was comparable with neutral-beam injection and radio-frequency heating for

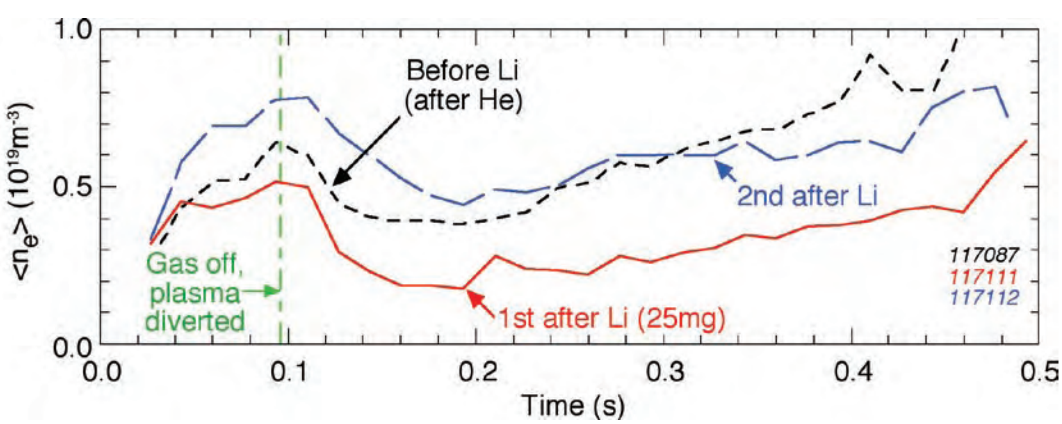


Figure 10. Waveforms of the plasma volume averaged density (calculated from the Thomson scattering profiles) for a reference NBI-heated deuterium discharge before deposition of lithium on the plasma contact surfaces, and for the first two similar discharges after depositing 25 mg of lithium in a series of ohmically heated helium plasmas.

the double-null configurations with similar densities in the L-mode phase.

An experiment was performed to measure the profiles in H-mode plasmas just before and after ELMs of different types to assess the MHD stability of the plasma edge. The conditions included Type I ELMs in double-null divertor plasmas with triangularity $\delta \approx 0.8$, Type I with transition to Type III ELMs in double-null with $\delta \approx 0.4$, the NSTX Type V ELMs, again in double-null (EFIT parameter $\delta r_{sep} < 0.3$ cm) with $\delta \approx 0.8$, and, finally, in a mixed Type I and Type V ELM regime in lower single-null divertor plasmas with $\delta \approx 0.4$. In addition to measuring profiles of the electron density and temperature with the MPTS diagnostic and the ion temperature and flow velocity with CHERS, data were taken with the far-infrared tangential interferometer and polarimeter (FIReTIP) diagnostic and a new filterscope array, and images of the ELM perturbation were recorded with a high-speed visible camera viewing the lower divertor.

Filamentary structures were observed propagating counter to the plasma current. The filaments associated with the Type V ELMs were found to be ribbon-like and aligned with the edge magnetic field, with a typical midplane vertical thickness five to ten times larger than the radial thickness of a few centimeters. Larger ELMs involved more filaments than the typical one or two for Type V ELMs. Based on these data, calculations are now underway of the stability of the plasma edge to various MHD instabilities.

The fast-reciprocating edge probe (FREP) diagnostic measured phenomena accompanying ELMs with high time resolution (1 M-sample/s), including the electric fields, velocity, and particle flux. These data showed that an ELM comprises several short (~10 μs) bursts in rapid succession (20–50 μs separation). The radial velocity of the ELM perturbation can be high, ~500 m/s, near the last closed flux-surface, slowing to ~200 m/s in the scrape-off layer. The ELM burst decayed exponentially away from the last closed flux-surface. In L-mode plasmas and between ELMs in the H-mode, intermittent plasma objects, commonly referred to as plasma "blobs" were also observed by the FREP. The velocity of these objects was typically ~400 m/s at the last closed flux-surface, decaying to ~100 m/s approximately 6 cm outside the last closed flux-surface.

Imaging and tomographic reconstruction techniques have been applied to data from the multi-chord soft X-ray detector system to follow the propagation of ELM perturbations from the plasma edge into the core. By using different filters to select the energy range, it was possible to change the region of observation within the plasma. Type I ELMs cause a large electron temperature crash at the edge which then propagates to the center on a timescale of 1–2 ms. Although the density at the edge is also reduced by the ELM, there is no significant perturbation of the central density. The central temperature perturbation appears to be the result of rapid thermal transport, as no large MHD modes are observed on the soft X-ray data.

An experiment was also conducted jointly with the DIII-D (General Atomics, California) and MAST (Culham Laboratory, United Kingdom) to assess the effect of aspect ratio and wall proximity on the height, width, and gradients in the pedestal of ELMy H-mode plasmas. This required a dedicated experiment to create in NSTX the low and high squareness shapes run in the other devices. Good data were obtained at an edge collisionality parameter $\nu^*_{e,ped} \approx 1$ and normalized ion-gyroradius $\rho^*_{i,ped} \approx 0.01$ which matched well with the data from the other experiments. Assessment of the pedestal widths and edge stability is in progress.

Finally, a dedicated experiment showed the onset of partial detachment of the plasma from the divertor strike plate on the outer leg of the divertor when deuterium gas was puffed into the private flux region of H-mode plasmas in a lower single-null configuration. The divertor detachment was accompanied by volumetric recombination in the outer-leg scrape-off layer resulting in a 75% decrease in the peak heat flux to the outer strike plate.

Wave-Particle Physics Studies

The absorption of and heating by HHFW power was studied as a function of the phasing of the antenna straps, which determines the parallel wavenumber $k_{||}$, or equivalently the phase velocity, of the launched waves. The time response of the plasma energy to the HHFW power pulse was used to determine the effective energy confinement time and the absorbed power. The 180° phasing, which produces a symmetric spectrum with $k_{||} \approx \pm 14\ m^{-1}$, achieved higher absorption, 40–60 %, than the ±90° phasings, which produce directed spectra with $k_{||} \approx \pm 7\ m^{-1}$ for counter- and co- current drive, respectively. However, the apparent confinement time with the $k_{||} \approx \pm 14\ m^{-1}$ spectrum was lower, probably because the power was deposited further out in minor radius in this case. Changing the plasma current from 0.3 to 0.6 MA, to vary the pitch of field lines with respect the antenna straps, did not affect the absorption. Measurements with the edge radio-frequency probe indicate that the signature of the parametric decay instability was strong for the ±90° phasing but undetectable for 180°.

The first measurements were made in NSTX with an obliquely viewing 20 to 40-GHz microwave radiometer to detect the second harmonic thermal electron Bernstein waves (EBW) inside the plasma. These plasma waves undergo mode conversion to detectable O-mode radiation at the upper-hybrid resonant layer near the edge of H-mode plasmas where there is a steep density gradient. The radiometer measurements indicated an apparent coupling efficiency for the second harmonic EBW of ~20%, compared with ~80% coupling of fundamental EBW previously measured. Modeling of the wave propagation and mode-conversion process has indicated that the low electron temperature and the relatively high $Z_{eff} \approx 3$ at the upper-hybrid resonant layer in these particular plasmas caused significant collisional loss of the power coupled from the EBW and that much of the EBW power may have come from the third harmonic layer, where electron temperature is much lower. This topic will be investigated in greater detail in FY06.

An experiment was performed in FY05 using the sightline scanning capability of the NSTX charge-exchange neutral-particle analyzer to make spatially resolved measurements of the energy distribution of the energetic ions introduced by NBI heating. For H-mode discharges, the measured neutral-particle analyzer spectra exhibit depletion of the energetic ion population primarily for ion energy $E > E_{inj}/3$; this depletion is not seen in the preceding L-mode phase however. The measured depletion of the population is greatest for a sightline tangency radius $R_{tan} = 0.50 \pm 0.10$ m, vanishing at larger R_{tan}. Charge-exchange emissivity effects can account for part, but not all, of the observed behavior. Modeling of the fast-ion orbits and classical loss processes with the TRANSP code reproduces some features of the measurements, but the predicted energy dependence of the depletion, which is largest at the injection energy, is different from the measurement, which peaks at intermediate energies.

The energetic ions from NBI heating in NSTX can excite toroidal Alfvén eigenmodes (TAE), which are fundamental modes of the background plasma, and energetic-particle modes (EPM) in which the energetic particles themselves are involved in the instability. A study was conducted in 2005 of the stability of TAE and EPM as a function of the central q, q(0), and the magnetic shear, S = (r/q)(∂q/∂r). In general, EPM were present with low q(0) and a monotonic q-profile with S > 0, whereas TAE were predominant with elevated q(0) and q-profiles with reversed shear, S < 0, in the center. The microwave reflectometer showed that in NSTX, rather than a few modes being present, many modes can occur simultaneously, similar to the "sea of TAE" activity predicted for ITER where a large population of energetic fusion alpha-particles will replace the NBI ions. The bursts of multiple-mode TAE/EPM activity in NSTX can cause significant transport of the energetic beam-ions, as evidenced by modulations in the signals from the neutral particle analyzer, which show reductions in the neutral flux predominantly well below the beam injection energy, and rapid drops of order 10% in the D-D fusion neutron emission, which suggest that the high-energy ions are also lost. These phenomena are shown in Figure 11. The broad range of

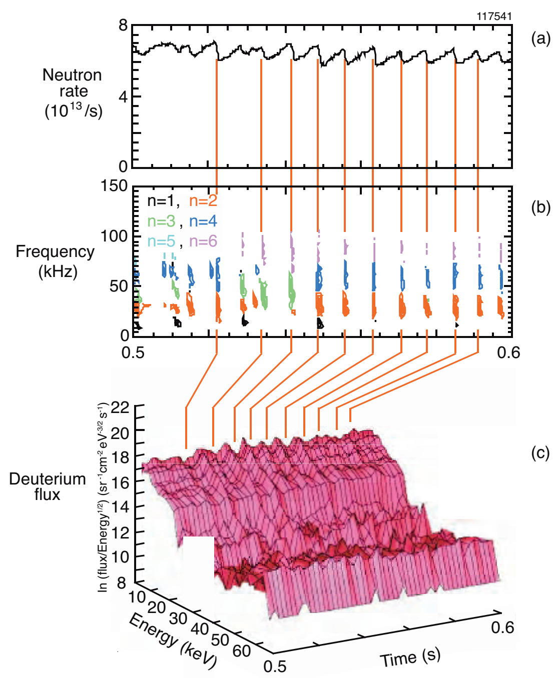


Figure 11. (a) Deuterium-deuterium (D-D) neutron rate showing sawtooth modulations in phase with high-frequency bursts of MHD activity seen in (b) a spectrogram of a Mirnov coil signal. These bursts cause repetitive depletion of (c) the charge-exchange neutral flux from the plasma in the range between the thermal ion component and the half-energy component of the beam-injected neutrals.

energy interaction is consistent with the loss being caused by bounce-resonances of the particles and waves, a key topic of importance for ITER.

Progress in NSTX Diagnostic Capabilities

Because of its low magnetic field and the exceptional tangential access afforded by its low aspect ratio, NSTX offers a unique opportunity to measure, through scattering of microwave radiation, turbulent density fluctuations with a scale length comparable to the typical gyroradius of thermal electrons. The spatial resolution of ~6 cm is unique in such diagnostic systems worldwide. During FY05, such a system was installed on NSTX.

A backward-wave oscillator generates microwaves with a frequency of 280 GHz. These microwaves are transmitted by low-loss corrugated waveguides to a launcher on the vessel midplane at Bay H, which can launch through the plasma collimated probe beams with a tangency radius of either 1.07 m or 1.41 m. Radiation scattered from these beams is collected and focused by a large mirror at the Bay K port through five vacuum windows into waveguides which convey the radiation to sensitive superheterodyne receivers. The vacuum ports at Bays H and K had been specially modified to accommodate this system during the preceding outage.

The system is designed to measure the amplitude of density fluctuations in a localized region between the magnetic axis and the outboard midplane edge in typical plasmas, with a radial component of their wavevector in the range k_r = 4–22 cm^{-1}, corresponding to $k_r\rho_e$ = 0.1–0.8 in typical conditions, where ρ_e is the thermal electron gyro-radius. The estimated detection limit is a fluctuation level $\delta n_e/n_e \sim 3 \times 10^{-5}$. Such fluctuations are thought to be important in producing electron transport, so it will be particularly interesting to measure their behavior in the reversed-shear regime where electron transport appears to be reduced. This diagnostic is expected to be fully commissioned for the experiments in FY06.

During the FY05 experiments, the far-infrared tangential interferometer and polarimeter (FIReTIP) was upgraded to make measurements on four channels. In addition to making routine measurements of the line integrated density, the instrument was used to measure the density perturbations associated with high-frequency MHD modes, such as Alfvén eigenmodes, energetic particle modes, and fishbone oscillations, to measure the edge density perturbation with high time resolution at the H-mode transition, and to follow the toroidal propagation of the filamentary structures observed by the fast visible cameras accompanying the Type V ELMs which occur in some H-mode plasmas in NSTX.

The analysis for the 51-channel charge-exchange recombination spectroscopy diagnostic has been automated to produce profiles as functions of time for the temperature, density, and toroidal rotation velocity of the carbon impurity ions in plasmas heated by the neutral beams. The analysis, which includes the full corrections for atomic physics effects, is completed and the results are stored and made available in the time interval between plasma discharges. These data, together with the MPTS data, provide an unprecedented amount of information to the members of the NSTX team while conducting experiments.

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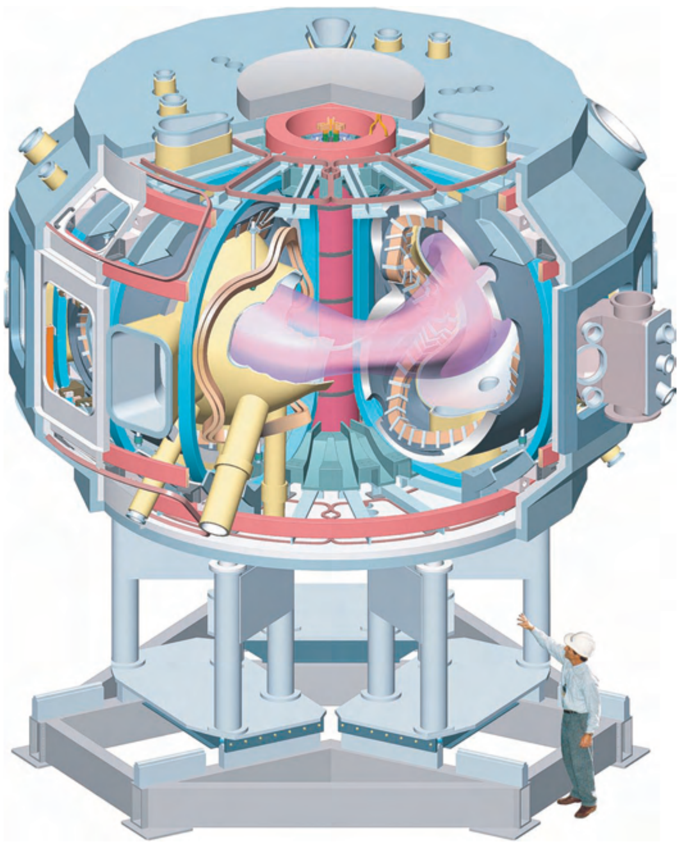
National Compact Stellarator Experiment



National Compact Stellarator Experiment

The National Compact Stellarator Experiment is a new magnetic confinement fusion experiment, currently being constructed at the Princeton Plasma Physics Laboratory (PPPL) in partnership with the Oak Ridge National Laboratory. It will be used to acquire physics data needed to evaluate the compact stellarator as a fusion concept and to advance the physics understanding of 3-D plasmas for fusion and basic science. In addition, technological developments made in the course of constructing the National Compact Stellrator Expriment (NCSX), for example the design and manufacture of complex-shaped parts, are important contributions to fusion technology.

Among the family of toroidal magnetic plasma configurations, stellarators are of interest because they solve important problems for fusion energy — achieving steady-state operation and avoiding plasma disruptions. Stellarators have unique flexibility to resolve scientific issues, for example the effects of 3-D plasma shaping and of strong external control on confinement, that are important to all magnetic configurations.

The "compact" stellarator shares the attractive properties of existing stellarators but has the additional advantages of lower aspect ratio and a quasi-symmetric magnetic field structure. In a quasi-*axi*symmetric stellarator (QAS) like NCSX, the charged-particle trajectories and plasma flow damping are similar to those of its axisymmetric relative, the tokamak, so a QAS device is expected to share the tokamak's good confinement performance. This physics link with tokamaks means compact stellarators can advance rapidly and economically, building on advances in the more mature tokamak concept, including the expected future advances in burning plasma physics and technology from ITER.

NCSX Stellarator Configuration Design

The compact stellarator is a result of the large advances in plasma physics understanding and computation that have occurred in recent years. The NCSX was designed by performing computer simulations of hundreds of thousands of plasma configurations to evaluate their physics properties: stability at high beta, degree of quasi-axisymmetry, quality of magnetic surfaces, and aspect ratio. Optimization algorithms based on the free-boundary VMEC and PIES equilibrium codes were used to design the coil geometry, targeting the desired physics properties while satisfying coil feasibility metrics such as minimum bend radius, minimum coil-to-coil spacing, and minimum coil-to-plasma spacing. Research on NCSX will test this modern approach to experiment design.

The NCSX plasma is designed to have an aspect ratio of 4.4 instead of the more typical (for stellarators) ~10; to have a quasi-axisymmetric magnetic field with an effective ripple less than 1.5%; to be MHD stable without active feedback control, current drive, or rotation drive; and to have good magnetic surfaces, all at high beta (4%).

The NCSX magnet system consists of eighteen modular coils, six groups each composed of three different shapes (Figure 1), plus toroidal-field coils, poloidal-field coils, and helical-field trim coils. These coils generate the 3-D magnetic fields required to realize the target equilibrium properties and provide the flexibility needed to vary the plasma configuration and test the physics. The device size (major radius R = 1.4 m), magnetic field range (B = 1.2–2.0 tesla), pulse length (0.3–1.2 s), and planned plasma heating power (1.5–12 MW) are set to produce the plasma conditions and profiles needed to test critical physics issues over a range of beta and collisionality values. An integrated machine design has been developed based on this configuration and these parameters.

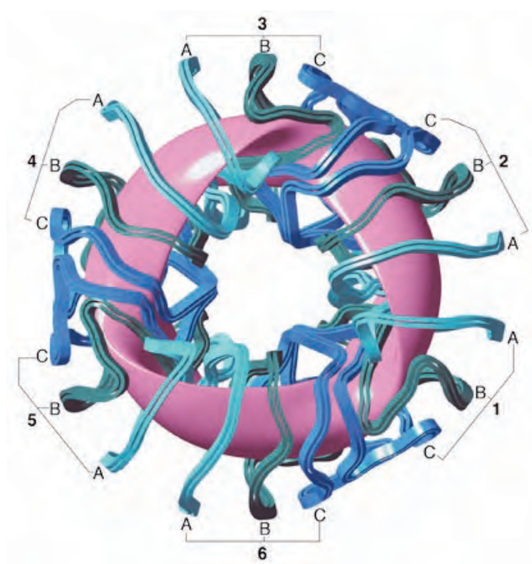


Figure 1. The NCSX plasma (magenta) and modular coils. There are a total of eighteen coils, six groups (1–6) each composed of three different shapes (A, B, and C).

Component Fabrication Progress

In FY05, the NCSX Project moved into the implementation phase following Department of Energy (DOE) approval of Critical Decision 3 (CD-3), "Start of Fabrication," at the end of FY04. The realization of the complex NCSX modular coil and vacuum vessel geometries with the accuracies required to achieve the design physics properties is a major engineering challenge.

The modular coil current centers must accurately follow the winding trajectories specified by the physics optimization. This is accomplished by winding each coil on a tee-shaped support feature that is an integral part of a structure called a modular coil winding form, or MCWF [Figure 2(a)]. Each MCWF comprises one-eighteenth of a complete toroidal shell and has the tee feature machined on its interior surface, precisely following the physics-specified trajectory. The coils are wound with a compacted copper cable conductor, which is flexible to facilitate handling and placement of its current center within ±0.5 mm of its nominal position on the winding form. The winding forms will be bolted together at precision-machined flanges to form the structural shell which locates the windings within ±1.5 mm of their nominal position in space and supports them against electromagnetic loads.

A production contract for the eighteen MCWFs was awarded to Energy Industries of Ohio, Inc. (EIO), of Independence, Ohio, in October 2004. During

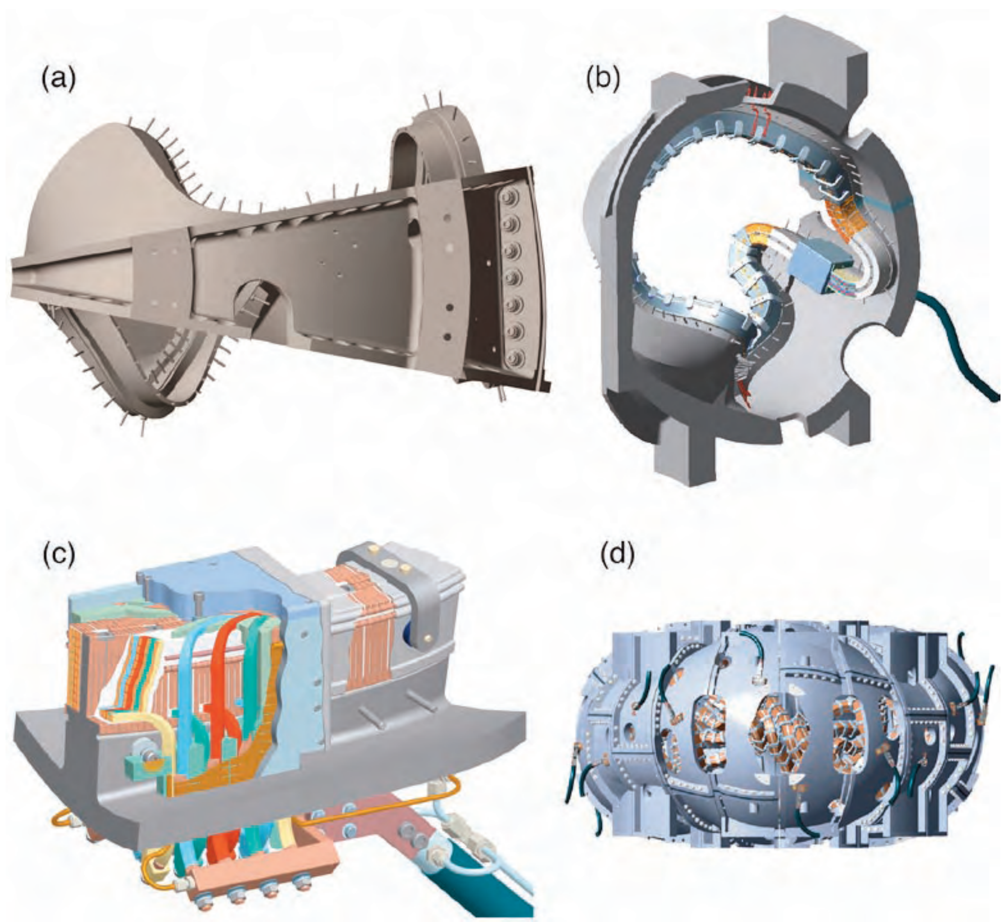


Figure 2. The NCSX modular coil system design: (a) modular coil winding form (MCWF), (b) coil, (c) winding pack and lead details, and (d) completed coil set.

FY05, the team of companies led by EIO made substantial progress. The pattern builder, C.A. Lawton Co. of De Pere, Wisconsin, fabricated all three of the wooden patterns used to make the casting molds for each of the three MCWF coil shapes. The foundry partner, Metaltek International of Pevely, Missouri, poured the first nine castings. The machining partner, Major Tool and Machine, Inc. of Indianapolis, Indiana, constructed fixtures and developed the machining programs and sequence of operations for finishing the winding forms.

All phases of the production effort benefited greatly from the manufacturing R&D activity that was completed the previous year through the construction of MCWF prototypes. However, many new challenges were encountered during the first year of production. In particular, the machining cycle times proved to be longer than expected. The NCSX Project Team and the suppliers worked together to optimize the technical requirements and the process and made steady progress toward the goal of achieving a delivery schedule consistent with the Project's needs. The machining of the first MCWF was completed and the part was shipped to PPPL on the last day of FY05 (Figure 3).

Modular coil manufacturing R&D by PPPL and its conductor suppliers supported both the design and manufacturing development of the modular coil assemblies. In previous years, a series of tests resolved design issues including conductor design, winding scheme, conductor installation, cooling scheme, insulation system, and epoxy impregnation materials and processes. In FY05, an integrated manufacturing demonstration was performed by constructing and testing a coil, the "twisted racetrack coil" (TRC), which was prototypical of the modular coils in its winding pack cross section and worst-case bends and twists (Figure 4). It was wound, epoxy impregnated, and tested, completing the manufacturing R&D for the modular coils.

The modular coil R&D program was very successful, supporting the completion of the winding pack design with many improvements for manufacturability. A practical manufacturing pro-

Figure 3. Finished modular winding form at the supplier's facility, ready to ship.

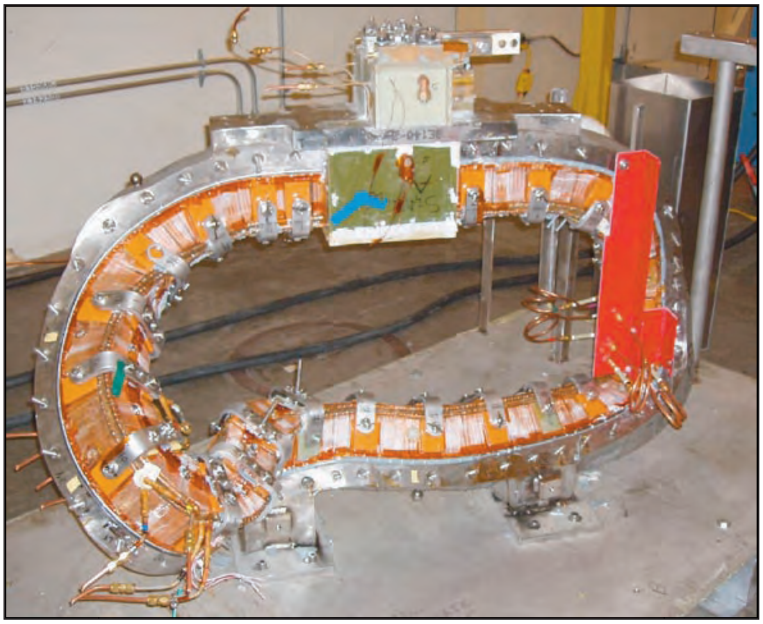


Figure 4. Completed twisted racetrack coil.

cess was developed for achieving the required geometries and tolerances in the production coils. Testing of the TRC validated the design and process. The coil was pulsed at cryogenic temperatures and near design levels of current and heat input. Cooldown following a pulse was consistent with analysis results. The final test, in which the TRC was sectioned in several places, confirmed good epoxy penetration throughout the coil pack and the success of the dimensional control strategy.

The NCSX vacuum vessel (Figure 5) is designed to provide: (1) a high-vacuum environment for plasma operation; (2) sufficient interior space for the plasma, its boundary layer, and the plasma-facing components; and (3) access for heating and diagnostic viewing. The vacuum boundary is located just inside the modular coils and as far from the plasma surface as possible, leaving the minimum assembly clearance to install the modular coils over the vacuum vessel. This results in a non-axisymmetric vacuum vessel shell with a shape reflecting that of the plasma and which must be realized within ±5 mm accuracy. Heating and diagnostic access requirements, including contingencies to allow for future innovations, are accommodated by providing 99 ports of various shapes, sizes, and orientations causing the vacuum boundary to protrude through all available openings in the surrounding magnets. To minimize field errors, inconel is used because of its high resistivity (to reduce eddy currents) and low magnetic permeability ($\mu < 1.02$) at the welds.

A production contract for the vacuum vessel was awarded to Major Tool and

Figure 5. NCSX vacuum vessel design.

Machine, Inc. (MTM) in October 2004. Manufacturing R&D completed the previous year led to a process in which panels are pressed formed on machined dies at room temperature, then assembled onto accurately machined skeletal fixtures where the seams are welded to form the shell.

In FY05, MTM fabricated the dies and fixtures and formed the shell panels and ports. The shell segmentation was re-optimized for production in response to modest but significant changes in the vessel shell geometry. The shell was segmented into 60 panels of ten distinct shapes, minimizing the amount of welding with its associated distortion risk and number of forming dies. By the end of FY05, MTM had begun to assemble and weld the panels together to produce the shell segment (Figure 6).

Directed Baseline Change

The NCSX Project baseline was initially established with the approval of Critical Decision 2 in February 2004. However, the DOE subsequently determined that it could not provide the increases, beginning in FY06, that were called for in the initial baseline funding profile. The DOE issued revised guidance based on flat funding at the rate of $15.9 M per year, and directed that the NCSX baseline be changed to fit that guidance. The NCSX Project Team responded in April 2005 with a revised plan that extended the project by 14 months to July 2009, and increased the total equipment cost by $6.1 M to $92.4 M. The DOE Deputy Secretary approved the new baseline in July 2005.

Summary

The NCSX Project had a successful first year of construction in FY05. The Project's two largest contracts, for the modular coil winding forms and for the vacuum vessel, were awarded at the beginning of the year. By the end of the year, the modular coil winding form supplier had half the order in production and had delivered the first unit.

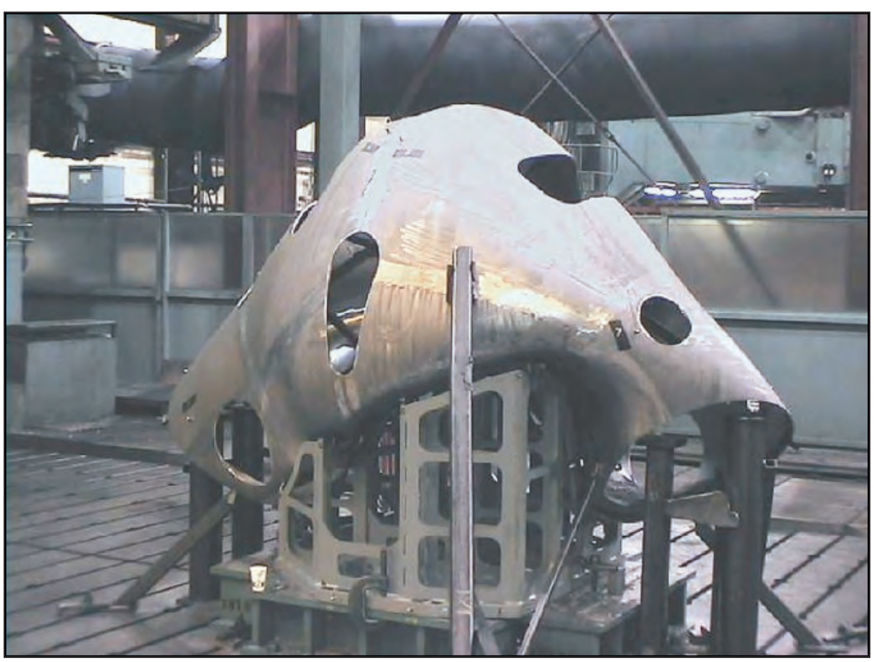


Figure 6. Vacuum vessel shell segment under construction at supplier's facility.

The vacuum vessel supplier had completed tool fabrication, formed all panels and ports, and had begun to weld the shell together.

Both contracts benefited from project-sponsored manufacturing process development completed the preceding year, however new challenges were encountered during the initial stages of production. A cooperative working relationship between the project and suppliers facilitated rapid resolution of issues as they arose and kept the production work moving forward.

The NCSX Project completed its coil manufacturing R&D program with the successful fabrication and testing of the twisted racetrack coil. The coil designs and the manufacturing process development were completed such that the Project was well prepared to start coil manufacture in FY06 following arrival of the first MCWF at the end of FY05.

The NCSX Project continues according to a new baseline plan which was approved in FY05 to fit a reduced DOE funding profile. The Project is on track for First Plasma in July 2009.

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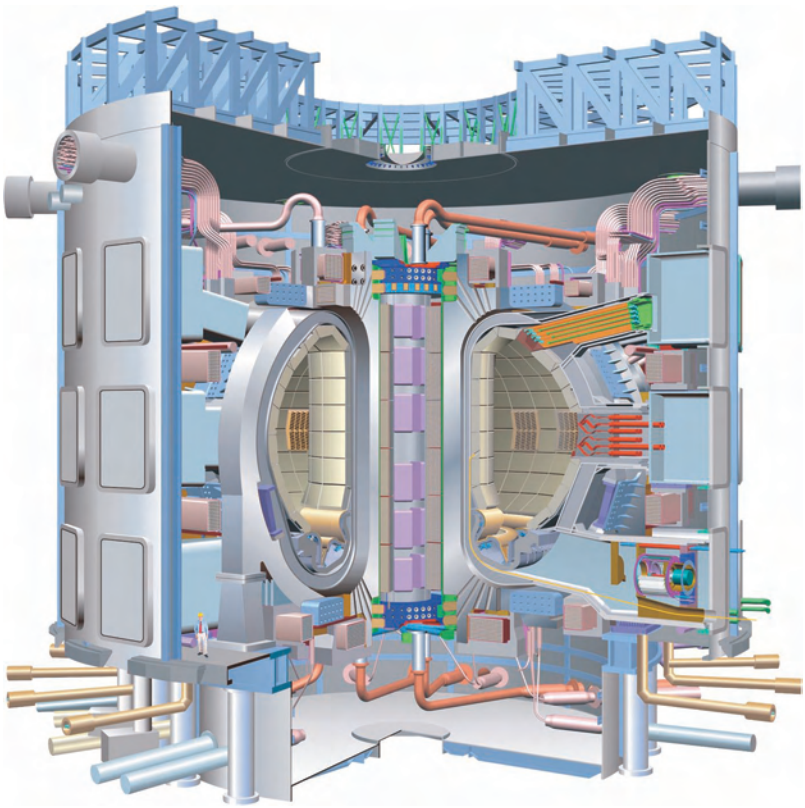
U.S. ITER Project Office



ITER

The international ITER Project became the primary focus of U.S. burning plasma research following President Bush's 2003 decision that the U.S. would enter into negotiations to join ITER construction. In February 2004, the U.S. Department of Energy (DOE) unveiled its "Office of Science Strategic Plan." A companion document, "Facilities for the Future of Science: A Twenty-year Outlook," listed the ITER experiment as the first in the 5- to 10-year scientific priorities. To implement this presidential priority, in July 2004 DOE announced that a Princeton Plasma Physics Laboratory (PPPL)/Oak Ridge National Laboratory (ORNL) partnership would host the U.S. ITER Project Office and the U.S. fusion research community began the development of the organizational structure for its ITER participation.

Fiscal year 2005 was an upbeat period for ITER, both for the international and the U.S. projects. In June 2005, Cadarache, France was selected as the ITER site. This decision unleashed previously constrained discussions on many other issues and enabled significant progress toward selection of the ITER Director General Nominee and completion of the text of the "ITER Joint Implementation Agreement." During FY05, U.S. activities accelerated with establishment of the initial configuration of the national ITER organization and the completion of the U.S. ITER Project's first DOE Office of Science (SC) review led by Daniel Lehman. This review focused on the estimated U.S. cost range and management arrangements for the U.S. contributions to ITER.

International Activities

Resolution of the site issue triggered resumption of discussions on a wide set of fronts including staffing regulations, management and organizational structure, financial regulations, privileges and immunities, and refinements of the assignments of procurement responsibilities to the parties. In September 2005, one multi-party meeting was held at the ITER site at Cadarache to review the status of the draft arrangements and to commence the next stage of discussions aimed at finalizing the texts of the "ITER Joint Implementing Agreement" and its annexes. PPPL Director Robert Goldston and U.S. ITER Project Manager Ned Sauthoff participated in that meeting, with Goldston focusing on the staffing regulations and Sauthoff on management structure and procurement allocations.

While the issues were not fully resolved in FY05, the momentum was established to enable further progress in FY06. Based on the management and organization discussions in Cadarache, it was agreed that the most senior management of the ITER Organization would be a team consisting of the Director General and the Principal Deputy Director General, the former being more outwardly focused and the latter being the construction project manager. Based on the negotiated plan between Europe and Japan and with the concurrence of the other parties, Japan commenced its search for candidates for the position of Director General Nominee.

Domestic Activities

During FY05, the PPPL/ORNL partnership focused on advancing the establishment of the U.S. ITER Project Office. This Office will serve as the U.S. Domestic Agency for ITER, leading the national ITER project, known officially as "U.S. Contributions to ITER." These contributions will include in-kind contributions, staff, and cash.

In FY05, the U.S. ITER Project concentrated its technical activity on completing the R&D, advancing the design, and reducing risk in the provisionally allocated U.S. in-kind contributions.

The **Central Solenoid Magnet** is the set of coils in the inner stack of ITER which will not only drive Ohmic current but also shape the plasma cross section to enable both enhanced performance and experimental flexibility. The U.S. is provisionally assigned responsibility for four of the seven modules of the central solenoid. Contracts for the qualification of industrial vendors for superconducting strand were placed to position the U.S. for a cost-effective acquisition of this key high-tech component. Characterization of the jacket material which surrounds and provides structural support for the superconducting strands and their wraps, studies of joints, and overall design of the central solenoid were conducted by both domestic institutions and U.S. persons assigned to work within the ITER International Team.

The **Shield/Blanket Modules** face the plasma's power and particle effluents, shield the coils and external components from the neutron flux, and support the power deposited by the fusion neutrons absorbed in the blanket. The U.S. performed R&D and design activities that addressed the bonding of beryllium plasma-facing materials to a copper heat sink and the bonding of the copper heat sink to a stainless steel support structure. Work also addressed structural loads from plasma disruptions and the thermo-hydraulics of the cooling configuration, as well as more effective fabrication methods for the stainless steel structure.

Diagnostics provide detailed measurements of the plasma behavior, enabling both control of the plasma and scientific studies aimed at understanding the self-heated plasma state. The provisional allocation for U.S. contributions includes 16% of the diagnostics, including integration of two upper ports, two equatorial ports, and one divertor port. Figure 1 shows examples of ITER port plugs. The design activity built upon the decision that the diagnostics would be allocated by ports, with the party responsible for the port not only providing the lead diagnostic for the port, but also performing integration of other diagnostics into the integrated port structure. The U.S. conducted studies of instruments and of the port plugs which house the diagnostics, with focus on the integration of multiple instruments in the plug, which must also provide shielding and cooling. An example of a U.S. obligated instrument is shown in Figure 2.

The **Ion Cyclotron Resonance Heating (ICRH) system** launches radio waves into the plasma to heat the plasma and to drive current. The provisionally allocated U.S. scope includes an equal sharing of responsibility with Europe for a state-of-the-art ion cyclotron antenna, and U.S. supply of all of the transmission lines, radio-frequency sources, and power supplies. The U.S. worked with Europe on prototyping the ITER ion cyclotron antenna on the Joint European Torus (JET) tokamak in England. The U.S. provided

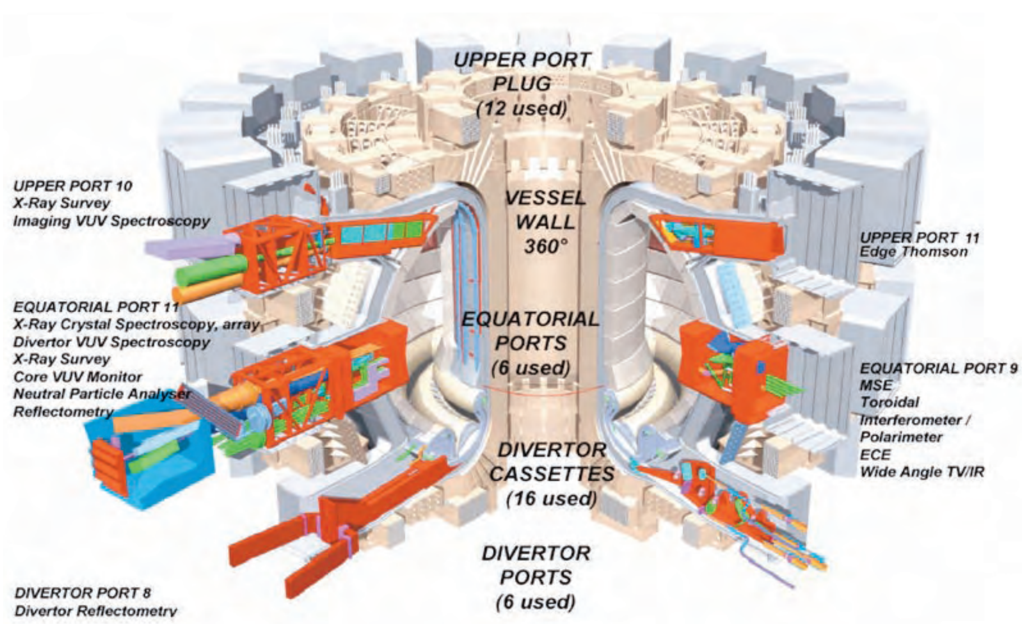


Figure 1. Examples of ITER diagnostic systems and diagnostic port plugs.

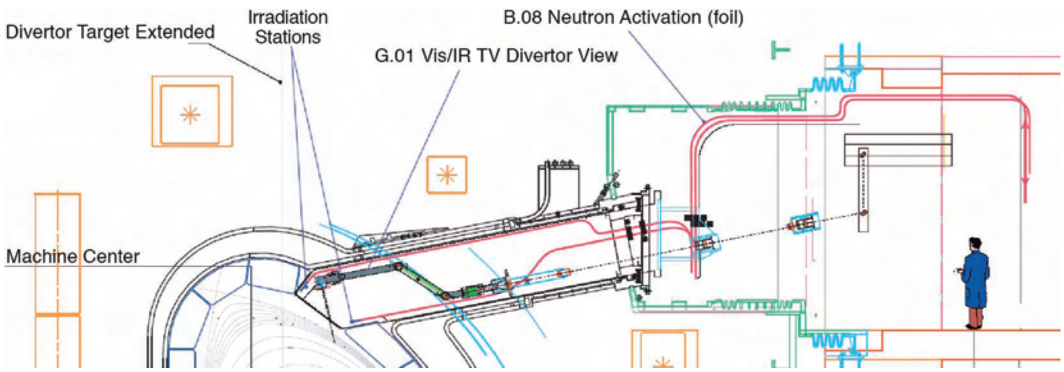


Figure 2. Design drawing illustrating the conceptual design of a visible/infrared (IR) viewing endoscope implemented in an upper ITER port plug. The U.S. is responsible for providing six viewing systems like this and two upper port plugs.

the international team's coordinator for the JET ICRH system.

The **Electron Cyclotron System** injects microwave power into the plasma to heat the plasma, to drive current in localized plasma volumes, and to stabilize MHD modes. The U.S. allocation includes all the 120-gigahertz start-up gyrotrons, all the transmission lines, and all the high-voltage power supplies. During FY05 research on the development of the 120-gigahertz gyrotron and of the steady-state transmission lines was conducted.

The **Pellet Injector** injects frozen deuterium and tritium into the plasma from the high-field side, in order to exploit the propulsion of the resultant ablation blob toward the plasma axis by magnetic forces. U.S. activity on the pellet injector included prototyping of the guide to be used to transport the frozen pellets to the high-field side and assessment of the survivability of pellets launched at 300 meters per second, the canonical ITER injection speed. A gas-gun injector is being studied as well as a centrifuge, with the objective to reduce risk.

Roughing Pumps and Standard Vacuum Components required no R&D or design activity in FY05.

The **Tritium Processing System** accepts the tokamak gas effluent, which is a mixture of hydrogen isotopes and other elements from the inside of the chamber. The system chemically processes the effluent to provide the hydrogen gases for repeated injection from the gas injectors, the pellet injector, and the neutral beams. The U.S. is responsible for the subsystem that takes the effluent from the ITER vacuum system and separates out hydrogen isotopes that are then passed to the European-led isotope separation system, that then leads to the Korean-led gas storage and delivery system. U.S. activity continued to focus on the integrated design of the tritium processing system, working with Europe and Korea.

Conventional Systems include the steady-state electrical power and cooling water for the divertor and vacuum vessel. U.S. activity focused only on cost estimation for these systems.

In the first half of FY05, the Project Team worked on cost estimating and management planning in preparation for the U.S. project's first DOE/SC Review led by Daniel Lehman. In most cases, the previous cost estimates were updated, but for the conventional systems, which had not been previously independently estimated, industrial estimates were procured. The draft "Project Execution Plan and Acquisition Strategy" were prepared and presented to the Review Committee. The outcome of the review was a recognition that significant risks remain due mostly to uncertainties in the international project management processes, in the final specifications of in-kind components, in the roles of the U.S. Domestic Agency and of the ITER International Organization, and in the overall project schedule.

The U.S. ITER Project Office also recognized the importance of engaging the U.S. physics and technology research communities in ITER. The Project encouraged the establishment of a separate organization to organize the U.S. participation in burning plasma studies and to thereby position the U.S. for research on ITER. In May, 2005, the DOE Office of Fusion Energy Sciences appointed Professor Raymond Fonck of the University of Wisconsin to lead such an organization. As stated by DOE, "the general mission of the organization is to coordinate and advocate technical work in burning plasma science research, with an emphasis on support of participation in ITER." The combination of the U.S. ITER Project Office and the burning plasma organization will enable the U.S. to participate in the design and construction of ITER, as well as conduct research relevant to burning plasmas both in the near term and on ITER.

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Theory and Advanced Simulations

The primary goal of the Theory Department at the Princeton Plasma Physics Laboratory (PPPL) is to help provide the scientific foundations for establishing magnetic confinement fusion as an attractive, technically feasible inexhaustible energy source. This involves (1) generating the physics knowledge required for realistic extrapolation to understand present experiments and future burning plasma experiments such as ITER; (2) suggesting new ideas and approaches to stimulate experimental campaigns leading to improved performance; (3) developing improved theoretical analysis capabilities and associated computational tools that are fundamentally sound as well as efficient; (4) contributing to the design of new diagnostics and innovative experimental devices; and (5) providing a stimulating research environment which enables attracting, training, and assimilating the young talent essential for future progress.

The Theory Department plays a major role in advancing fusion science through the study of a variety of topical areas. These include: magnetohydrodynamics (MHD), turbulent transport, energetic particles' interaction with MHD, and boundary physics. The methods used include analytical theory and numerical codes applied to advancing the understanding of tokamaks, spherical torii, stellarators, and field-reversed configurations. The goal is to achieve predictive capability, relevant to future devices that might be used as energy sources. In addition to the study of magnetic confinement, the Department also engages in research in heavy ion beams and space plasma physics.

Turbulence Spreading

One of the persistent, unresolved questions in fusion theory is concerned with the physical extent of the behavior near the edge region of the plasma. Gyrokinetic particle simulations of toroidal ion-temperature-gradient-turbulence spreading using the Gyrokinetic Toroidal Code (GTC) and its related dynamical model have been extended to a system with radially varying ion-temperature gradient, in order to study the inward spreading of edge turbulence toward the core plasma. Due to such spreading, the turbulence intensity in the core region is significantly enhanced over the value obtained from simulations of the core region only, and the precise boundary of the edge region is blurred. Even when the core gradient is within the Dimits shift regime (i.e., dominated by self-generated zonal flows which reduce the transport to a negligible value), a significant level of turbulence can penetrate to the core due to spreading from the edge. The scaling of the turbulent front propagation speed is closer to the prediction from a nonlinear diffusion model than from one based on linear toroidal coupling.

Simulation of Steady-state Turbulence

Simulations of steady-state turbulence due to collisionless ion-temperature-gradient (ITG) drift instabilities in tokamak plasmas have been carried out using the gyrokinetic Particle-In-Cell (PIC) method, including the effects of the parallel acceleration of the particles. This effect, which has generally been ignored by the microturbulence simulation community, has been shown to provide another channel of nonlinear mode coupling in addition to the usual nonlinear $\mathbf{E} \times \mathbf{B}$ interactions. As a result, an increased level of nonlinearly generated zonal flow has been observed, which, in turn, expedites the evolution of the ITG turbulence to its steady-state at a faster rate and at a lower level of thermal transport (Figure 1). These simulations have been carried out on the Seaborg supercomputer at the National Energy Research Supercomputer Center (NERSC) and on the X1E supercomputer at the Oak Ridge National Laboratory. The X1E supercomputer has provided the opportunity to carry out convergence studies on ITG simulations using from 10 particles per cell to 800 particles per cell. Through these studies, it has been concluded that discrete particle noise does not play a role in the steady state of these simulations.

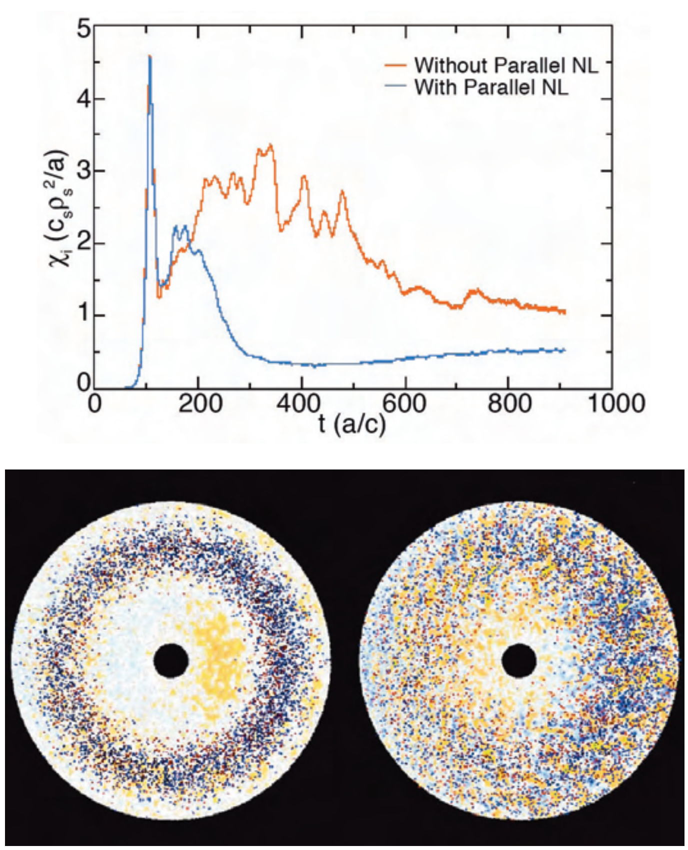

Figure 1. (Top) Graph shows the effect of including the parallel nonlinearity, blue versus red lines. This shows the evolution of ion-temperature-gradient turbulence to its steady- state at a faster rate and at a lower level. (Bottom) Left "with" and right "without" parallel velocity-space nonlinearity. These simulations show that there is less diffusion (spreading) of the particles and also that there is a well-defined internal structure in the electrostatic potential (in yellow) when the term is included.

NCSX Magnetic Flux Loops

Calculations have been completed on the design of magnetic flux loops for the National Compact Stellarator Experiment (NCSX) vacuum vessel. The loops will facilitate the numerical reconstruction of 3-D stellarator-symmetric MHD equilibria, and the diagnosing of non-stellarator-symmetric field perturbations that will be present in the experiment due to symmetry-breaking perturbations from the plasma and the coils.

A large database of approximately 2,500 NCSX equilibria was generated, which encompasses the range of plasma current, toroidal field, beta, and shapes that can be achieved in NCSX. A Singular Value Decomposition analysis was performed on a matrix relating flux measurements at a candidate set of trial loops to equilibrium magnetic field values evaluated at a dense mesh of points on a single toroidal control surface surrounding all of the equilibria. A novel method for ranking the diagnostics was developed, and an understanding of which regions of the vacuum vessel are most important for the placement of flux loops was obtained (Figure 2). As a result of the analysis, 138 two-turn flux loops have been designed for installation in NCSX and will be used for determining the stellarator-symmetric signals; an additional 52 loops will be used to characterize the non-stellarator-symmetric signals.

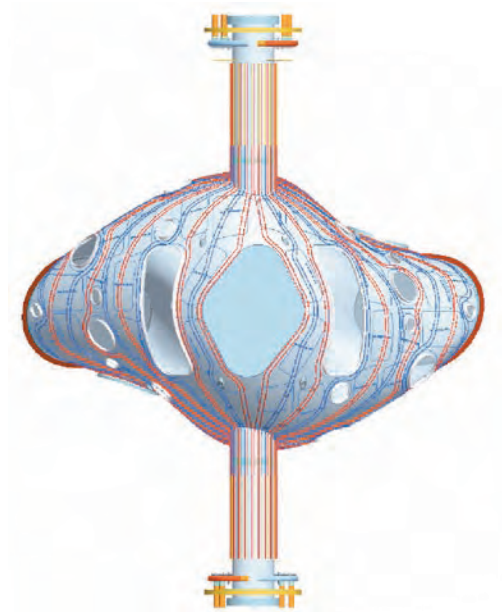

Figure 2. A perspective view of the National Compact Stellarator Experiment (NCSX) vacuum vessel showing some of the magnetic flux loops — approximately rectangular loops in blue. The loops have been optimized to enable reconstruction of the three-dimensional plasma equilibrium. The ports for diagnostic and heating access are shown as cutouts.

CDX-U Simulation

In a computational tour de force, PPPL researchers have used the Scientific Discovery through Advanced Computing (SciDAC) program 3-D extended MHD code to simulate the macroscopic dynamics of an actual laboratory tokamak experiment, the Current Drive Experiment-Upgrade (CDX-U) at the PPPL (Figure 3), using fully realistic plasma parameters, such as the magnetic Reynolds number, the ratio of the Alfvén transit time to the resistive diffusion time. This comprehensive simulation, which utilized the same parameters as those in the experiment, was able to reproduce a key feature of that experiment — the sawtooth oscillation — in unprecedented detail.

A single simulation required piecing together hundreds of segments that were run over a period of four months at the NERSC teraflop computing facility. Previous simulations had been carried out with scaled-down values of the magnetic Reynolds number and other dimensionless parameters in order to ease the computational requirements. By using the actual experimental parameters, the team was able to make direct comparisons with the period and waveform of the

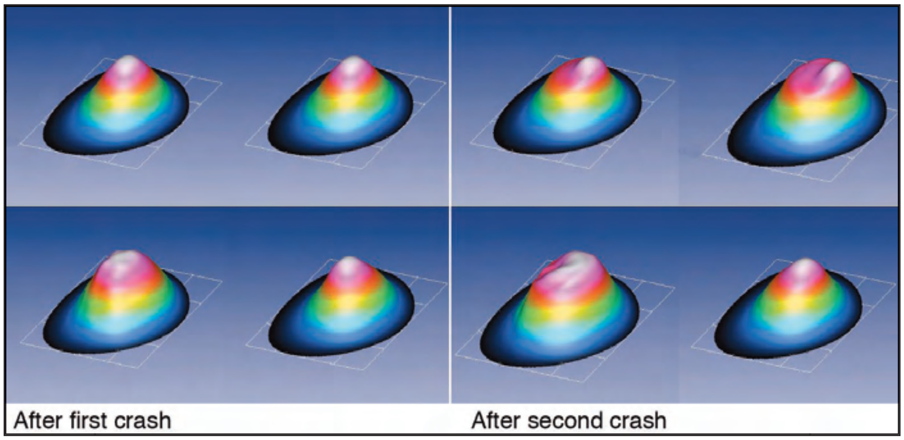

Figure 3 Simulation of a sawtooth oscillation from the CDX-U experiment. The sawtooth period in the simulation is approximately 100 μs, in good agreement with the experimental observation of 125 μs.

sawtooth oscillation, and obtained agreement to within 25% of the experimental results. More refined simulations are presently underway, including additional physical effects. These simulations are providing an important benchmark for these computational codes and underlying theory, which will next be applied to larger existing experiments and, within a decade, to ITER parameters.

Stability of ITER-like Plasmas

The Alfvén eigenmode stability properties of ITER-like plasmas have been studied by employing the global, hybrid-kinetic perturbative code NOVA-K. The code has been benchmarked to study Alfvén eigenmodes in reversed-shear plasmas against observations on the DIII-D tokamak at General Atomics in California (Figure 4). Simulations show that the most unstable toroidal mode numbers are shifted towards very high values. In plasmas with regular shear, toroidal Alfvén eigenmodes with mode numbers n spanning from 7 to 12 were found to be unstable due to the drive produced by both the alpha particles and the beam ions. Simulations also show that the damping is strong at the plasma center due to ion Landau damping and at the periphery due to trapped-electron collisional damping.

From the simulations, it also follows that the more the beam is directed off-axis vertically, the stronger the drive is. This is because during on-axis neutral-beam injection, the beam ion beta builds up near the plasma center, where the ion Landau damping is very strong. For off-axis neutral-beam injection, the region of the strong gradients in beta is shifted outward to the middle of the minor radius, so that both central ion Landau damping and edge-trapped electron collisional damping are decreased. Neutral-beam injection may provide an important tool for the experimental study of different types of Alfvén eigenmode instabilities by creating the additional drive that is required.

Simulations of Field-reversed Configurations

A new series of three-dimensional hybrid simulations have been performed in order to study the nonlinear evolution of field-reversed configurations (FRC) in the presence of a conducting shell and the energetic beam ions as envisioned in the

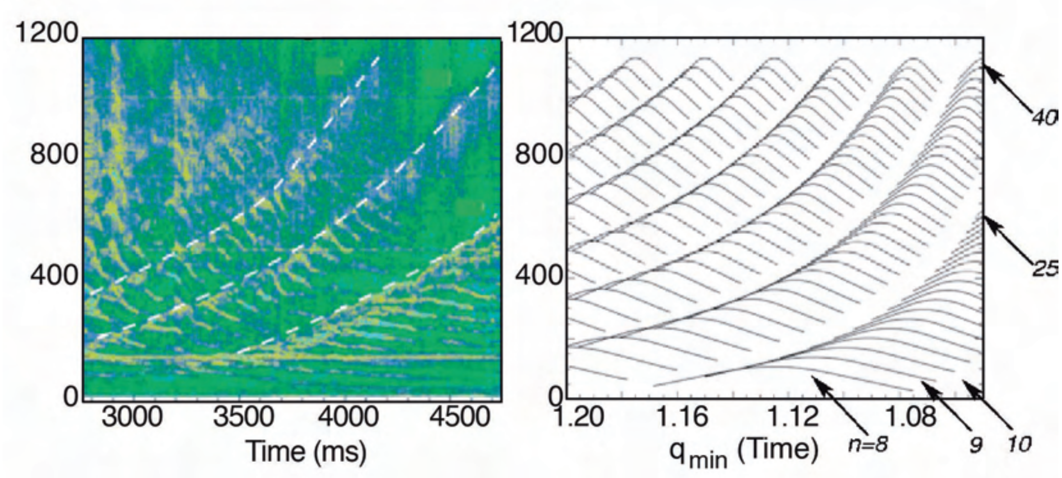

Figure 4. Power spectrum from DIII-D (left) and theoretical model (right).

proposed Magnetic Reconnection/Field-Reversed Configuration experimental geometry. These simulations show that the residual instability (n = 3) saturates nonlinearly at a low amplitude, and therefore is not a dangerous mode. Simulations that model "sustained" FRC operation (i.e., without a decay in the equilibrium current) show that after the n = 3 mode saturates, the resulting configuration remains stable with respect to all global MHD modes, as long as the current in the field-reversed configuration is sustained. In contrast, when the configuration is allowed to decay resistively in the simulations, the slow reduction in the separatrix radius results in a reduction of the conducting-shell effects, and the eventual destabilization of the n = 1 tilt mode.

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Computational Plasma Physics

The mission of the Computational Plasma Physics Group at the Princeton Plasma Physics Laboratory (PPPL) is to advance and disseminate modern computational methods throughout PPPL and the fusion community and to use these methods to improve the calculation of critical experimental and theoretical program elements. Areas of activity include transport analysis and FusionGrid, applications of the adaptive mesh refinement techniques in three dimensions, the use of high-order discretizations, advanced data transfer and visualization, and optimization techniques for parallel-vector computers.

The FusionGrid

The Princeton Plasma Physics Laboratory's FusionGrid TRANSP computational service completed its third full year of operation. During FY05, about 1,600 TRANSP analysis runs were completed for ten tokamak experiments in the U.S., Europe, and Asia (Figure 1). Users can follow the progress of their runs, via log files and browser-enabled Java graphics (ElVis), using links on the TRANSP website (http://w3.pppl.gov/TRANSP). Problem runs are diagnosed by a team of PPPL experts in a process that leads to continual improvement of the software. In an improvement to ease of use,

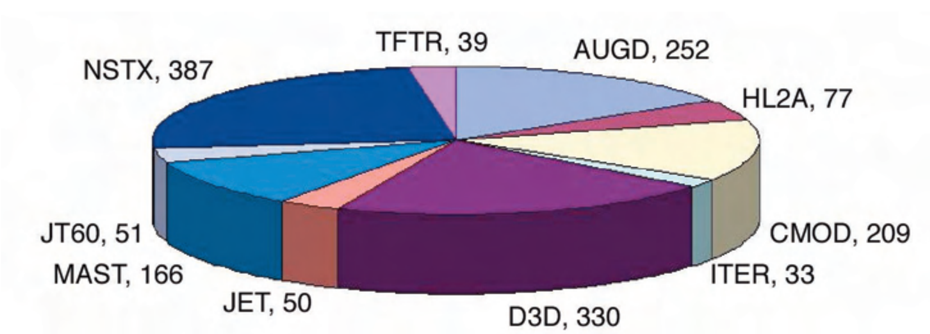

Figure 1. Between November 1, 2004 and October 15, 2005, there were 1,594 TRANSP code analyses runs on the PPPL servers. Key (clockwise): TFTR = Tokamak Fusion Test Reactor at PPPL (decommissioned in 1997); NSTX = National Spherical Torus Experiment at PPPL; AUGD = ASDEX Upgrade at the Institut für Plasmaphysics, Garching, Germany; HL2A = tokamak at the Southwest Institute of Physics in Sichuan, China; ITER = to be built by an international collaboration of countries; C-MOD = Alcator C-mod at the Plasma Science and Fusion Center at the Massachusetts Institute of Technology; DIII-D = Doublet-III-D at General Atomics; JET = Joint European Torus, European Development Agreement, United Kingdom; MAST = Mega-Ampere Spherical Tokamak at Culham Laboratory, United Kingdom; JT-60U = Japanese Tokamak at the Japanese Atomic Energy Research Institute, Japan.

the internet X.509 certificate/proxy system, which authenticates run requests, is now managed on a mirrored central server (http://cert.fusiongrid.org). There are now 75 authenticated FusionGrid TRANSP users worldwide. This service is built from tools developed in the Department of Energy Office (DOE) of Science's "Scientific Discovery through Advanced Computing (SciDAC)" Fusion Collaboratory, a collaboration funded by the DOE Office of Advanced Scientific Computing Research involving PPPL, General Atomics, the Massachusetts Institute of Technology, Argonne National Laboratory, Lawrence Berkeley National Laboratory, and the computer science departments at Princeton University and the University of Utah.

Preliminary tests indicate that the FusionGrid TRANSP service can be generalized to support a coordinated suite of applications operating on a network using heterogeneous hardware. Software architectures are being developed and tested that will enable a serial TRANSP "driver" to invoke MPI-parallelized services (see Figure 2) e.g., for accurate calculation of neutral-beam and radio-frequency heating in tokamak plasma simulations. A single parallel service would be shared by multiple serial drivers, assuring efficient utilization of computational resources even in the context of a mixed serial-parallel multi-physics simulation.

NUBEAM Code Parallelization

The parallelization of guiding-center drift-orbit calculations in PPPL's Monte Carlo fast-ion package NUBEAM has been completed using MPI (Message Passing Interface). The performance of the particle-orbit portion of the calculation (ORBALL, taking 90–95 per cent of the total time) has been shown to scale with near linearity for up to 32 processors (Figure 3) on a Linux cluster. The recent Fortran-90 modernization of the NUBEAM code removed all limits on the size of NUBEAM's Monte Carlo particle lists, allowing use of a large number

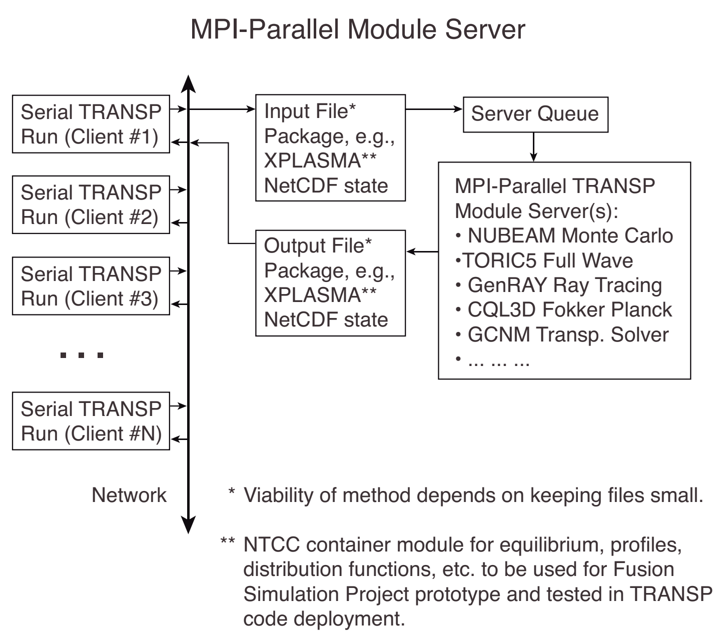

Figure 2. Preliminary design for a serial-parallel multiprocess hybrid architecture for the TRANSP FusionGrid service. Serial-serial multiprocess tests have been completed which indicate that the process-to-process file communications overhead is manageable.

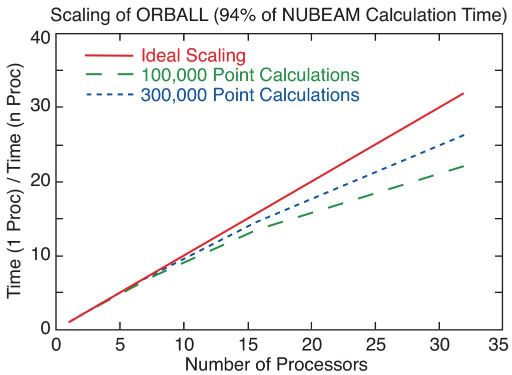

Figure 3. Measurements of parallelization efficiency of the NUBEAM Monte Carlo fast-ion orbit and slowing down code calculations. Shown is time spent in ORBALL subprogram.

of Monte Carlo particles (>1 million), which is required for the computation of smooth fast-ion distribution functions. A random number generator developed at PPPL has been used to reproduce to 64-bit precision all the particle variables regardless of the number of processors in use. It is expected that the MPI parallelization will make it practical to routinely compute fast-ion distribution functions with unprecedented statistical fidelity in time-dependent calculations. Additional improvements for the NUBEAM code are being made to improve scaling, and further tests to ascertain the scaling of the entire TRANSP calculation that utilizes NUBEAM are planned. The MPI-parallel NUBEAM code is being installed as a FusionGrid service on the PPPL cluster, where it will be linked to the existing TRANSP service and made available as an option to all FusionGrid TRANSP users.

3-D Simulation of Pellet Fueling using AMR

In a successful collaboration between computational scientists at PPPL and the Lawrence Berkeley National Laboratory (LBNL), a unique computational tool based on the adaptive mesh refinement (AMR) method for simulating pellet fueling of tokamak plasmas has been developed. This fully 3-D code, which operates at the National Energy Research Supercomputing Center (NERSC) and at the Leadership Class Computing Facility at the Oak Ridge National Laboratory (ORNL), can calculate the multi-scale multi-physics processes involved in both the initial pellet ablation and the subsequent classical and anomalous mass distribution.

A crucial aspect of this project was to apply the AMR technique developed at LBNL in the curvilinear coordinate system defined by the complex magnetic fields in a tokamak. Figure 4 shows a time sequence of density images for high-field side (top panel) and low-field side

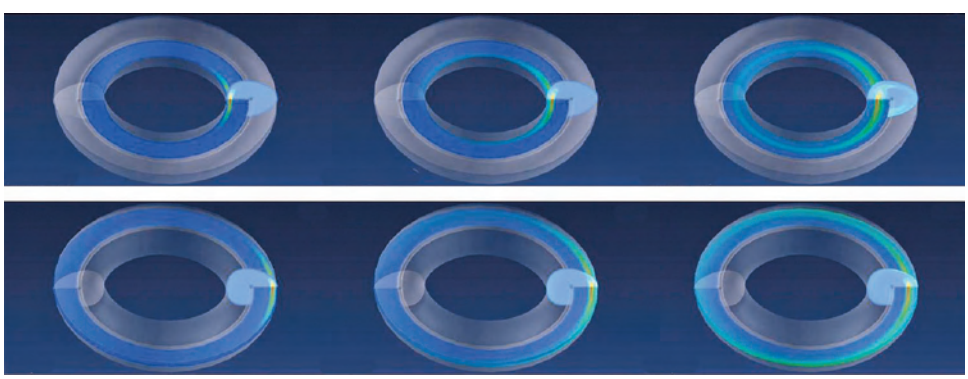

Figure 4. Time sequence of density images for high-field side (top panel) and low-field side (bottom panel) pellet injection.

(bottom panel) pellet injection. Flux-averaged density profiles show that high-field side pellet injection leads to better core fueling than low-field side injection, consistent with previous experiments. This unique tool is currently being validated against experiments on DIII-D at General Atomics, and will be used to evaluate the design of the pellet fueling system on ITER. This work was presented as an invited talk at the 2005 American Physical Society Division of Plasma Physics Meeting.

Compute Power of the GTC Code

A new level of parallelism has been implemented in the 3-D gyrokinetic particle-in-cell code (GTC) in order to increase its concurrency and compute power. Within each toroidal domain, the new algorithm adds the capability of splitting the particles between several processors, allowing the GTC code to efficiently utilize thousands of processors and reach a very high phase space resolution. New optimizations have also made the code more efficient on the new class of vector computers, such as the ORNL CRAY-X1E and the Japanese Earth Simulator (ES). As a result, we have been able to run 13 billion particles at a sustained speed of 7.2 teraflops using 4,096 processors on the ES, with similar results (but on fewer processors) on the CRAY-X1E.

As part of a study in collaboration with the Future Technologies Group at LBNL, the GTC code has been ported and benchmarked on the most powerful computers currently available, including the IBM Blue Gene/L, the CRAY-XT3, and the already mentioned CRAY-X1E and ES. On the IBM Blue Gene/L, the code reached a sustained speed of 1.7 teraflops on 16,384 processors with near perfect scaling. These scaling studies are illustrated in Figure 5. High-resolution, high-concurrency runs on the CRAY-X1E were also used in a convergence study aimed at demonstrating the validity of the particle approach in predicting turbulent levels in tokamaks and stellar-

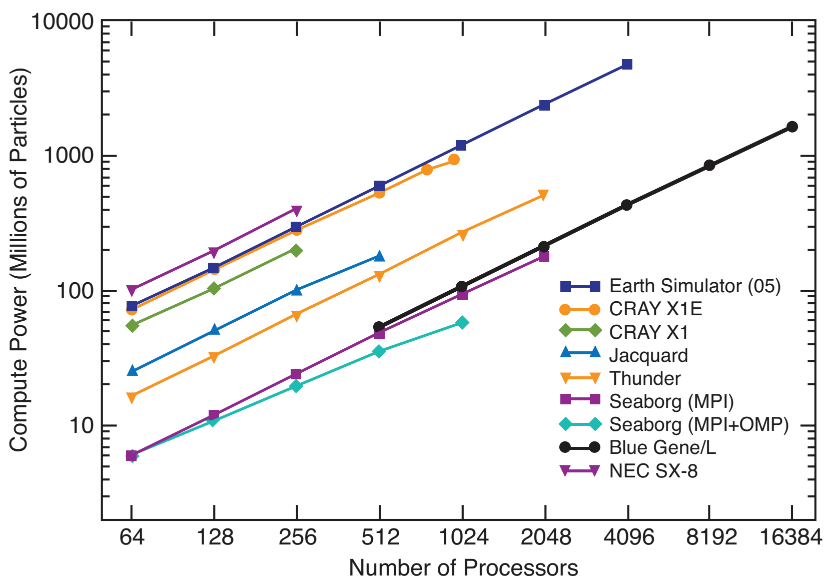

Figure 5. Compute performance of the new high-concurrency version of the GTC code. The MPI-based particle splitting algorithm allows the code to scale to more than 16,000 processors. The highest performance was achieved on 4,096 processors of the Earth Simulator computer, reaching 7.2 teraflops with 13 billion particles.

ators. Simulations at an unprecedented 1,000 particles per cell were performed in record time.

Optimization of the Elliptic Solves in M3D Code

The majority of the time used in the 3-D extended MHD code M3D (for a non-hybrid run) is in the elliptic solves. These are 2-D solves, within each poloidal plane, that are performed each time step. There are 13 different solves required for each poloidal plane for each time step. There can be 100 (or more) poloidal planes in one calculation, and these solves can all be done concurrently so only a modest degree of parallelism is required for each solve.

Throughout the year, working with our SciDAC collaborators, we have made it a priority to optimize these solves utilizing the most effective linear solver for each operator and boundary condition. The speed of the symmetrized version of the M3D code has now been increased two to three times for the typical mesh size now being used (typically 100 to 150 radial grid points). As shown in Figure 6, the ratio increases as we increase the size of the mesh as is planned for the future.

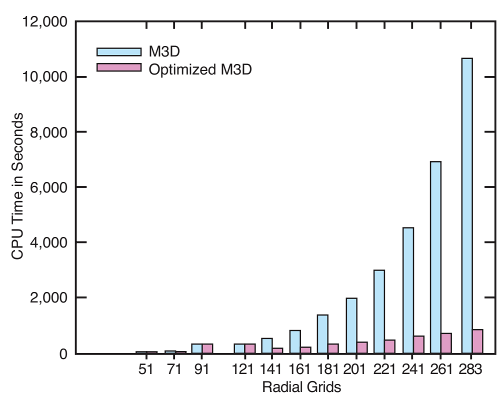

Figure 6. CPU time per timestep for the old M3D code and the optimized version.

Six-field Extended MHD now in C^1 Finite Element Code

An extended-MHD code (M3D-C^1) has been developed based on high-accuracy triangular finite elements that are constructed to have continuous first derivatives. The Galerkin method allows these elements to be used on equations having up to fourth-order spatial derivatives.This system has now been implemented on the full set of extended-MHD equations, including the Hall and Gyroviscous terms, and promises to provide a very efficient and accurate tool for studying global stability and reconnection phenomena in tokamak and stellarator plasmas.

In Figure 7 is shown the contours of the current density during the late phase of a reconnection calculation. Preliminary results of the M3D-C^1 code were presented as an invited talk at the 2004 American Physical Society Division of Plasma Physics Meeting.

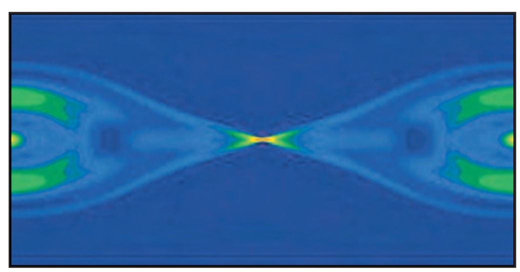

Figure 7. Contours of the current density during the late phase of a reconnection calculation using the full set of extended-MHD equations.

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Space Plasma Physics

The Space Physics Group at the Princeton Plasma Physics Laboratory (PPPL) has been modeling the dynamical evolution of the solar-terrestrial system so as to understand how energy and momentum are coupled between the sun, magnetosphere, and ionosphere. In this report, progress in understanding (a) substorm growth phase, onset, and dipolarization and (b) the roll effect in solar prominence eruption is described.

Identification and Modeling of Substorm Growth Phase

Substorms are dynamical events that reconfigure the magnetosphere and are associated with significant deposition of energy into the ionosphere. One of the challenges in space physics is to understand the underlying physical processes responsible for substorms. The dynamical evolution of the substorm is divided into several phases. The growth phase occurs prior to the onset of the substorm, and it is during this phase that energy is stored in the magnetotail by the addition of magnetic flux. The increased magnetic pressure leads to a compression and elongation of the magnetotail and the intensification of the cross-tail current sheet. Understanding the evolution of the magnetosphere during the growth phase is important for understanding conditions favorable to the rapid onset of the substorm because the stability of the tail depends significantly on the plasma configuration. After the substorm, the magnetosphere relaxes to a more dipolar configuration.

During the period of September 2001 to December 2002, ten events detected by the POLAR satellite were identified that showed a clearly defined sequence of substorm growth phase, onset, and dipolarization. Each substorm onset event was accompanied by Pi-2 activity recorded by the CANOPUS array of ground-based magnetometers, and many of the onsets were characterized by auroral brightening seen in FUV (far-ultraviolet) auroral image data from the IMAGE spacecraft. POLAR magnetic field data was analyzed and an instability with a period of about one minute (in Pi-2 frequency range) was identified. A substorm growth phase observed by POLAR on August 31, 2002 was identified and due to its long duration and clear tail-like field geometry renders itself perfectly to modeling. The data shows a steady decrease of the magnetic field, to a B_Z value of about 10 nT. The overall plasma pressure is quite anisotropic, with anisotropy $P_\perp/P_{||} \approx 1.4$.

To model the 3-D magnetospheric structure for the substorm growth phase of the events encountered by POLAR, three-dimensional magnetospheric equilibrium calculations were performed. The constraints that POLAR observational data placed upon the modeling were as follows: POLAR data prescribes the particle pressure (both electrons and ions) along the spacecraft trajectory. Because the trajectory during the growth phase is limited in space, it is assumed an equatorial global distribution for both the pressure and the degree of anisotropy. The assumptions used a continuation of the pressure profiles and anisotropy elsewhere in the plasma sheet by employing empirical formulas. The normalization was such that the pressure in the 3-D equilibrium code at location of the POLAR satellite matched exactly the pressure obtained from the satellite particle data. Using boundary conditions from empirical magnetic field models, the force-balanced configuration in the whole domain under study was computed. Results from modeling a substorm growth phase identified from POLAR observations are shown in the following figures.

An interesting observational feature is that the plasma pressure obtained from particle data measured by the HYDRA instrument is very anisotropic: $P_{\perp}/P_{||} \approx 1.4$ at the satellite location during the late stage of the growth stage. The 3-D quasi-static magnetosphere with force-balance between plasma perpendicular and parallel pressures and magnetic field was obtained from the MAG-3D code. The numerical solution was clearly able to reproduce the magnetospheric state during the substorm growth phase observed by POLAR. Moreover, using the particle data constraints, the code-computed magnetic field in the near-Earth region had a local minimum of around 10 nT, very close to the values measured by POLAR toward the end of the growth phase. Figure 1 shows the azimuthal current density in the equatorial plane that is highly localized in the region with the radial distance between $6R_E$ and $8R_E$ in the night side and the peak current density in the equatorial plane is about 4.5 nA/m^2.

The pressure anisotropy causes a current sheet splitting, with maximum cross-tail current density value above and below the equatorial plane. This is indeed visible in Figure 2, which shows the azimuthal current density distribution in the noon-midnight meridian plane. The

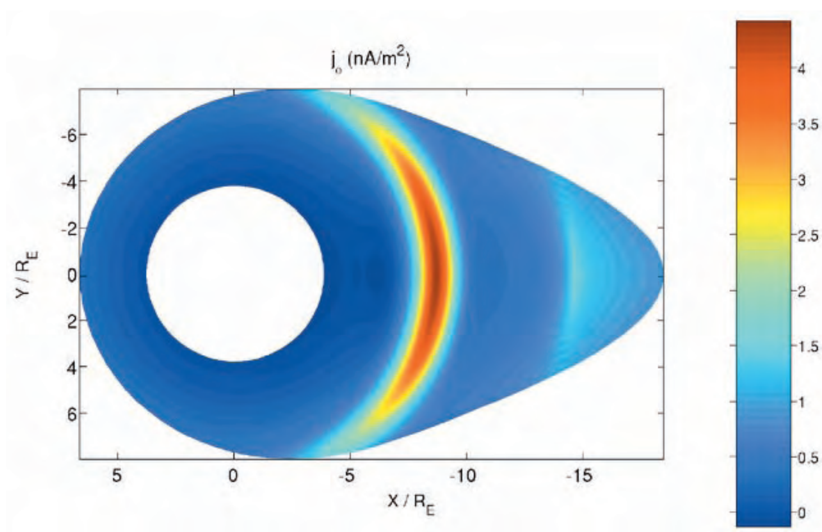

Figure 1. Azimuthal current density in the equatorial plane for the 08/31/02 substorm growth phase identified by the POLAR satellite. The maximum current density in the equatorial plane is only about 4.5 nA/m^2.

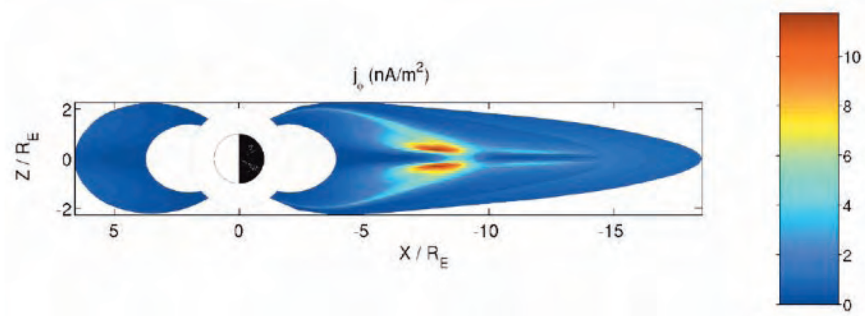

Figure 2. Plot of the computed azimuthal current density in the noon-midnight meridional plane. Due to the relatively large anisotropy, the maximum current density is not in the equatorial plane (where the maximum is only around 4.5 nA/m^2), but rather in very thin twin current sheets above and below the plane (with a maximum roughly of 11 nA/m^2).

north-south extent of the cross-tail current density is very narrow and is about $0.2R_E$ with the peak values located at about $Z = \pm 0.3R_E$. The current sheets are spatially limited to only an extent of about $2R_E$ along the tail direction.

The double current sheets using the MAG-3D code, although much thinner than what was found before with isotropic pressure, do not lead to an extremely large curvature of the field lines. Therefore, for anisotropic pressure cases, observations of very thin current sheets in the magnetosphere do not necessarily mean extreme magnetic field curvature at locations in the equatorial plane, because the double current sheets reduce the field curvature at locations in the equatorial plane.

Theory and Modeling of the Roll Effect in Solar Prominence Eruption

Solar prominences are ribbon-like structures composed of cool ($T \sim 10^4$ K) and dense ($n_e \sim 10^{11}$ cm^{-3}) partially ionized gas suspended in the hot ($T \sim 10^6$ K) and tenuous ($n_e \sim 10^9$ cm^{-3}) solar corona. A solar prominence spends most of its lifetime (a day to a month) rather stably, but eventually ends its life with eruption. It is often observed in prominence eruptions that the top part of the prominence ribbon bends in one direction to make the ribbon horizontally flat. Also the legs of the erupting prominence undergo twisting motions of opposite senses (Figure 3). This effect has recently been discovered and named as "roll effect" by S.F. Martin of Helio Research.

The sense of rolling is found to depend on the chirality of the prominence, which is related to the sign of magnetic helicity. The roll breaks the geometrical symmetry of the system. Unless the prominence environment is systematically asymmetric, the symmetry-breaking evolution of a prominence can hardly be understood in the framework of the conventional magnetohydrodynamics (MHD) with isotropic electrical conductivity. When the electrical conductivity is anisotropic, the symmetry of the system is not conserved.

The solar magnetic field evolution with anisotropic electrical conductivity was investigated. Now the motion of the magnetic field is not tied to the plasma center of mass, but has a component against the current direction. Thus, the rising motion of the magnetic field is skewed to a certain direction conditioned by the current. When magnetic reconnection

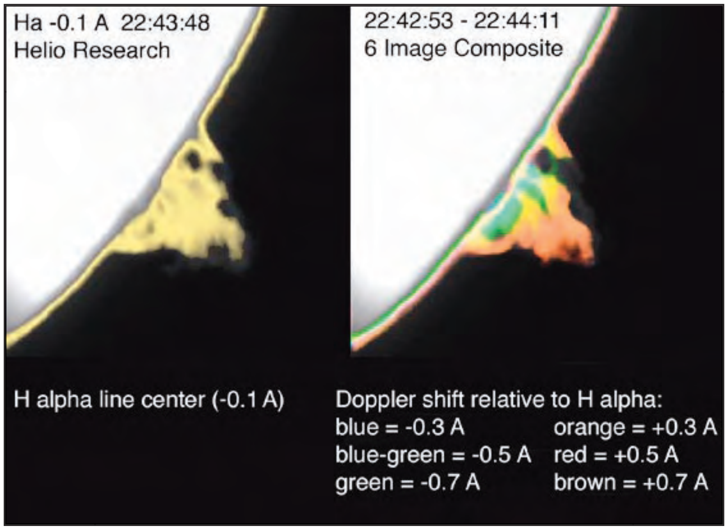

Figure 3. Hα observation of an erupting prominence exhibiting a roll effect (picture courtesy of S.F. Martin). The left picture is taken at the Hα line-center. The right picture is a composition of images taken at six different Hα wings. The top and the outer part of the prominence are receding from the observer (red shift) while the inner part of the prominence is approaching the observer (blue shift). The overall structure is undergoing a rolling motion.

takes place in a magnetic loop or arcade, the direction of the current in the current sheet region and in the legs of the current sheet is almost opposite to the current direction in the underlying reconnected loops. This explains why the Doppler shift at the top and outer parts of the erupting prominence is of the opposite sense to that in the bottom part between the prominence legs (Figure 4). Furthermore, this theory can account for how the sign of the roll effect depends on the chirality of the prominence as observed.

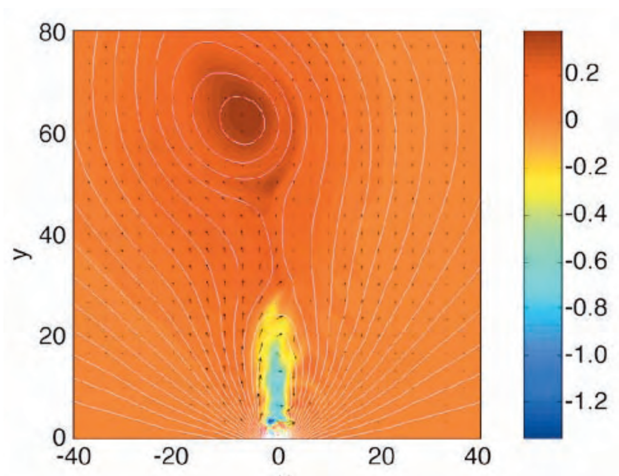

Figure 4. Simulation of a magnetic arcade evolution with a helical flux rope, which corresponds to an erupting prominence. The colors show the line-of-sight component of velocity and the arrows show the velocity components in the vertical plane. The skewing of the magnetic field structure only arises when the electrical conductivity tensor is anisotropic.

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Off-site Research

The Off-site Research Department at the Princeton Plasma Physics Laboratory's (PPPL's) seeks to broaden the contributions of our engineers and scientists by providing access to leading fusion research facilities worldwide. Working side-by-side with their colleagues in multi-institutional teams allows PPPL researchers to learn from others as well as to impart their knowledge and experience. Integrated teams of experimentalists, theorists, and engineers can tackle the important scientific and technical issues on a variety of devices, comparing and contrasting phenomena on different scales and in different configurations. In particular, the Off-site Research Program provides PPPL researchers with access to the largest tokamak facilities throughout the world.

DIII-D Collaborations

PPPL collaboration on the DIII-D tokamak, located at General Atomics (GA) in La Jolla, California, continued to make major contributions toward the development of the Advanced Tokamak (AT) reactor concept through active control of resistive wall modes, fast-wave development for Advanced Tokamak plasma control, diagnostic upgrades and scientific advances in macroscopic MHD, microturbulence, and energetic particle phenomena. The Laboratory has also been a major contributor to machine operation, providing mechanical, radio-frequency, and diagnostic engineering support to the DIII-D facility.

Fast-wave Heating and Current Drive

A key element of PPPL's mission on DIII-D is to work with an interdisciplinary team from Oak Ridge National Laboratory (ORNL) and GA to effectively couple fast waves into Advanced Tokamak plasmas for electron heating and current drive. Advanced Tokamak research seeks to replace inductive (finite duration) currents with steady-state noninductively driven current. Rapid progress has been made in restoring the operational capabilities of the fast-wave systems on DIII-D where up to 3 MW of fast-wave power has been coupled into low-confinement mode (L-mode) edge plasmas for a duration of one second. The pulse duration and power are expected to increase next year, along with efforts to couple the fast-waves into Advanced Tokamak plasmas. Figure 1 shows the application of 3 MW of fast-wave power into a DIII-D plasma with an L-mode edge.

Resistive Wall Mode Control

The maximum attainable plasma pressure in a tokamak can be limited by MHD instabilities. These instabilities can be suppressed by the presence of a close fitting conducting shell around the plasma. Image currents in the wall can cancel the magnetic perturbations of the instability and limit its growth. The finite resistivity of the real wall in a tokamak limits the ability of the wall to suppress modes and leads to a class of instabilities that grow on the resistive time scale, the so-called "resistive wall modes" (RWM). To sup-

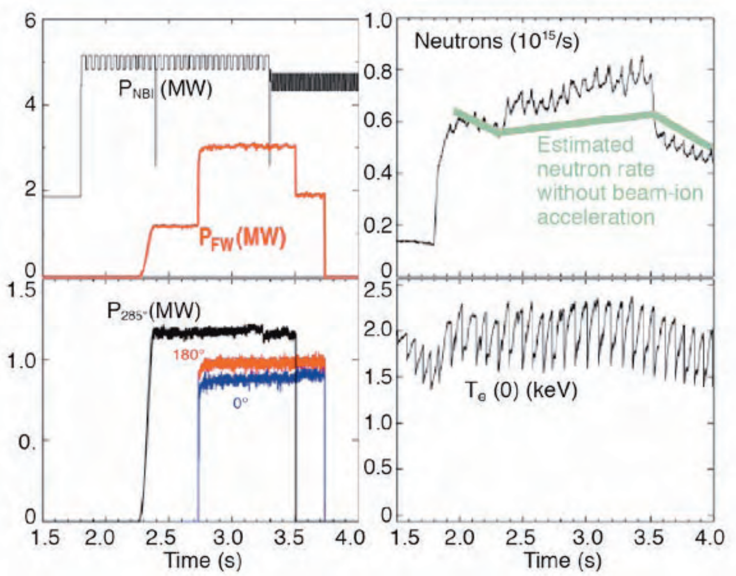

Figure 1. A fast-wave power of 3 MW (top left) applied for one second in DIII-D plasma. The predicted neutron emission underestimates the measured value (top right). The phase of the three fast-wave antennas is given (bottom left) and the central electron temperature is shown (bottom right).

press these modes external fields can be applied that mimic the image currents. These currents are applied from external coils powered by supplementary power supplies. PPPL, Columbia University, and GA collaborate to provide a system to perform this action and to perform experiments detailing its effectiveness.

In FY05, PPPL had primary engineering responsibility for the audio amplifier upgrade to the RWM system. A total of 12 audio amplifiers were installed, one for each coil, and tested during plasma operation in this period. The testing revealed that the faster response time of the audio amplifiers was adequate to lock onto the RWM in closed loop feedback operation. The results of these experiments were presented at the American Physical Society Division of Plasma Physics meeting by Michio Okabayashi of PPPL who is also the leader of this thrust on DIII-D. Figure 2 shows the n = 1 sensor signal with and without feedback control using the high bandwidth audio amplifiers. The residual level of n = 1 oscillations with feedback control is reduced during edge-localized mode activity. The assessment is that the number of amplifiers needs to be increased in order to operate at high plasma pressure.

Understanding a "Sea of Alfvén Eigenmodes"

Last year, PPPL researchers made an important observation in the area of energetic-particle-driven instabilities. This observation was the existence of a "sea of Alfvén eigenmodes," with as many as five such modes present at the same time. In FY05, PPPL researchers resolved the mystery surrounding such a broad spectrum of high-frequency core localized modes on DIII-D. These modes are of the scale of ion-temperature gradient (ITG) mode turbulence and like ITG modes they most likely derive some fraction of their drive from the background thermal ions. The key contributions of the PPPL team include: (i) detailed modeling of the mode-frequency evolution, (ii) identification of the mode localization to the region of

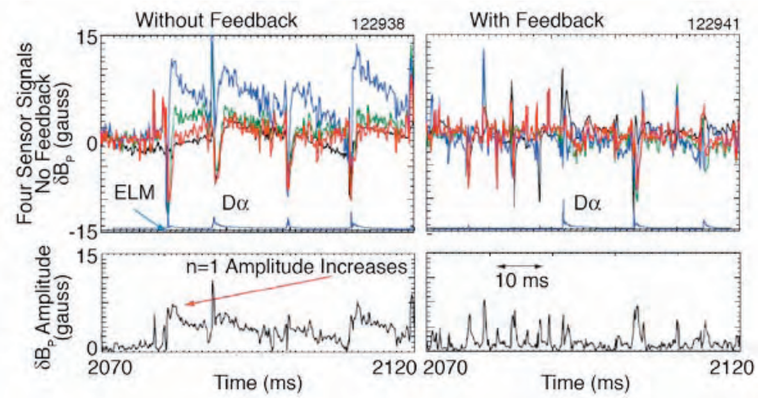

Figure 2. The n=1 sensor signal with (right) and without (left) audio amplifier feedback. The residual level of n=1 signal after edge-localized modes is reduced with the application of feedback control.

shear reversal, (iii) direct measurement of the poloidal wavelength of the instabilities, and (iv) calculation of the thermal ion drive and identification of the dominance of the thermal drive at high toroidal mode numbers (short perpendicular scale). Figure 3 displays a spectrum of modes together with the model analysis that identifies the mode spectrum and reproduces the evolution of the magnetic safety factor from the frequency fitting.

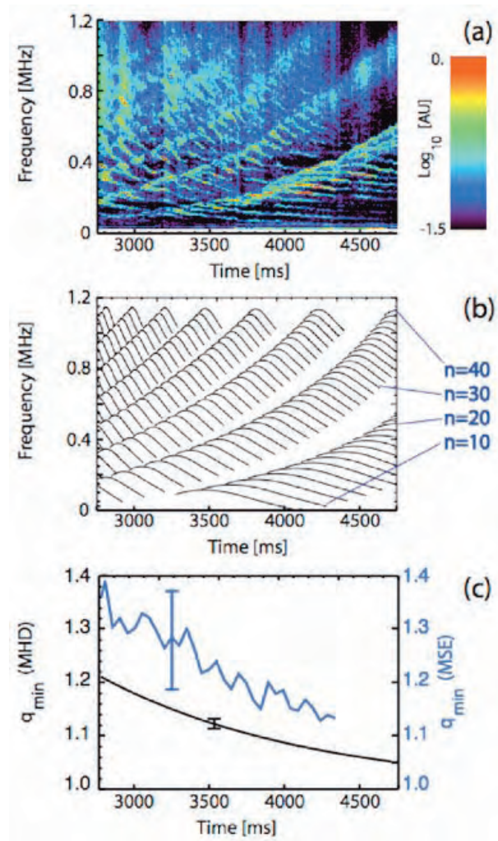

Figure 3. (a) Evolution of density fluctuation spectrum using the far-infrared scattering system on DIII-D. (b) Model analysis of frequency evolution based on the theory of Alfvén waves at the radial location of the minimum of the magnetic safety factor, q_{min}. The model analysis indicates toroidal mode numbers in the range n = 8–40. (c) Comparison of model prediction of the evolution of q_{min} to the motional Stark effect measurement.

Operations Support and LTOA Activities

PPPL continues to provide essential on-site support of tokamak operations during the experimental run on DIII-D. In addition, on-site PPPL staff are currently responsible for a number of high-profile activities during the Long Torus Opening Activity (LTOA). These are: (i) Relocation of the radio-frequency transmission line to accommodate the rotation of one of the neutral-beam lines. (ii) Relocation of the far-infrared scattering diagnostic on DIII-D, again to accommodate the beam line rotation. (iii) Removal of in-vessel tiles and installation of new divertor tiles. (iv) Design and installation of the new counter-beam charge-exchange recombination system that will enable precision measurements of plasma rotation.

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Alcator C-Mod Collaborations

The PPPL-Massachusetts Institute of Technology (MIT) Alcator C-Mod collaboration program concentrates on issues associated with advanced tokamak development and ITER-relevant tokamak research utilizing the Alcator C-Mod tokamak at MIT in Cambridge, Massachusetts. PPPL researchers play an active role in diagnostic development and support (motional Stark effect, microwave reflectometry, X-ray measurements, and gas-puff imaging measurements) and also in heating system research and technical support.

Motional Stark Effect Diagnostic

Motional Stark effect (MSE) diagnostics are used routinely on tokamaks to measure the q-profile and distribution of driven currents. These diagnostics are based on the principle that a rapidly moving neutral hydrogen atom in a magnetic field experiences a strong electric field in its reference frame ($\mathbf{E} = \mathbf{v} \times \mathbf{B}$, where **E** is the electric field, **v** is velocity, and **B** is the magnetic field). The electric field slightly alters the energy levels of the hydrogen atom and causes its radiation to be polarized either parallel to or perpendicular to the electric field — this is the well-known Stark effect. Motional Stark effect diagnostics measure the polarization direction of the light emitted by an energetic hydrogen beam as it passes through the plasma, and thereby infer the direction of E, and hence B, from which the q-profile can be determined.

Historically, the analysis of MSE data has simply evaluated the physics in the presence of a "pure electric field" given only by $\mathbf{E} = \mathbf{v} \times \mathbf{B}$. Because the energy splitting arising from the magnetic field itself (Zeeman splitting) is very small compared to the Stark splitting in most tokamak environments, the standard treatment of MSE ignores the additional complication of the simultaneous presence of a magnetic field in addition to the $\mathbf{E} = \mathbf{v} \times \mathbf{B}$ electric field. It has been have shown that this simplified treatment is incorrect: a proper quantum mechanical calculation of the polarized emission pattern that includes both an electric and magnetic field indicates that the polarization direction of particular transitions (Stark σ lines only) can be shifted by several degrees compared to the simplified treatment, despite the fact that the Zeeman splitting is much smaller than the Stark splitting.

When the emission is integrated over all transitions with degenerate energy levels, the effect disappears, i.e., the net polarization direction is identically equal to the simple result one would obtain with an $\mathbf{E} = \mathbf{v} \times \mathbf{B}$ electric field only. But this is true only if the upper states are populated statistically. Nonstatistical upper states populations are "expected" in certain situations including the propagation of beam neutrals through neutral gas, which is often used to calibrate MSE diagnostics in situ. These results may clarify calibration difficulties in some MSE diagnostics that utilize the σ line and which rely on beam-into-gas for their calibration.

Lower-hybrid Current Drive

Advanced tokamak operation requires careful tailoring of the current profile. MIT and PPPL have collaborated over several years to construct a high-power radio-frequency system to drive radially localized plasma current. During FY05, the system was installed and initial operation commenced (Figure 4). Lower-hybrid current drive involves careful control over the launched wave's toroidal wavelength, which is obtained by having a large number (in this case 96) of waveguides with individually controlled

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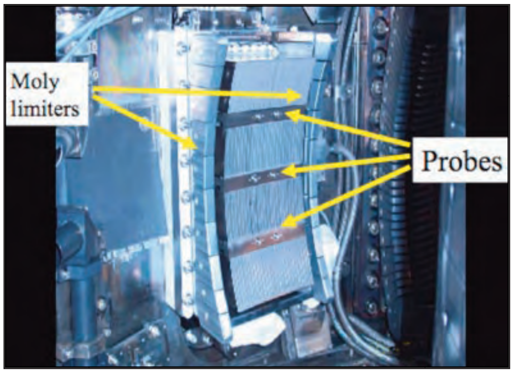

Figure 4. Lower-hybrid launcher installed in C-Mod showing 96 individual waveguides.

power and phase. PPPL's responsibilities included design, construction, installation, and calibration of the power-splitting and phase-shifting waveguides which take the power from 12 microwave klystrons and divide it into 96 waveguides (Figure 5). Correct operation of the system was verified and small amounts of power were applied to the C-Mod plasmas.

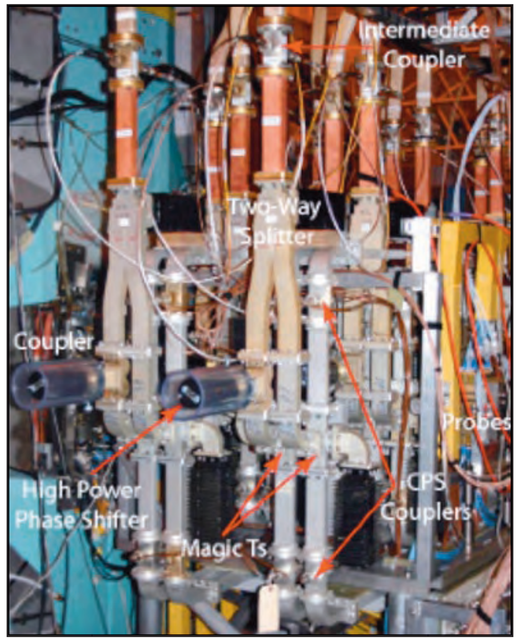

Figure 5. High-power lower-hybrid phase and amplitude splitting network.

International Collaborations

In order to take full advantage of the world's investment in fusion research facilities and to better prepare PPPL researchers for the international ITER Project, the U.S. Department of Energy has funded a program in international collaborations. This allows PPPL researchers access to the Joint European Torus (JET) tokamak in Great Britain and to the JT-60U tokamak in Japan, both of which have plasma parameters closest to ITER. PPPL staff also have access to the new long-pulse superconducting tokamaks being constructed in Korea and Japan and to stellarator devices worldwide in preparation for the U.S. revival in stellarator research.

Joint European Torus

The Joint European Torus device pursues research addressing burning plasma physics issues with plasma parameters closer to ITER's than domestic devices. JET is also the only facility available that can operate with tritium plasmas.

Reversed-shear Alfvén Eigenmodes. In Advanced Tokamak scenarios with inverted magnetic shear profiles, a class of Alfvén eigenmodes can be excited in the weak shear region near the minimum of the magnetic safety factor or q-profile which are called reversed-shear Alfvén eigenmodes (RSAE). They have been observed in various tokamaks: JT-60U, Alcator C-mod, JET (where they were called Alfvén cascades), the Tokamak Fusion Test Reactor (TFTR), and DIII-D. These modes often appear in plasma discharges that will likely be utilized for future burning plasma experiments such as ITER. An important question to answer for ITER is whether these RSAEs degrade the fast-alpha-particle confinement to a level that alpha-particle heating in the core becomes ineffective.

A JET plasma discharge has been analyzed with the NOVA-K code to evaluate its stability to these modes. In the NOVA-K code, ideal-MHD is used to calculate the eigenmodes that can be present in the plasma and kinetic extensions are used to study the stability of those modes. Good agreement between the NOVA-K simulations and the observed frequency behavior of the n = 1 and n = 2 RSAEs can be seen in Figure 6. It was crucial to include the coupling between the Alfvén waves and the sound waves in the model to get the correct frequency near the observed minima. These results are an important benchmark for the NOVA-K code with reversed magnetic shear profiles because envisioned plasma operation schemes in proposed burning plasma experiments like ITER depend heavily on advanced scenarios with such profiles.

Fast-particle Research. The lost alpha diagnostic is designed to measure the loss of MeV fast ions from JET plasmas, particularly 3.5-MeV alphas produced in deuterium-tritium fusion reactions. It consists of two actual diagnostics: a Faraday cup array and a scintillator-based magnetic spectrometer. These diagnostics, whose fabrication began in FY04, were completed in FY05 and installed in the JET device (Figure 7). This diagnostic was part of a collaboration with the

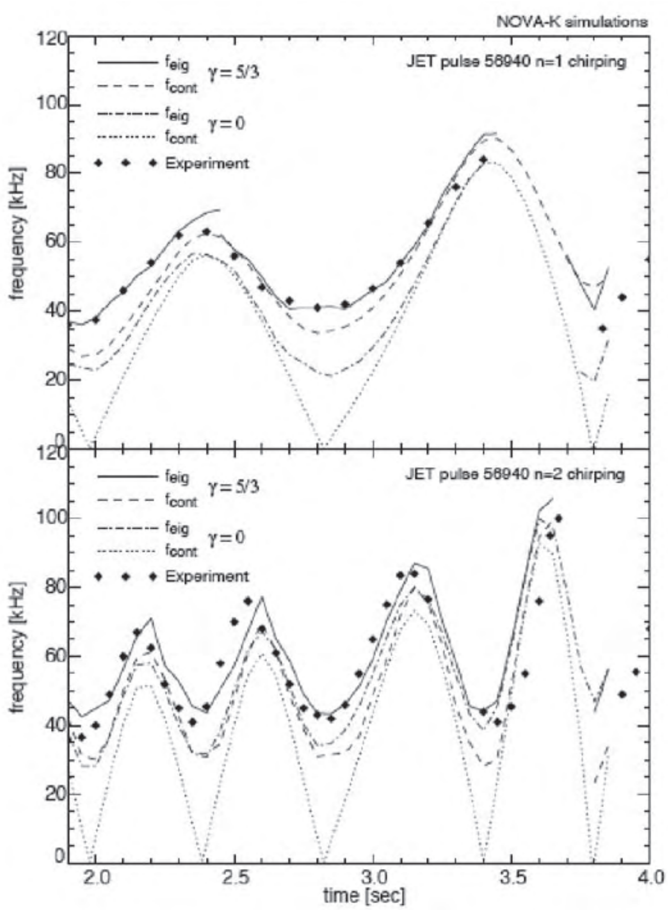

Figure 6. NOVA code simulation of the n = 1 and n = 2 reversed-shear Alfvén eigenmode activity of JET plasma discharge 56940. Measured frequencies are indicated with diamonds while the solid and dash-dotted curve indicate the eigenmode frequency with and without the inclusion of sound-wave coupling. The Alfvén continuum q_{min} for the two cases are indicated with the dashes and dotted line respectively.

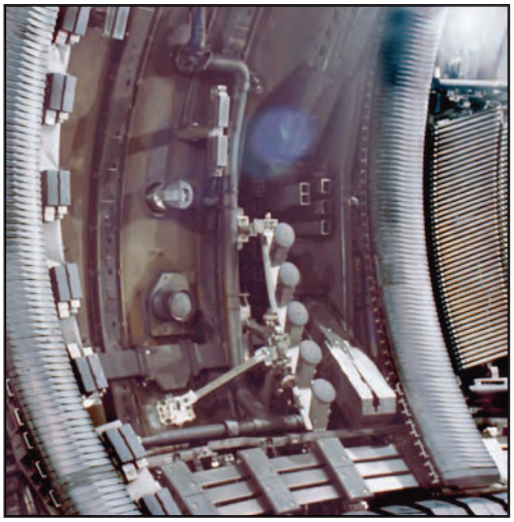

Figure 7. Lost alpha diagnostic installed in JET (Joint European Torus).

Colorado School of Mines and the Max-Planck Institut für Plasmaphysik.

Radio-frequency Technology Development. During FY04, PPPL, in conjunction with the Oak Ridge National Laboratory, built and tested a high-power prototype ion-cyclotron radio-frequency antenna in support of a new JET ITER prototype antenna (Figure 8). During the testing several design limitations were uncovered, and during FY05 new solutions were found, implemented, and their effectiveness demonstrated by additional testing.

Korea Superconducting Tokamak Advanced Research

PPPL's collaboration with the Korea Superconducting Tokamak Advanced Research (KSTAR) Project in Taejon, South Korea, involves hardware design and construction. The Laboratory has been engaged in the fabrication and assembly of a microwave launcher for delivery to KSTAR in calendar year 2006. The launcher, to be used for plasma initiation, is based on the successful design implemented for the DIII-D electron-cyclotron-heating launchers (Figure 9). This work is conducted under a cost-sharing agreement between KSTAR and PPPL. During this period, PPPL also successfully completed the final design review of the KSTAR Bay-N diagnostic cassette that will house the microwave launcher and the Thomson scattering system.

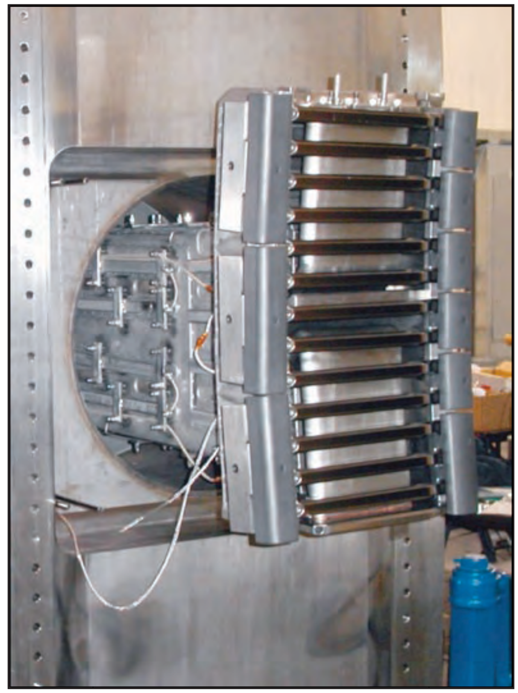

Figure 8. High-power prototype ion-cyclotron radio-frequency antenna for JET.

JT-60U

The collaboration with the Japan Atomic Energy Research Agency on the JT-60U tokamak has continued to focus on negative-ion neutral-beam development for ITER. This work consisted of several extended visits by PPPL researchers to JT-60U for the purpose of designing and conducting experiments on the beam-line and assessing the data. During FY05, a PPPL researcher wrote a review paper at the request of the Japanese summarizing the operational experience with negative-ion neutral-beam injection from 1996 onwards. This work resulted in four other papers published in the past year.

Figure 9. KSTAR electron-cyclotron-heating launcher assembly.

Stellarator Collaborations

In preparation for renewed stellarator research at PPPL on NCSX (National Compact Stellarator Experiment), there has been a renewed interest in international collaboration on existing stellarator facilities in Europe and Japan.

Transport. The Laboratory continued its collaboration on the Wendelstein-7 Advanced Stellarator in Germany with analysis of parametric scans of high-beta data. This continued the work begun in 2004 that demonstrated that magnetic stochasticity sets in above a toroidal beta of 3.5% and that this, rather than ideal-MHD instability (which sets in at low beta) determines the limit to plasma pressure.

Edge Turbulence. Collaboration with on TJ-II, a “flexible” Heliac (stellarator) located at the CIEMAT Institute in Madrid, Spain, on the imaging of edge turbulence continued with analysis of data on the 2-D gas puff images of edge blobs. This work complements work done on the Alcator C-Mod tokamak and National Spherical Torus Experiment (NSTX) to detail the similarities and differences in edge turbulence structure for the different magnetic configurations.

Neutral-beam Deposition Modeling. Collaboration with Large Helical Device (LHD) researchers in Japan and Max Planck Institut für Plasmaphysik-Greisfswald involved modeling of neutral-beam orbits in stellarators including benchmarking against the TRANSP tokamak code. An analytic representation of neoclassical mono-energetic diffusion coefficients appropriate for NCSX was developed.

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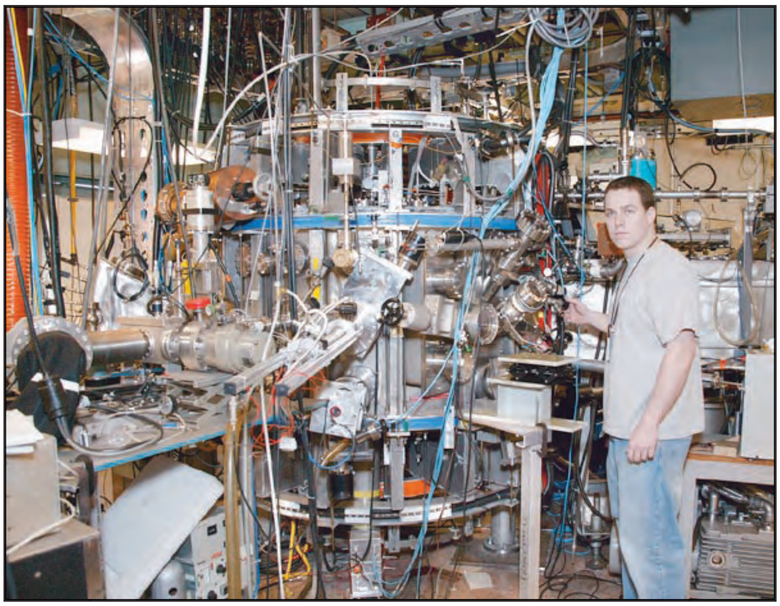
Lithium Tokamak Experiment



Lithium Tokamak Experiment

Experiments to investigate the effects of liquid lithium walls on plasma-facing components have been the focus of the Lithium Tokamak Experiment (LTX), formerly the Current Drive Experiment-Upgrade (CDX-U). The prime motivation of this research is that all major tokamaks have achieved their highest performance in regimes characterized by low recycling — the reintroduction of cold gas back into the plasma from the vacuum chamber walls. A fully non-recycling wall has been theoretically predicted to fundamentally alter the nature of magnetically confined plasmas, as the temperature and plasma current distributions would be much flatter, such as to minimize deleterious instabilities. Under such conditions, the transport mechanisms that result in the loss of energy and particles could be suppressed, and higher values of beta, the ratio of plasma pressure to the pressure of the confining magnetic field, could result.

The use of lithium as a first-wall material is an attractive way to achieve low recycling. The low-recycling would be effected by the high chemical reactivity of lithium with atomic hydrogen, which reduces its influx back into the plasma. Furthermore, flowing liquid lithium could be a means of dissipating the heat from the high power densities anticipated on the plasma-facing components, or PFCs, of fusion reactors. Any PFC materials with high atomic number Z can cause energy losses by radiation should they sputter off the walls and enter the plasma. Because lithium has a low Z, this problem is also reduced.

An important step in determining the feasibility of liquid lithium as a PFC was taken in CDX-U, a spherical torus with a major radius, or distance from the axis of the torus to its center, of 34 cm. The torus cross section is an ellipse with a minor radius of 22 cm and an elongation of 1.6. The maximum plasma current is about 900 kA, during a total discharge duration of up to 20 ms. This current is driven inductively using a solenoid in the center column (centerstack) of CDX-U. This device was first intended to explore various means of driving the plasma current using radio-frequency waves and other techniques, hence the CDX-U label.

While the name was retained, the CDX-U mission was shifted to emphasize lithium PFC research. For the first time in any magnetic confinement device, a large pool of liquid lithium was introduced into a tray that completely encircled the bottom of CDX-U. This toroidal container had a major radius of 34 cm and width of 10 cm, and when filled to a depth of a few millimeters, it presented a lithium surface of 2,000 cm^2 to the plasma. This served as a "limiter" in contact with the plasma discharge. A section of the tray is shown in Figure 1. The reflected image of the centerstack clearly shows its mirror-like surface.

High Confinement Achieved with Liquid Lithium

The last phase of research in CDX-U was completed in FY05, prior to the installation of a shell that is intended to enclose the plasma with a liquid lithium PFC. Dramatic improvements in plasma confinement were obtained with lithium in the tray and also coating the walls of this device. Plasma discharges under these conditions exhibited energy confinement times (τ_E) of up to 5 ms, or four times what would be expected if the results from other tokamaks ["ITER98P(y,1)"] were scaled to a machine the size of CDX-U (Figure 2). This result also surpassed, by a factor of five or more, the best values obtained prior to the introduction of lithium into the device.

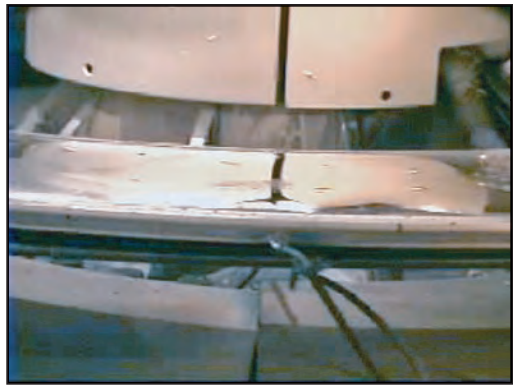


Figure 1. Section of toroidal CDX-U tray containing liquid lithium.

To obtain the energy confinement times, reconstructions of CDX-U plasma equilibria were required. Doing this accurately has been a major challenge for magnetic confinement devices, and this has been particularly true of small experiments like CDX-U. In this device, short pulse lengths make its equilibria particularly sensitive to the effects of eddy currents generated in its walls. Furthermore, ports and other features make the CDX-U vacuum vessel complex. This limits the validity of assuming axisymmetry, or the approximation that CDX-U is an ideal torus.

To address these issues, a new version of the Equilibrium and Stability Code (ESC) was developed. The ESC uses measurements from magnetic sensors in-

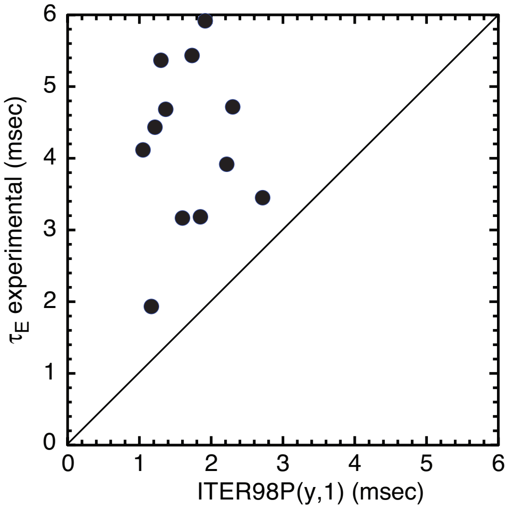


Figure 2. Experimentally measured confinement times τ_E (dots) for plasma discharges with lithium-coated walls compared to ITER98P(y,1) scaling (line).

Figure 3. Supersonic gas injector nozzle inside the CDX-U vacuum vessel.

side the CDX-U vacuum vessel. These sensors are calibrated by their response to the magnetic field coils that confine the plasma as they are individually pulsed. The "response functions" so obtained can then predict how the sensors would respond to actual CDX-U plasmas. They can be subsequently used in the ESC equilibrium reconstruction calculations, with the sensor calibrations as the only prerequisite.

An estimate of a particle confinement time that includes the effects of wall recycling (τ_p^*) was obtained using a supersonic gas injector (Figure 3). The supersonic gas injector has a fast valve that allows the injection of a short gas pulse, and the τ_p^* was determined from the subsequent decay of the density. It was assumed that the energy confinement time obtained with the ESC provides a bound on what the particle confinement times would be without wall recycling. In that case, a recycling coefficient of about 30% was deduced. This meant that less than a third of the deuterons impinging on the walls reentered the plasma, which is a record for magnetic confinement devices.

New Techniques for Creating Lithium Coatings Tested

The high-confinement results described above were achieved in the process of testing two new techniques for producing wall coatings of lithium — a resistively heated evaporator system and an electron beam (e-beam) evaporation system.

The resistive evaporator system consists of a wall-mounted collimated lithium oven, and is used to continuously deposit lithium on the walls and centerstack of CDX-U, which also served as a plasma limiter. The resistive evaporator system was used to deposit up to ~100 Å of lithium during the period between discharges (typically seven minutes).

The e-beam system used the lithium in the tray as a target. The lithium evaporated by the e-beam created films up to 1,000 Å thick in four to five minutes, also between discharges. Both systems were operated simultaneously, producing near 100% coverage of the vessel wall and centerstack.

During past experiments, the lithium in the tray was melted by heaters located underneath it. In the present experiments, the lithium was liquefied by the e-beam system alone, which created a "pool" with an area of 600 cm^2. The combination of tray and wall lithium PFC's resulted in edge plasma pumping rates of $1–2 \times 10^{21}$ particles per second. This is comparable to the wall-pumping rate achieved in the lithium-aided Tokamak Fusion Test Reactor (TFTR) plasmas that had the highest stored energies ever obtained in TFTR (supershots). However, the active wall area in CDX-U is only 0.4 m^2, or two orders of magnitude smaller than that in TFTR. In CDX-U, furthermore, the lithium was deposited on stainless steel or other materials that are impermeable to lithium. By contrast, graphite tiles formed the deposition substrate in the TFTR experiments, and lithium is known to rapidly penetrate into graphite and form compounds (carbides) in a process called "intercalation."

An evaluation of the relative effectiveness of solid and liquid lithium as a PFC was made. Comparisons between results from recent experiments, which used primarily solid lithium-wall coatings, and earlier results from larger-area (2,000 cm^2) liquid lithium PFCs, but without significant wall coatings, were performed. This was done by comparing the driving (loop) voltage required to sustain an increase of the plasma current at a rate of 2 MA/s.

The earlier discharges with a large area liquid lithium limiter performed significantly better than the discharges with solid wall coatings. The superiority of liquid lithium as a PFC may be due to saturation of the surfaces of the solid coatings with the deuterium use to fuel the discharge as it progresses. In contrast, the diffusion of deuterons in liquid lithium is very high, so that no surface concentration gradients can be sustained, even in a device with as low a particle confinement time as the CDX-U.

High-power Handling Capabilities of Liquid Lithium

The e-beam experiments simulated conditions of high localized power deposition (power density up to 50 MW/m^2 in a 0.3-cm^2 spot) during evaporation. Although the total beam power is modest (1.6 kW), heating cycles of up to 300 seconds have been employed, for a total injected energy of ~0.5 MJ.

The surface temperature distribution of the liquid lithium was recorded with an infrared camera during e-beam heating (Figure 4.) The swirling regions are "false color" contours that are separated by a maximum temperature of 50 °C. They show that, surprisingly, the transport of heat away from the beam spot by convection was so effective as to necessitate the heating of the entire lithium inventory (140 g), rather than just the area under the beam spot, to the point of evaporation (T > 400–500 °C). There was no observable hot spot within the beam footprint for the entire 300-second duration of the heating cycle. These results are promising for the implementation of lithium plasma-facing components in reactor-scale devices.

Figure 4. Infrared image of liquid lithium in toroidal CDX-U tray during electron-beam heating.

Installation of New Inner Shell in Progress

The CDX-U was vented in FY05 to prepare for the installation of a conducting shell inside the existing vacuum vessel. The shell has a stainless steel liner that is explosively bonded to a thicker copper substrate. The stainless steel liner will be coated with a 1,000-Å thick layer of lithium, and the copper substrate is then heated to melt the lithium. The coated liner will comprise 90% of the PFC area (~4 m^2). This new configuration, now called the Lithium Tokamak Experiment, will enable the study of plasmas almost fully enclosed by a low-recycling wall.

The conducting shell is comprised of four identical quadrants, each consisting of seven approximately triangular segments. All of these segments were machined and formed to shape in FY05, and they are being assembled (Figure 5). The shell will be placed inside the LTX vacuum vessel in the spring of 2006, and present plans are to resume plasma operations before the end of CY06.

Figure 5. Conducting shell quadrant welded together by S. Jurczynski (pictured) of PPPL.

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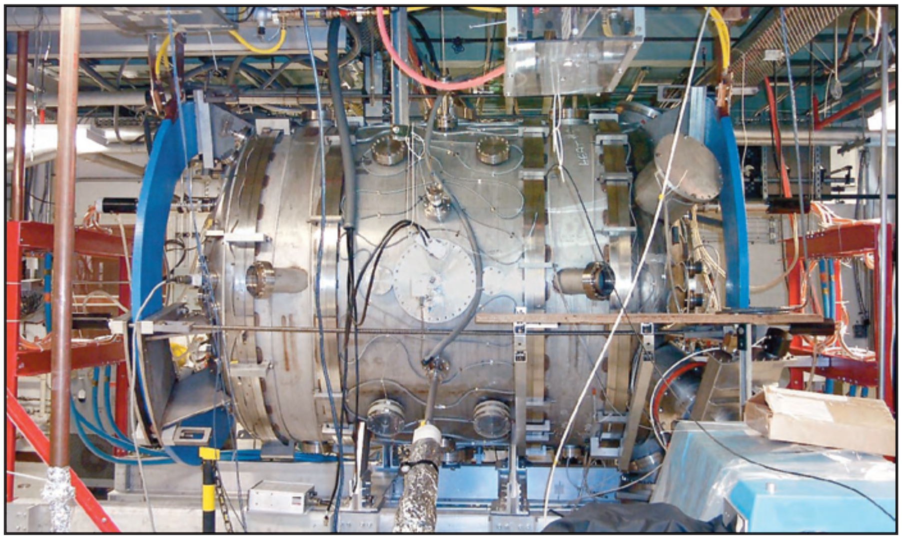
Magnetic Reconnection Experiment



Magnetic Reconnection Experiment

The Magnetic Reconnection Experiment (MRX), shown above, was built to study the fundamental physics process of magnetic reconnection in a controlled laboratory environment. Magnetic Reconnection — the topological breaking, annihilation, and reconnection of magnetic field lines — can occur in virtually all magnetized plasmas, in both the laboratory and in nature. This is illustrated in Figure 1, where plasma and magnet field line flow together into a thin region called the dissipation region. The field lines break in the dissipation region, reconnect, and exit out the ends of the region.

Magnetic reconnection is commonly invoked to explain observations in solar physics, space physics, and laboratory physics, and it is a key to understanding plasma's self-organization phenomena. For example, the release of high-energy particles that occurs during a solar flare, shown in Figure 2, is believed to be due to magnetic reconnection. In this phenomenon, the magnetic field imbedded in interacting solar flares is pushed together, causing reconnection to occur. However, the rate of energy release is not resolved by the present understanding of reconnection physics. The observed "fast reconnection" has made magnetic reconnection a very active area of research. Experiments on MRX have provided crucial data with which the theoretical and observational research communities can compare their work.

The modest size and versatility of MRX make it an ideal facility to study basic science and to train graduate students. The

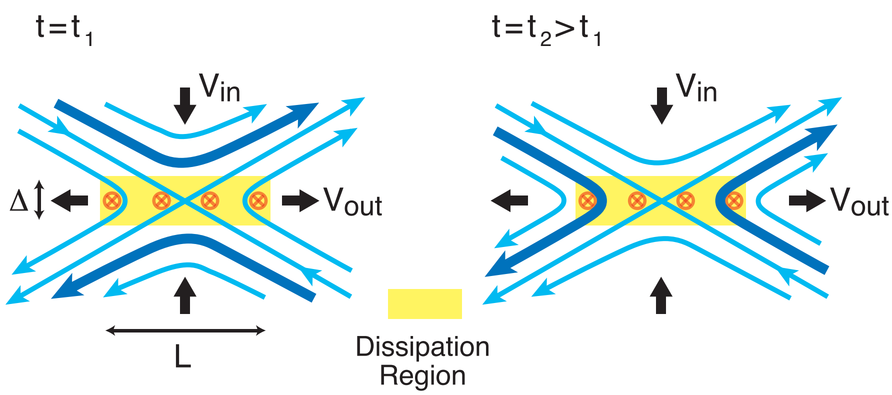


Figure 1. The process of magnetic reconnection. The dark field lines in the left-side frame move toward the dissipation region and magnetic reconnection occurs. After reconnection, the field lines move into the outflow region, as illustrated in the right-side frame.

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), illustrating the broad applicability of its scientific output.

Research Objectives

The primary purpose of MRX is the comprehensive analysis of magnetic reconnection and related physics, which are crucial for understanding self-organization phenomena of fusion plasmas as well as solar and magnetospheric plasmas. In particular, MRX has the following research goals:

- Test 2-D and 3-D theoretical models of magnetic reconnection.
- Investigate the role of effects beyond resistive MHD (for instance, turbulence and Hall-MHD) in the reconnection layer.
- Identify the mechanisms by which magnetic energy is efficiently con-

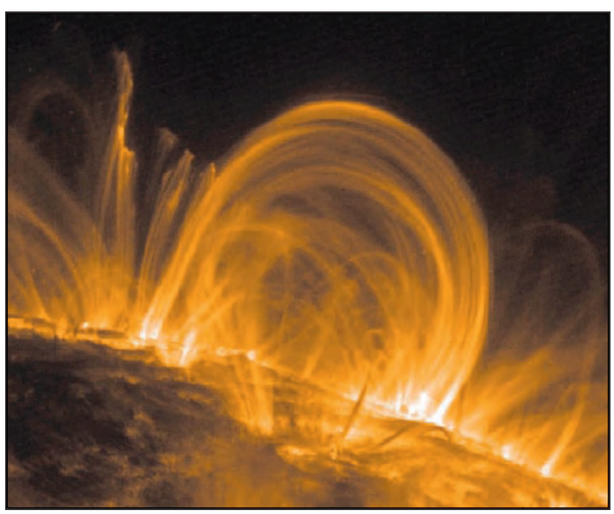


Figure 2. Reconnection in solar flares, illustrated here in data from the TRACE satellite, is thought to lead to the anomalously high plasma temperatures measured in the solar corona.

verted to plasma kinetic and thermal energy.

- Explore the role of boundary effects on the rate and spatial structure of magnetic reconnection.
- Explore the application of magnetic reconnection science to fusion concepts, including spheromak merging for the formation of large-flux Field-reversed Configurations (FRCs).

In FY05, magnetic reconnection was studied in two very different geometries that are accessible in the MRX device. In both cases the impact of the Hall effect was studied, allowing a more generalized understanding of this phenomenon. These studies have documented the universality of the Hall effect as a contributor to fast reconnection. An experimental campaign of spheromak merging was also carried out, with the goal of forming long-lived FRC plasmas. These studies demonstrated the importance of plasma shape control for the formation of improved-stability FRCs.

Experimental Device and Past Major Results

The key components of the MRX device are two flux cores: doughnut-shaped devices containing multiple magnet windings, which inductively produce the plasma and magnetic fields in MRX. These flux cores allow two distinct magnetic reconnection geometries in MRX: the "pull" reconnection geometry and the "push" reconnection geometry. Experiments in FY05 studied both reconnection geometries in order to achieve a more universal picture of magnetic reconnection.

In the "pull" reconnection geometry, plasma is formed around the cores, and then the currents in the windings are quickly decreased. This has the effect of pulling oppositely directed magnetic fields together, causing magnetic reconnection to occur and a current sheet to form. This geometry leads to long-lived and stable current sheets, allowing detailed study of reconnection physics. The flexibility of this configuration is further enhanced by the ability to form current sheets with a guide-field (co-helicity), or without a guide-field (null-helicity).

In the "push" reconnection configuration, two independent toroidal plasmas, known as spheromaks, are formed adjacent to the flux cores. These spheromaks, which sustain their own internal magnetic fields, are then allowed to merge via their mutual attractive force. Magnetic reconnection occurs during this merging (i.e., the magnetic field lines are pushed together), and a fusion relevant FRC is formed. This FRC is an attractive candidate for a fusion power source due to its very high ratio of plasma pressure to magnetic field strength.

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, electron temperature, and plasma flows), spectroscopic probes (ion temperature and plasma flows), arrays of magnetic probes (spatial profiles of the local magnetic field), and large pick-up loops (global currents and magnetic fluxes).

The Sweet-Parker model of magnetic reconnection is a resistive MHD model that assumes a two-dimensional, incompressible, steady-state plasma. It captures many of the essential local features of the magnetic reconnection layer and predicts reconnection rates faster than resistive dissipation, but still much slower than that observed in solar flares. The reason for the too slow prediction is simple: all of the plasma is forced to flow through a very narrow dissipation region, restricting the amount of plasma allowed to participate in the reconnection process.

The first laboratory experiments testing the Sweet-Parker model were performed in 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. The effective plasma resistivity was found to be enhanced over the classical Coulomb-collision value by up to a factor of ten; this enhancement plays a crucial role in determining the reconnection rate. These results suggest that the Sweet-Parker model with nonclassical resistivity may explain the fast reconnection required to be consistent with, for instance, solar flare observations. Two theories exist for this apparently enhanced resistivity: turbulent resistivity and the two-fluid Hall effect.

Current sheets formed in MRX contain strong gradients in the plasma density and cross-field currents, both of which can drive unstable fluctuations and result in turbulence. Electromagnetic fluctuations found in MRX correlate well with fast reconnection. The fluctuation amplitude is similar for the three magnetic field components, and the spectrum is peaked near the lower-hybrid frequency. The radial spatial profile measurements show that the magnetic fluctuation amplitude is strongly peaked near the center of neutral sheet. It is found that the amplitude of magnetic fluctuations is sensitive to plasma density or, equivalently, collisionality. As the resistivity enhancement also depends on the plasma collisionality, a clear positive correlation between magnetic fluctuations in the lower-hybrid frequency range and resistivity enhancement is established in the low-collisionality regime.

In MRX, the precise profile of the magnetic field in the current sheet has been measured by a very high-resolution magnetic probe array. The measured magnetic profiles fit very well to the Harris solution, which was developed in 1962. This agreement is remarkable since the Harris theory does not take into account the electric fields and dissipation associated with reconnection. The current sheet thickness is found to be on the order of the ion skin depth, which agrees with a generalized Harris theory incorporating different electron and ion temperatures and finite electric field. Interestingly, very similar scaling has been observed both in the magnetotail and the magnetopause of the Earth's magnetosphere.

Highlights of FY05

The MRX research activities in FY05 reaped the benefits of the facilities upgrades in FY04. Studies of the Hall effect in magnetic reconnection continued, in both the "push" and "pull" reconnection geometries. These different geometries served to illustrate the universality of the Hall-mechanism during magnetic reconnection. The "push" reconnection studies were part of a series of experiments studying the formation and stability of FRC plasmas via the merging of spheromak plasmas.

Studies of the Hall Effect during "Pull" Reconnection in MRX

As noted above, the simple resistive MHD model is unable to adequately describe the observed fast reconnection for plasmas in the low-collisionality regime. In addition to turbulent resistivity, the Hall effect has been considered as a mechanism leading to fast reconnection. When the Hall effect is included, electron and ion flows near the center of the current sheet are allowed to decouple in a manner not allowed in resistive MHD. The ions are not forced to flow through the narrow dissipation region, thus allowing faster reconnection. The electrons do flow through the narrow dissipation region, where their out-of-plane current pulls the magnetic field lines of the reconnection plane. These field lines, which are pulled out of the reconnection plane, lead to a quadrapole out-of-plane magnetic field, a key signature of the Hall effect.

This quadrapole out-of-plane magnetic field has been observed in MRX, as illustrated in Figure 3. The arrows in this figure represent the reconnection magnetic field and the colors represent the out-of-plane magnetic field. There are four lobes of out-of-plane field, which change sign when moving horizontally or vertically from one lobe to the next: these are the features of the Hall quadrapole field. The MRX is the first laboratory plasma experiment to clearly observe the quadrapole field and confirm the importance of the Hall effect. Further measurements demonstrated that the Hall effect, which allows the heavy ions to avoid the narrow dissipation region, leads to an increase in the reconnection rate.

The three-dimensional features of the magnetic field lines are visible in the computer-generated representation of reconnection in Figure 4. Electrons flowing out at the center of the reconnection layer drag out the magnetic field lines, as illustrated by the white lines. These extended field lines have components alternatively pointing towards or away from the reconnecting plane, the effect that gives rise to the quadrapole field signature.

Observation of the Hall Effect during "Push" Reconnection

The Hall effect was also observed in the early stages of "push" reconnection in MRX, as illustrated in Figure 5. In "push" reconnection, the reconnection plane is tilted with respect to the fixed

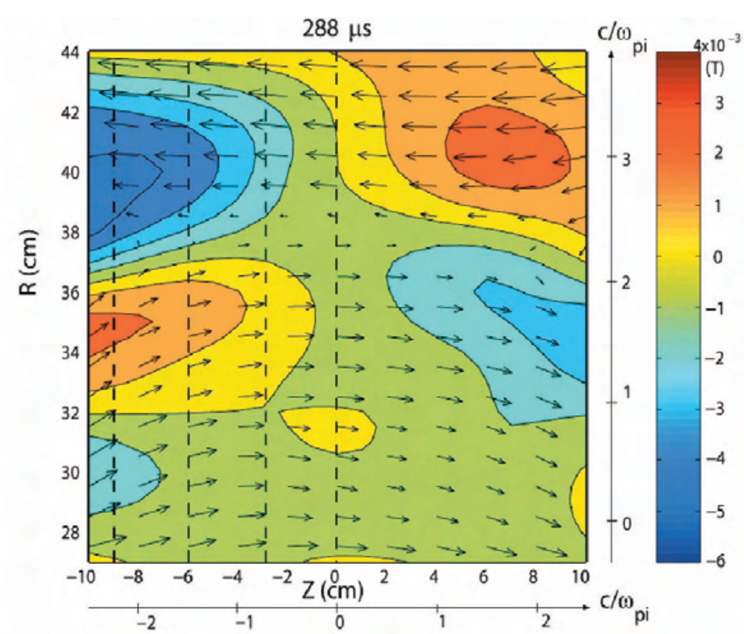


Figure 3. The Hall quadrapole magnetic field measured in MRX.

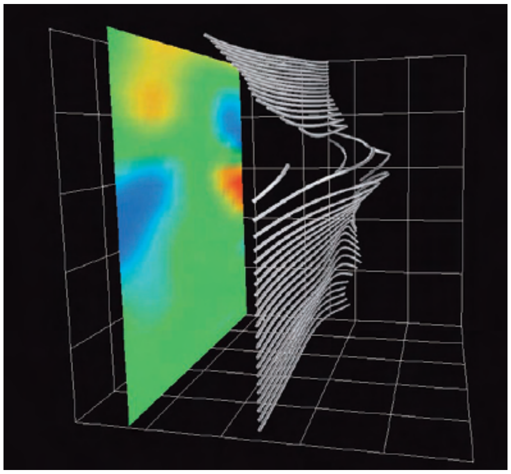


Figure 4. Three-dimensional visualization of the Hall effect. Electrons flowing in the reconnection current sheet drag magnetic field lines out of the reconnection plane. The out-of-plane component of the field lines generates the signature quadrapole field.

r-z plane in which the measurements are taken, as illustrated in Figure 5(c). By reversing the signs of the toroidal field in the reconnecting plasmas, the reconnection plane angle is flipped. As discussed above, the quadrapole field can be thought of as the effect of the electron current "pulling" the magnetic field lines out of the reconnecting plane. Since the reconnection plane is tilted, the electron current "pulls" the field lines in a direction with both radial and toroidal components. When the field lines are viewed in the r-z plane, this effect causes the reconnection X-line to appear to shift up or down depending on the direction of the opposing toroidal fields, as illustrated in Figure 5(b). Hence, the effect that causes a quadrapole field in "pull" reconnections causes an apparent shift of the reconnection position in "push" reconnection.

More quantitative studies have revealed that the Hall effect contributes to a significant increase of the reconnection rate in addition to the modification to the geometry. Interestingly, the case with inward shifted X-line shows slower reconnection than with the outward shift. This is because the inward shift leads to a large compression of the magnetic field in the center of the device, leading to large val-

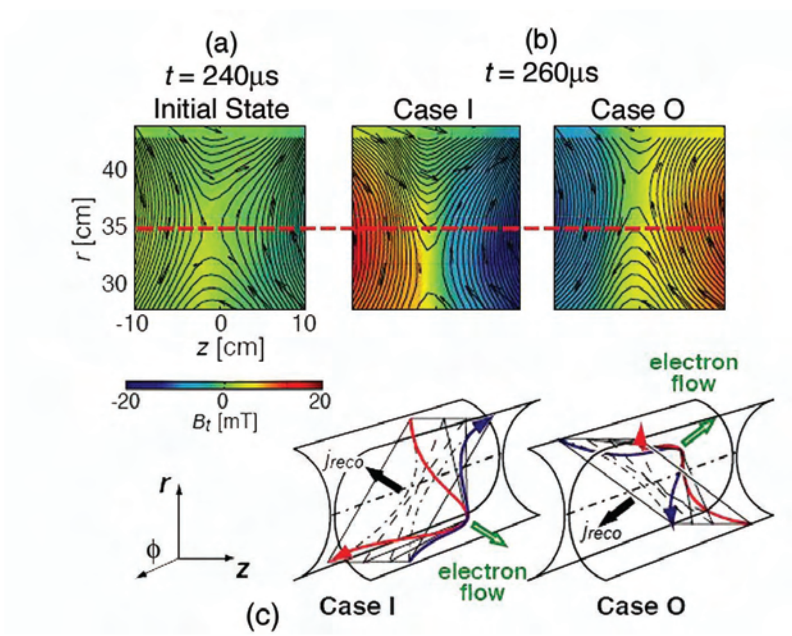


Figure 5. The Hall effect in push reconnection. The direction of the electron flow changes when the toroidal fields are reversed, causing the X-line to shift in different directions.

ues of the magnetic pressure in this region. This pressure prevents the plasma from flowing into this region; in essence, one end of the reconnection layer in Figure 1 is plugged, reducing the reconnection rate. The outward shifted case does not lead to such severe magnetic flux compression, and the plasma can flow out both ends of the reconnecting layer. Hence, in the inward shifted case, the local Hall effect introduces a change in the global boundary conditions, which then modifies the reconnection rate. These observations indicate the universal importance of the Hall effect.

Plasma Merging for Fusion Science Applications

In addition to the Hall effect studies, the spheromak merging experimental campaign has been successful in forming long-lived FRC plasmas. This process is illustrated in Figure 6(a-c). Two spheromaks are formed near the flux cores (a) and translate towards each other and begin to merge (b). The magnetic fields inside the spheromaks reconnect, and the final state is an FRC (c).

The formation of these long-lived FRCs requires a number of conditions to be met. First, the two spheromaks must have approximately equal magnetic field strengths, or else one will dominate the other. Secondly, a passive stabilizer is helpful in reducing the global motions of the plasma. In MRX, a 10-cm diameter hollow copper tube is used to provide passive stabilization; if the plasma begins to move, electric currents in the center column "push" the plasma back to its original location. These two steps are useful in eliminating large plasma motions, but destructive fine-scale plasma motions have also been observed. The key final step is to control the shape of the plasma boundary. This is shown in Figure 6 where a plasma with more oblate shape (pulled away from the center of the machine) is observed to have a long life in panels 6(d-g), while a plasma which is more pushed toward the machine center displays a quick decay in panels 6 (h-j).

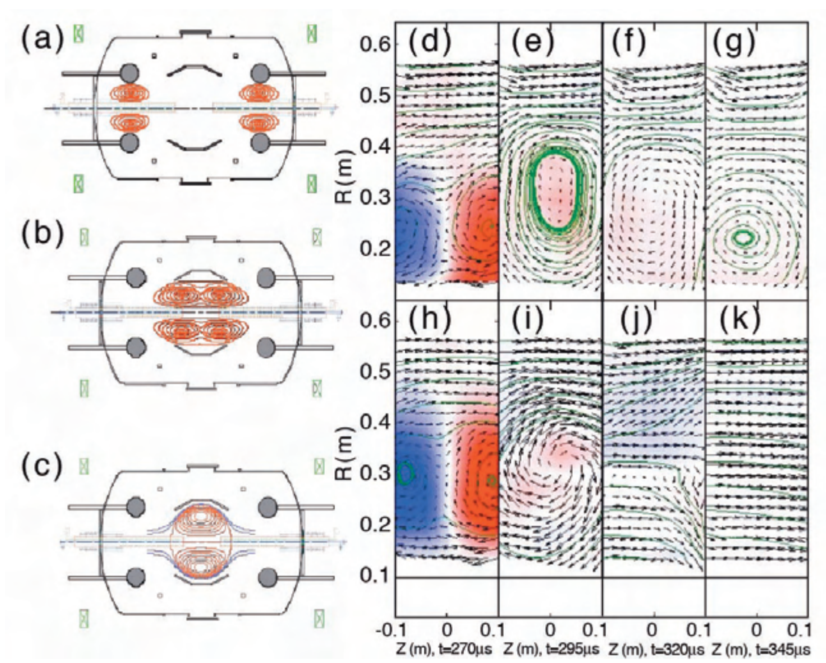


Figure 6. Spheromak merging for FRC formation. Stable and unstable examples are shown in (d-g) and (h-k) respectively.

Future Work

The research conducted in FY05 has clarified the role of the Hall effect in magnetic reconnection. However, the Hall effect alone cannot explain fast reconnection in nature; some other mechanism must be responsible for the breaking of magnetic field lines at the very center of the reconnection layer. The observed electromagnetic fluctuations are a prime candidate to provide this effect. Hence, the relationship between the Hall effect and electromagnetic fluctuations will be a prime subject in future research. The MRX group will also continue to pursue the topic of FRC formation and stability studies, with the goal of improving the viability of this fusion concept.

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Plasma Science and Technology

The Princeton Plasma Physics Laboratory (PPPL) has an active program in Plasma Science and Technology 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. The Lithium Tokamak Experiment, the Magnetic Reconnection Experiment, and Applications Research and Technology Transfer, discussed elsewhere in this report, form part of this program.

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 the 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, the work on high-intensity accelerators is directly applicable to future experiments in high energy physics, and the Hall Thruster Experiment may develop into superior propulsion technologies for spacecraft.

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. The vast majority of satellites worldwide have relied on chemical thrusters, although chemical rockets have very limited fuel exhaust speed. Plasmas can be ejected at much higher speeds, therefore less fuel needs to be carried on board. Until recently, the Hall Thruster approach has been pursued most vigorously in Russia; during the past quarter century, they have placed about 100 Hall Thrusters in orbit.

In 1999, a Hall Thruster Experiment (HTX) was established at the Princeton Plasma Physics Laboratory (PPPL). The PPPL effort was the result of a collaborative theoretical research effort with the Center for Technological Innovation at Holon, Israel. This study, initially funded by the U.S. Air Force Office of Scientific Research (AFOSR), 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. In addition to support from AFOSR, the program has received support from the Defense Advanced Research Projects Agency, the New Jersey Commission on Science and Technology, and the U.S. Department of Energy. The HTX facility is shown in Figure 1.

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. Because a positive charge builds up in the space between the grids, the ion flow and, therefore, the magnitude of the thrust that can be attained are limited.

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 (Figure 2). The ions, too heavy to be affected by the field, continue their journey through the virtual cathode. The movement of the positive and negative electrical charges through the system results in a net force on the thruster in a direction opposite that of the ion flow.

Figure 1. The PPPL Hall Thruster Experiment (HTX) and research team.

Plasma thrusters for current space applications employ xenon propellant. Xenon is relatively easy to store onboard the spacecraft and to ionize within the thruster. It also has a high atomic number (54), which means a lot of mass per ionization energy expended. The ionization energy is an unavoidable inefficiency. In the range of exhaust velocities most useful for current space applications, about 15 km/sec, the 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.)

Thruster Applications

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. For each kilogram of satellite mass it turns out that about one or two watts of on-board power are available. At PPPL Hall thrusters ranging from below a 100 watts to more than two kilowatts have been built. PPPL physicists hope that their ideas can be useful both for thrusters operating at many thousands of watts, e.g., for planetary missions, as well as in the low power limit, e.g., for very small satellites with masses of 50 to 100 kilograms.

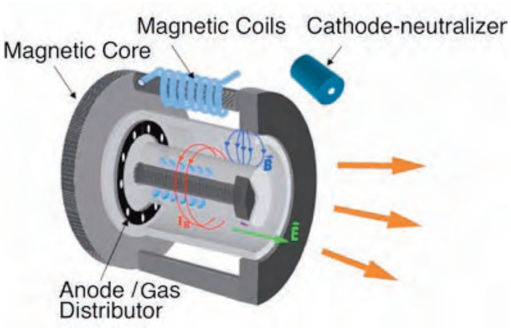

Figure 2. The Hall thruster concept.

Thruster Results

Recent work at the PPPL HTX facility (Figure 3) demonstrated that steep voltage drops could be diagnosed, localized, and controlled in a Hall-thruster geometry using segmented electrodes. These techniques now support new thruster configurations and new methods for focusing neutralized ion beams, thereby achieving significant beam current densities. Experiments on the recently upgraded HTX facility with unique plasma probe diagnostics began to challenge accepted limits on the magnetic insulation properties of plasma. The importance of plasma-wall interaction was demonstrated and the role of secondary electron emission in power losses at the walls and electron cross-field transport was shown. The collaboration with the Aerospace Corporation on ion beam focusing and beam neutralization in segmented Hall thrusters continued.

Hall Microthruster

In addition to imagining larger, more powerful thrusters capable of accelerating satellites more quickly or powering larger satellites, scientists also envision a large satellite disbursing hundreds of smaller ones for the exploration of a planet or as a space-based radar array. The PPPL Hall Microthruster was invented to scale to low power. This device employs a cylindrical rather than the conventional annular configuration. Because of its low surface-to-volume ratio, the cylindrical geometry is better adapted for microthruster operation.

The technological problems associated with scaling to low power are by no means straightforward. The power density tends to grow at small sizes, and the smaller features are more susceptible to

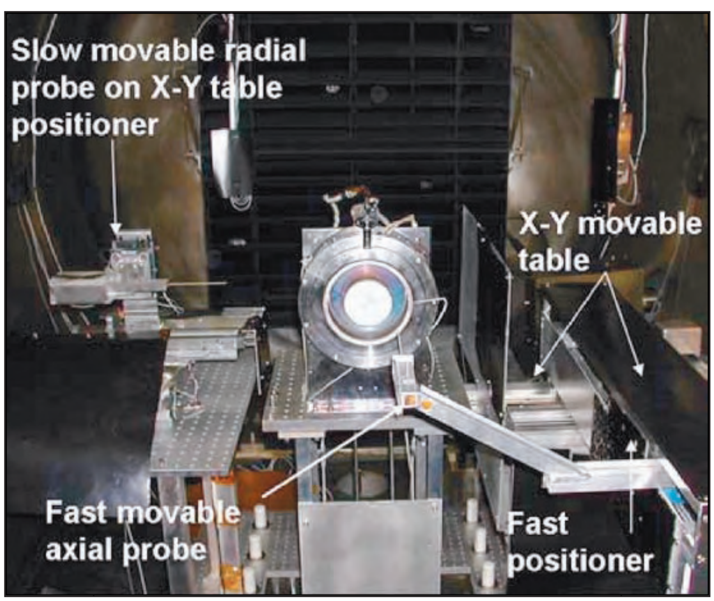

Figure 3. Interior view of the Hall thruster vacuum chamber.

heat loading. In attacking these technological constraints, in the cylindrical design, the central magnetic pole is almost eliminated, as shown in Figures 4 and 5.

The cylindrical thruster geometry is fundamentally different from the conventional configuration in the way the electrons are confined in the plasma discharge and in the way the ion space charge is neutralized. Here, the electrons in the cylindrical part of the channel are trapped axially in a hybrid magneto-electrostatic trap: on the anode side they are reflected by the strong magnetic mirror, while on the cathode side they are reflected by the potential drop in the plume. Electrons neutralize the ion space charge not by being held axially by the radial magnetic field, like in the conventional thruster; rather, electrons are allowed to move axially back and forth, while being trapped axially in the hybrid trap. Therefore, one of the fundamental constraints of the conventional thruster configuration is loosened, and the associated physics of this new thruster is quite different.

The PPPL Hall Microthruster has now been operated below the 100-watt range,

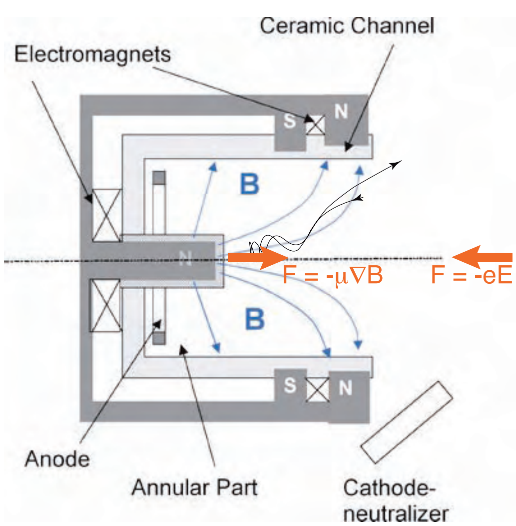

Figure 4. Schematic of the PPPL Hall microthruster with cylindrical geometry.

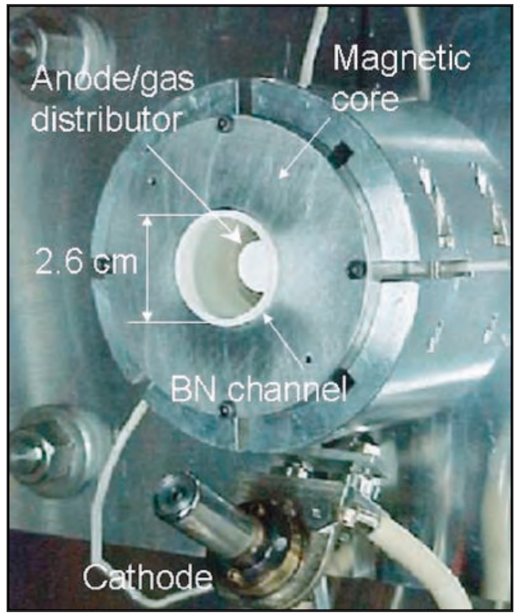

Figure 5. Pictured is a 100-watt cylindrical Hall thruster.

useful for very small satellites with masses of 50 to 100 kilograms. Efficiencies in the range of 20 to 30% for 100-watt power-level operation were attained, surpassing present-day microthruster technology. Present research on the cylindrical Hall thrusters focuses on understanding the magnetic field topology, electron crossed-field transport, and ion thrust generation. Performance evaluations of PPPL cylindrical Hall thrusters has been done at the Air Force Research Laboratory, Edwards, CA; the NASA Marshall Space Flight Center; and at the Princeton University Mechanical and Aerospace Department. The results of these evaluations indirectly confirmed unusually high ionization in cylindrical Hall thrusters and the suitability of this thruster for microthruster (low-power) regimes, an idea that has been proposed by researchers at PPPL.

Magnetic Nozzle Experiment

The Magnetic Nozzle Experiment (MNX) studies the physics of mirror-geometry helicon-heated plasmas expanding through magnetic field gradients.

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MNX research is applicable to fusion science, solar physics, and spacecraft propulsion. A productive collaboration with Professor E. Scime, West Virginia University (WVU), continued in FY05. Graduate students X. Sun (WVU), M. Miah, and N. Ferraro performed research on MNX.

The primary scientific investigations during FY05 were explorations of electrical potential changes along the plasma column performed with a laser-induced-fluorescence system loaned by WVU. Ion acceleration to supersonic speeds occurs by passage through a double layer formed by mechanical or magnetic apertures placed in helicon plasmas, see Figure 6. The high directed energy achieved, 70 eV for argon ions, shows that the double-layer ion-acceleration method has potential for use in spacecraft propulsion missions to remote planets.

Experiments on the role of superthermal electrons in determining the strength of the double layer were begun. Diagnosis of the helicon-heated plasmas was preformed with passive emission spectroscopy, interpreted with collisional-radiative models, and Langmuir probes. The results, to appear in *IEEE Transactions in Plasma Science*, are consistent with a small superthermal population (E_s ~ 100 eV and n_s/n_e ~ 10^{-3}) being responsible for the strong ion acceleration.

Princeton Field-reversed Configuration Experiment

The Princeton Field-reversed Configuration Experiment (PFRC) was built to study the physics of odd-parity rotating magnetic fields (RMF_0) interacting with magnetized plasmas. Theory predicts that field-reversed configurations (FRCs) formed by odd-parity rotating magnetic fields should have closed magnetic field lines, hence good energy confinement properties. Other favorable theoretical predictions for odd-parity rotating magnetic fields are excellent ion heating in the ion-cyclotron range-of-frequencies and good electron heating, even far below the electron-cyclotron resonance frequency. The PFRC was designed to use commercially available equipment and to operate at low power. Both choices improve facility safety and lower facility costs, important aspects to the eventual commercial success of fusion power.

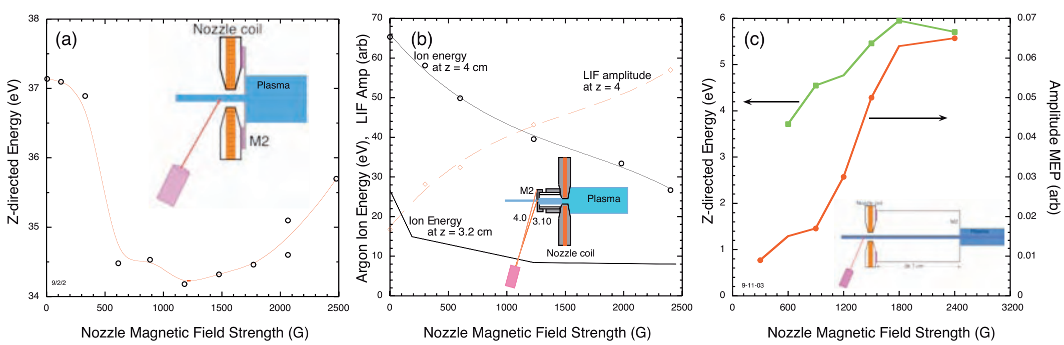

Figure 6. (a) Axially directed ion energy E_z versus nozzle-field strength at z = 2 cm in the MNX expansion region. The plate M2 was located one centimeter upstream of the nozzle-coil midplane, as shown in the inset. (b) E_z versus nozzle-field strength at z = 3.2 and 4.0 cm from the nozzle-coil midplane. The M2 plate was located 3.1 cm downstream of the nozzle-coil midplane, see inset. (c) E_z of the medium-energy ions versus nozzle field strength at z = 2 cm from the nozzle-coil midplane. The M2 plate was located 26.7 cm upstream of the nozzle-coil midplane, see inset.

In FY05, graduate students S. Landsman, N. Ferraro, A. Roach, D. Lundberg, and D. Fong performed PFRC research. The research strongly benefited from collaborations with theoreticians at Los Alamos National Laboratory (A. Glasser) and the Courant Institute of Mathematics of New York University (G. Zaslavsky and M. Edelman).

Theoretical investigations during FY05 were on the mechanism for odd-parity rotating-magnetic-field plasma heating (Figure 7). The heating of figure-8 orbits was shown to be large compared to that of betatron and cyclotron orbits. Heating occurred at resonances of the odd-parity rotating-magnetic-field frequency with the ion orbital frequency. The onset and saturation of figure-8-orbits heating was explained. These studies show how it is possible to tune the energy of heated ions, allowing use of a resonance in fusion rates, as occurs in a p-B^{11} fuel mixture.

During FY05, improvements to the PFRC experimental hardware were made in the odd-parity rotating-magnetic-field radio-frequency system, in the axial field capabilities, and in the implementation of noninvasive diagnostics.

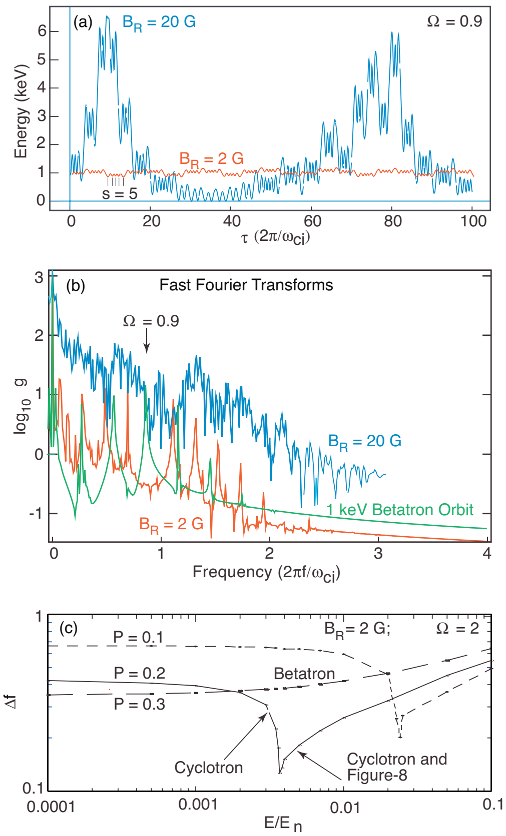

Figure 7. Results of numerical simulation of ion trajectories in a field-reversed configuration with odd-parity rotating-magnetic fields. (a) **Figure-8 ion energy versus time for two values of rotating magnetic field amplitude B_R.** (b) **Fast Fourier transforms of ion energy for the two cases shown in** (a) **and also for a betatron orbit.** (c) **Separation between resonances, Δf versus normalized initial energy for normalized azimuthal canonical momentum P = 0.1, 0.2, and 0.3, at B_R = 2 G.**

Nonneutral Plasma, High-intensity Accelerators, and High Energy Density Physics

A nonneutral plasma is a many-body collection of charged particles in which there is not overall charge neutrality. Such systems are characterized by intense self-electric fields and, in high-current configurations, by intense self-magnetic fields. Nonneutral plasmas, like electrically neutral plasmas, exhibit a broad range of collective properties, such as plasma waves and instabilities. The intense self-fields in a nonneutral plasma can have a large influence on detailed plasma equilibrium, stability, and confinement properties, as well as on the nonlinear dynamics of the system.

There are many practical applications of nonneutral plasmas. These include:

- improved atomic clocks;
- positron and antiproton ion sources;
- antimatter plasmas, with application to antihydrogen production;

- coherent electromagnetic radiation generation, including free electron lasers, cyclotron masers, and magnetrons;
- advanced accelerator concepts with high acceleration gradients;
- investigation of nonlinear collective processes and chaotic particle dynamics in high-intensity charged-particle beams; and
- applications of intense ion beams to studies of high energy density physics properties of warm dense matter and heavy ion fusion.

Research on nonneutral plasmas and high-intensity accelerators at PPPL focuses on three areas:

- 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;
- 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 ion-beam-driven high energy density physics and fusion, spallation neutron sources, and high-energy physics applications of intense charged-particle beams; and
- experimental investigations of radio-frequency and ferroelectric plasma sources for intense ion beam space-charge neutralization; experimental and theoretical studies of ionization and stripping cross sections, and multielectron loss events; and optimization of negative ion beams for heavy ion drivers.

Paul Trap Simulator Experiment

The Paul Trap Simulator Experiment (PTSX) is a compact experiment that simulates intense beam propagation through periodic focusing magnetic alternating-gradient transport systems over distances of tens of kilometers by placing the physicist in the frame-of-reference of the beam. The transverse dynamics of the particles in the two systems is the same. Plasmas are trapped for hundreds of milliseconds in the PTSX device, which corresponds to equivalent propagation distances of tens of kilometers. The PTSX device confines cesium ions in the transverse plane by applying oscillatory voltages to the four quadrants of a 2-m-long 20-cm-diameter, segmented primary cylinder. Static voltages, applied on 40-cm-long end cylinders, provide axial confinement of the trapped one-component pure ion plasma. The amplitude V_0 and "temporal" frequency f of the oscillating voltage in PTSX correspond to the amplitude and "spatial" frequency of the magnets in the actual alternating-gradient transport system.

Recent experiments have concentrated on studying the effects of changes in the "strength" of the transverse focusing field. The focusing field strength is proportional to V_0/f, and experiments were performed to explore the effect of instantaneously decreasing V_0/f during the experiment. The results, when V_0/f is reduced by a factor of 1.5, are shown in Figure 8 and demonstrate that the effect is the same, regardless of how the focusing field strength is reduced. The strength can be reduced either by decreasing V_0, by increasing f, or by changing them simultaneously. The radial density profile of the plasma becomes broader and, since

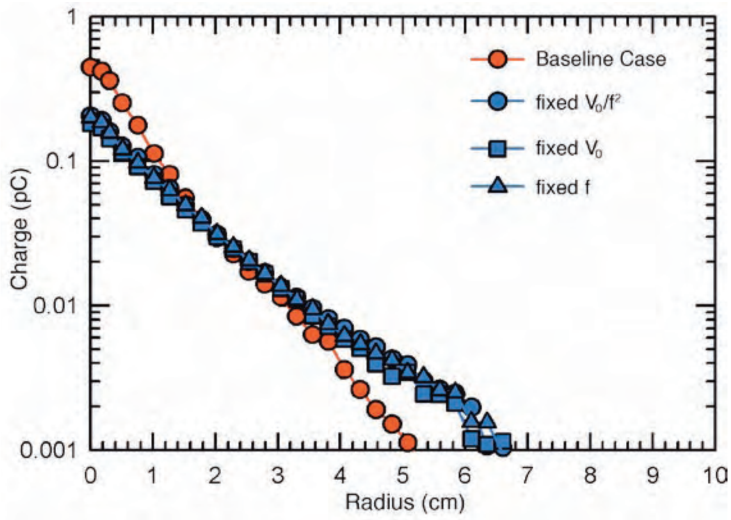

Figure 8. Instantaneously decreasing the "strength" of the transverse confinement allows the plasma to become broader and less peaked as compared to the baseline case. The transverse beam emittance increases by forty percent.

the total number of particles is preserved, less peaked. The emittance, which is a quantitative measure of the transverse pressure of the beam particles, increases by forty percent.

High-intensity Accelerators

Collective Excitations in a Bunched Beam: The nonlinear delta-f method, a particle simulation method for solving the nonlinear Vlasov-Maxwell equations, is being used to study the collective effects in high-intensity bunched beams. For high-intensity bunched beams, the equilibrium and collective excitation properties are qualitatively different from those for long coasting beams. Due to the coupling between the transverse and longitudinal dynamics induced by the 2-D nonlinear space-charge field, there exists no exact kinetic equilibrium which has anisotropic temperature in the transverse and longitudinal directions. Even in a thermal equilibrium with isotropic temperature, the particle trajectories on constant energy surfaces are nonintegrable, which implies that it is impossible to perform an integration along unperturbed orbits to analytically calculate the linear eigenmodes.

For the case of thermal equilibrium with isotropic temperature, the self-consistent kinetic equilibrium for a bunched beam is first established numerically. Then, the collective excitations of the equilibrium are systematically investigated using the nonlinear delta-f method implemented in the Beam Equilibrium Stability and Transport (BEST) code. The BEST code has been recently parallelized in the transverse direction using a particle decomposition method, in addition to the previously implemented domain decomposition in the longitudinal direction. The parallel scheme utilizes the advanced communicator functions provided by the MPI protocol. For parallelization in the transverse direction, the particle decomposition method has much better efficiency than the commonly used domain decomposition. This is because the communication load for transverse domain decomposition is very heavy due to the frequent domain crossing of a single particle in the external focusing lattice and the space-charge potential.

The newly updated BEST code has been used to study self-consistently the collective effects of 3-D bunched beams. For routine production runs with 1,500 processors on the IBM SP supercomputer at the National Energy Research Supercomputer Center, the performance of the BEST code scales almost linearly with respect to the number of processors. For the case of thermal equilibrium with anisotropic temperature, an approximate equilibrium is adopted when the nonlinear coupling due to the space-charge field is weak, and the validity and collective excitations of this approximate equilibrium are numerically studied.

Temperature-anisotropy Instability: Temperature anisotropies develop naturally in accelerators during the acceleration phase. In intense charged-particle beams with large temperature anisotropy, free energy is available to drive a classical electrostatic Harris instability. The instability is kinetic in nature and is due to the coupling of the particles' transverse betatron motion with the longitudinal plasma oscillations excited by the perturbation. For a long, coasting beam, the delta-f particle-in-cell code BEST and the eigenmode code bEASt have been used to determine detailed 3-D stability properties over a wide range of temperature anisotropy and beam intensity. The delta-f particle-in-cell code BEST has also been used to study the nonlinear evolution and saturation of the instability.

The nonlinear saturation is governed by longitudinal particle trapping by a spectrum (not just a single wave) of fast-growing waves with a broad band of longitudinal wavenumbers and zero oscillation frequency. The presence of many waves leads to the nesting and overlapping of particle resonances in longitudinal phase space, and as a consequence, to the fast randomization of the trapped-particle distribution and longitudinal heating of the beam particles (Figure 9). The nonlinear interactions lead to the shift of the wave's spectrum into the long-wavelength region. This can be explained qualitatively as follows. The instability is self-quenching, since as the instability grows, the plasma heats up longitudinally due to particle trapping and phase-mixing. The large wavenumber modes saturate first, but as the smaller wavenumber modes grow and saturate, they increase the longitudinal temperature even further, which in turn begins to damp the saturated modes at large wavenumbers. As a result, the wave energy spectrum transfers to the smaller wavenumber region. This is qualitatively consistent with the behavior of the mode spectrum observed in the simulations. The final longitudinal velocity distribution is not Maxwellian and can be characterized by a remnant temperature anisotropy, where $T_{||}/T_{\perp} = 10\%$, where $T_{||} \equiv m_b \langle v_{||}^2 \rangle$. A very interesting feature of the nonlinear saturation is the formation of a stable, longitudinal, nonlinear BGK-like wave structure with a negligible number of trapped particles.

Neutralized Transport: Ion-beam pulse propagation through a background plasma in a solenoidal magnetic field is an important technique for beam focusing that has been studied analytically. The neutralization of the ion-beam current by the plasma has been calculated using a fluid description for the electrons. This study is an extension of our previous studies of beam neutralization without an applied magnetic field. The high solenoidal magnetic field inhibits radial electron transport, and the electrons move primarily along the magnetic lines. Analytical studies show that the sole-

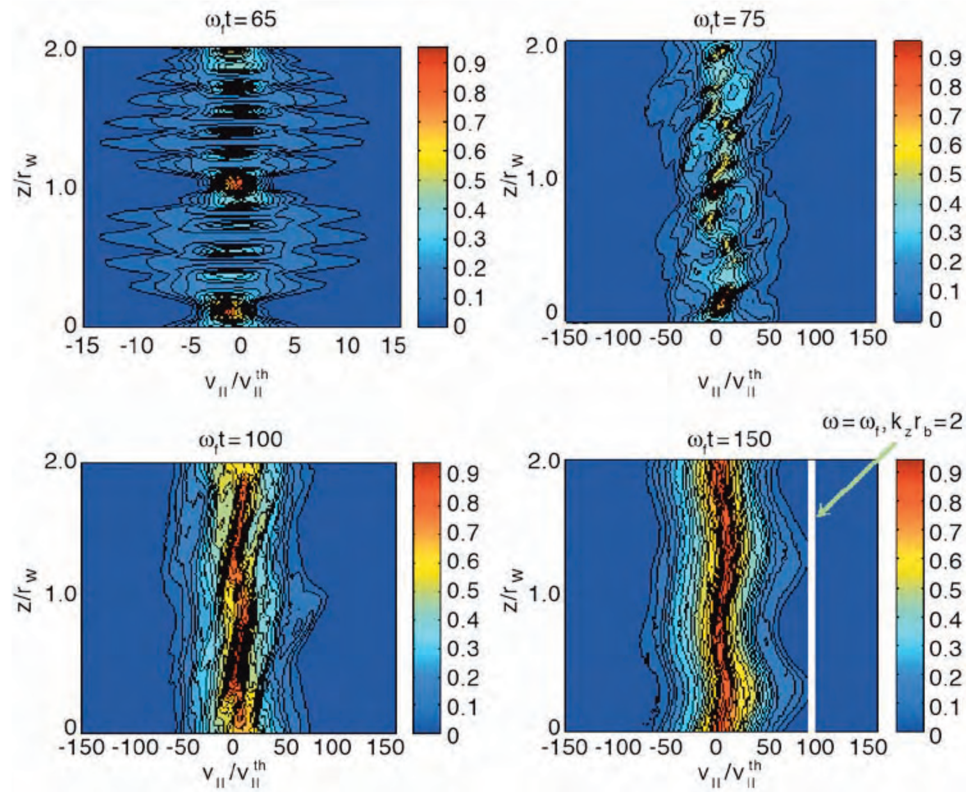

Figure 9. Contour plots in longitudinal phase space for a beam with normalized tune depression $\bar{v}/v_0$ = 0.6 at times (a) $w_f t$ = 65, (b) $w_f t$ = 75, (c) $w_f t$ = 100, and (d) $w_f t$ = 150. Here, w_f is the transverse focusing frequency.

noidal magnetic field starts to influence the radial electron motion if $\omega_{ce} \geq \omega_{pe}\beta$, (where ω_{ce} = eB/mc is the electron gyrofrequency, ω_{pe} is the electron plasma frequency, and $\beta = V_b/c$ is the ion-beam velocity relative to the speed of light). This condition holds for relatively small magnetic fields. For example, for a 100-MeV, 1-kA Ne^+ ion beam, B corresponds to a magnetic field of 100 G (Figure 10).

The Neutralized Drift Compression: Heavy ion drivers use space-charge-dominated beams which require longitudinal bunch compression in order to achieve high beam current. The Neutralized Drift Compression Experiment (NDCX) carried out in collaboration with the Lawrence Berkeley National Laboratory (LBNL) investigates the key scientific issues that determine the effective limits of drift compression. The LSP particle-in-cell simulation code is used to model the longitudinal and transverse compression of an intense ion beam, achieved by imposing a large initial velocity tilt on the drifting beam and by neutralizing the intense beam space-charge with a high density background plasma. Measuring the beam compression and current density with high resolution is critical for NDCX, and an understanding of the accessible parameter space is possible with advanced numerical simulations. Knowledge of the current density of the compressed heavy ion beam is important for determining the amount of power that can be delivered to a target for warm dense matter and heavy ion fusion experiments.

The NDCX measured a record longitudinal compression factor of 60 times the initial beam current of a 300-keV K^+ ion beam after it drifted through two meters of background plasma. The final pulse width of the compressed beam was

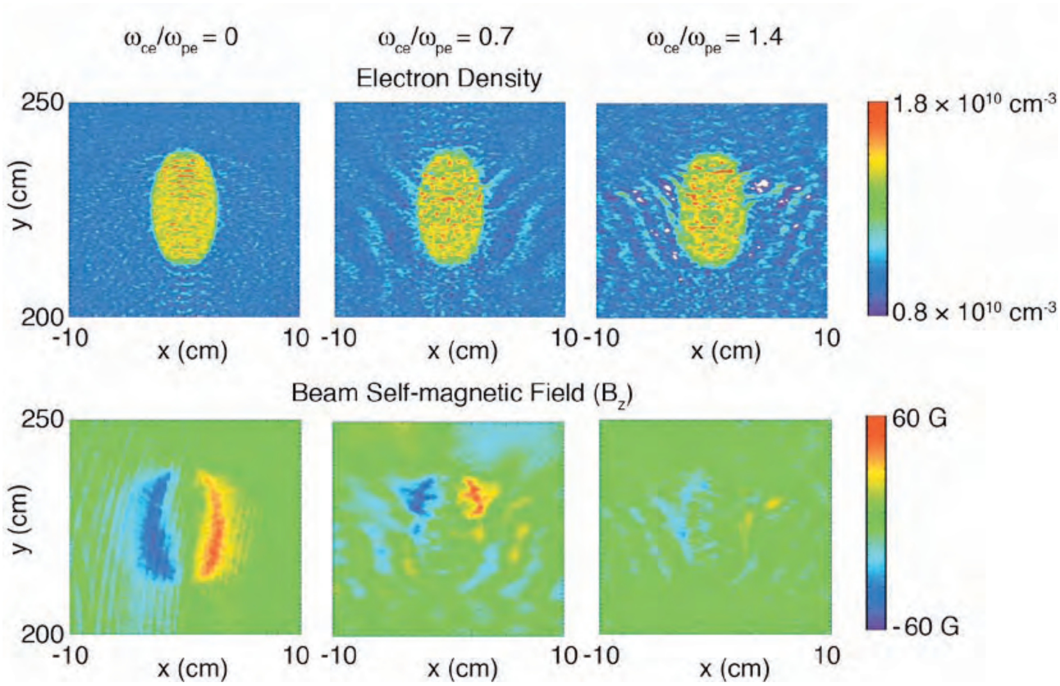

Figure 10. The charge and current neutralization of the ion-beam pulse is calculated in two-dimensional slab geometry using the LSP simulation code for various magnetic field strengths corresponding to ω_{ce}/ω_{pe} = 0, 0.7 and 1.4. Shown in the figure are the electron charge density (top) and the beam self-magnetic field (bottom) contour plots in (x,y) space. The background plasma density is $n_p = 10^{11}cm^{-3}$. The beam velocity is V_b = 0.2c, the beam current 48.0 A corresponds to the ion-beam density $n_b = 0.5n_p$, and the ion-beam charge state is equal to unity. The beam dimensions (r_b = 2.85 cm and τ_b = 4.75 ns) correspond to a beam radius $r_b = 1.5\omega_{ce}/\omega_{pe}$, and pulse duration $\tau_b\omega_{pe}$ = 75.

4 nanoseconds. The measurement was made by a fast Faraday cup diagnostic, which was designed at PPPL to measure the absolute beam current in the presence of background plasma as a function of time at the longitudinal focal plane. Comparison with LSP particle-in-cell simulations was very good (Figure 11). Two other models, a nonlinear fluid code and a kinetic code, were developed in order to corroborate experimental data and LSP simulations. All four were in excellent agreement with each other (Figure 12). The theoretical studies suggest that larger compression factors with smaller pulse widths can be achieved on NDCX after optimization of experimental parameters. For example, in one case, the peak current density achieved at the focal plane could exceed 1 kA/cm^2, corresponding to an increase in beam density by a factor of more than 10^5.

Charge Neutralization Experiments: Researchers at PPPL have developed advanced plasma sources to support the charge neutralization studies conducted on the NDCX. One of the sources developed at PPPL is a radio-frequency plasma source that operates at 13.6 MHz. For radio-frequency waves, the skin depth is on the order of one centimeter. Therefore, the radio-frequency antenna is placed as close as possible to the interaction-region with the ion beam. Operating in a pulsed mode, the source is able to produce plasma densities exceeding 10^{11} cm^{-3} at background gas pressures in the few microTorr range. This plasma source provided a sufficient source

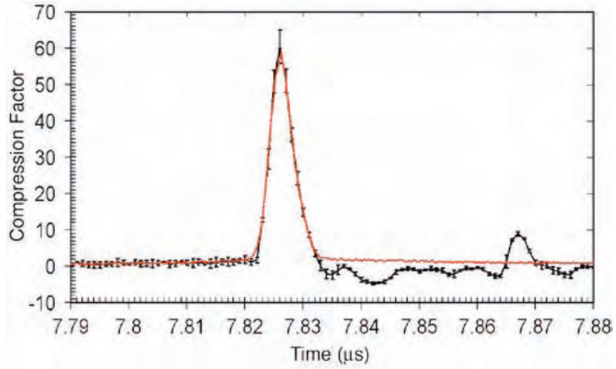

Figure 11. Comparison of LSP particle-in-cell code simulations with experiment. The LSP code results are shown in red and the experimental results with error bars are shown in black. The plots show the beam current as a function of time at the focal plane, normalized to the initial beam current.

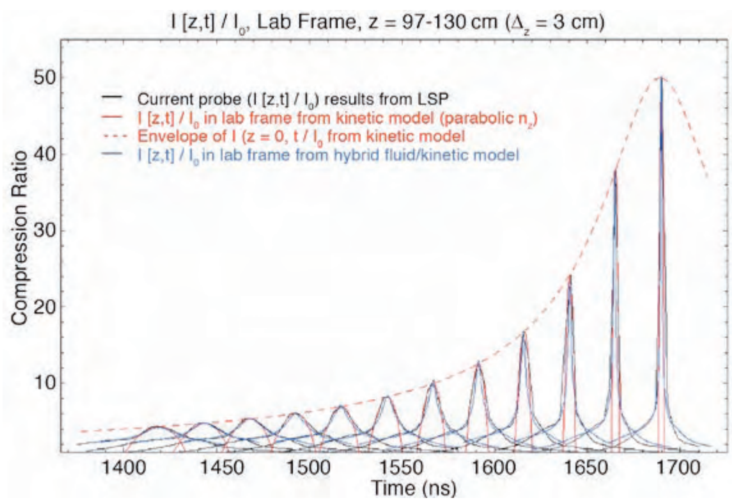

Figure 12. The beam current is plotted as a function of time at various axial locations, including the longitudinal focal plane, normalized to the initial beam current.

of electrons for charge neutralization on the Neutralized Transport Experiment to allow focusing of the ion beam to a spot size of 2 mm. To create plasmas that are one-meter long, as required for NDCX, a ferroelectric ceramic plasma source has been built and tested. Barium-titanate ceramic rings, with a relative dielectric coefficient of several thousand, are stacked together to form a one-meter long, three-inch-diameter, thin-walled cylinder (Figure 13). A 6-kV pulse applied between the outer surface and the inner surface creates a strong radial electric field that is greatly enhanced at the inner surface of the cylinder because of the large relative dielectric coefficient of the ceramic. The ceramic material itself is vaporized at the inner surface and converted into a plasma. Measurements show that plasmas with densities of 10^{11} cm^{-3} and temperatures less than 10 eV are created.

Negative Ion Beams

Some years ago, PPPL proposed the use of negative halogen beams as possible

Figure 13. The one-meter-long ferroelectric plasma source is comprised of five shorter sources connected together, leaving space for diagnostic access.

drivers for heavy ion fusion, since they would not collect electron clouds. Such clouds can increase the beam emittance and lower the power density on the target. They could be efficiently photo-detached to neutrals, which could reduce beam expansion due to space charge between the final focus element and the target. An initial feasibility experiment produced usably high current densities of Cl^-, along with conditions strongly suggestive of the existence of a plasma in the ion source extraction plane composed mostly of positive and negative ions, with relatively few electrons. This would be a novel and interesting state of matter, of both basic and practical interest.

Accordingly, a second experiment was carried out. The primary purpose of this experiment was to compare current densities and beam emittance for Cl^- and Cl^+ beams, extracted from an ion-ion plasma, with the current densities and emittance of Ar^+ beams extracted from ordinary ion-electron plasmas, and to see whether negative halogen beams could be produced with parameters roughly comparable to those of similar mass positive ions at similar discharge parameters. For this purpose, a new radio-frequency (rf) ion source was built, and all experiments were conducted using the same ion source, beam extractor, emittance scanner, and Faraday cup, so that any systematic errors should cancel out.

The absolute current densities in this experiment were lower than those in the earlier one because the plasma confinement was lower in this source (the magnetic cusp field strength at the source wall was about half that of the earlier source), and the radio-frequency power density was lower because this source was considerably larger. However, by using one source, beam extractor, and set of diagnostics to measure Ar^+, Cl^+, Cl^-, and e^-, the present experiment demonstrated that halogens can be used to produce negative and positive ion beams at current densities quite close to those which can be produced of similar mass noble gases under similar discharge conditions.

For instance, with 15.4-kW radio-frequency and 30-kV extraction at 1.5 mTorr, the positive chlorine current is 89% and the Cl^- current is 76% of the Ar^+ current at 2 mTorr. The normalized emittance as a function of perveance is similar for Ar^+, Cl^+, and Cl^-, and the effective beam ion temperature of the minimum normalized perveance beams is essentially the same, about a third of an eV, for all three beams. The relatively low amount of co-extracted electrons (e^-/Cl^- = 7 for the best conditions) without any electron suppression other than the internal filter field, is probably in large part the result of an ion-ion reduced-electron plasma in the extraction plane, as is also suggested by the near-equivalence (80–95%) of the Cl^- and positive chlorine currents at similar source conditions. In a heavy ion driver beam injector, this level of electrons could either be eliminated after extraction, or eliminated during extraction by techniques developed for H^- beams in magnetic confinement fusion. Since the electrons move much faster than the Cl^-, their space charge contributes only a small amount to the extraction perveance (about 3% for the minimum electron

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ratio measured). Both Langmuir probe measurements of the plasma density and Faraday cup measurements of the beam current density found a linear relationship between these quantities and the radio-frequency drive power. Based upon these experiments, it appears that, if negative halogen beams are eventually chosen as heavy-ion fusion drivers, then the current density obtainable with a given source and extractor should be nearly as high for the negative ion as for a positive noble ion of similar mass, and the emittance should be similar.

Magnetorotational Instability Experiment

Astrophysicists have long surmised that accretion disks, orbiting around such objects as forming protostars or black holes, are in a turbulent state. The inferred accretion rates imply a turbulent outward flux of angular momentum, which is necessary for accretion to occur. But how do these disks become turbulent? The rotational equilibrium profile of a fluid disk bound by the gravity of a central object (Keplerian) produces a circumferential velocity that decreases radially as $\Omega(r) \propto r^{-3/2}$, so that this arrangement has angular momentum increasing outwards. Thus Keplerian disks are linearly stable to the centrifugal instability according to the Rayleigh criterion. It is now commonly held that the turbulence in astrophysical accretion disks is caused and maintained by the magnetorotational instability (MRI). This instability is essentially the coupling of the flow shear inherent in a Keplerian profile with the Maxwell stresses of an ambient magnetic field.

The apparatus for this experiment is shown in Figure 14. It is essentially a Taylor-Couette flow device; that is, a cylinder within a larger cylinder. The apparatus can generate a sheared velocity profile within the fluid annulus in between the cylinders. The traditional Taylor-Couette design described above has been further modified to accommodate two intermediary rings at both axial boundaries. These rings are to reduce the unwanted secondary flows (Ekman circulation) produced by the frictional effects of the top and bottom boundaries.

Key to the success of this experiment is the generation of specified Keplerian-like velocity (and thereby momentum) profiles, which are effectively free from distortions due to end-cap friction. To study the efficacy of the end-rings, a series of

Figure 14. The Magnetorotational Instability Experiment.

experiments were performed using water as the working fluid within the apparatus. The transparency of water allows for the utilization of traditional fluid imaging diagnostics. This fact was taken advantage of and a Laser Doppler Velocimetry system was used for a series of hydrodynamic experiments.

The initial hydrodynamic experiments had two goals: (1) to assess the efficacy of the rings in establishing an ideal profile, and (2) to assess the background fluctuation level of the resultant flows. The effectiveness of the intermediary rings upon the flow can be seen in Figure 15(a), where a velocity profile with the rings activated is contrasted with one where the rings are mechanically coupled to the outer cylinder (the latter is a typical arrangement for most Taylor-Couette experiments). Furthermore, the flow profiles appear to scale well, as seen in Figure 15(b). As for the background fluctuation levels, they appear to be nearly quiescent in this centrifugally stable regime, even at high fluid Reynolds numbers (10^5–10^6). This fact is important because there is a rather contentious ongoing debate on whether "nonlinear" (or "subcritical") shear instabilities could occur in these types of flows, and hence also in Keplerian disks. No evidence is seen for such instabilities. This fact, along with the demonstrated control we now have over the fluid through increased boundary conditions (the rings), lays a good foundation for experimental studies of the magneto-rotational instability.

Preparations to begin MRI studies are well underway. Among other things, the vessel has recently been refitted to hold an electrically conducting fluid (an alloy of liquid Gallium) and to be surrounded by six electromagnets. It already has been demonstrated that, in principle, it is feasible to produce the MRI in the laboratory based on the achieved radial profiles in water and theoretical analyses. For anticipated experimental parameters, several MRI modes are expected to be unstable and so a nonlinear or (possibly) weakly turbulent state may be obtained. The nonlinear saturation of the instability should prove useful in providing insight into physical mechanisms that are important to accretion disks, as well as benchmarking astrophysical codes. In fact, a first attempt using a well-known astrophysical code (ZEUS) is well underway to predict the nonlinear evolution of the MRI.

Use of rapidly rotating liquid metal presents certain diagnostic challenges however. In particular, its opacity means

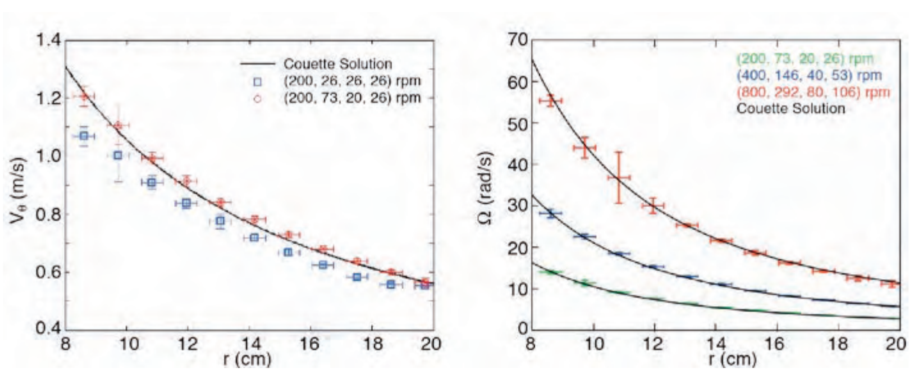

Figure 15. (Left) Measured radial profiles of toroidal velocity with intermediary rings activated (red) and deactivated (blue). (Right) Radial profiles of toroidal velocity with three different speeds. Solid lines indicate ideal Couette profiles.

that the plethora of optical-based diagnostic techniques available for water is of no use. Instead, various methods for diagnosing the velocity field, which is an opaque flow field, are being pursued. Separately, an array of magnetic sensors, both of inductive coils and Hall probes, is also being constructed for the detection of the perturbed magnetic field associated with the MRI. Fortunately, the most important characteristic of the flow astrophysically — the angular momentum transport — will be measurable simply as torques upon the driving motors. These diagnostics altogether will ensure that when the MRI is produced, it will be well characterized. If successful, the MRI experiment will be a significant advancement in astronomical knowledge generally, and for the budding field of 'laboratory astrophysics' in particular.

Diagnostic Development

Electron Bernstein Wave Emission Diagnostic

The National Spherical Torus Experiment (NSTX) and many other plasma devices with high ratios of plasma pressure to confining magnetic field pressure, operate in a regime where the electron plasma frequency far exceeds the low harmonics of the electron cyclotron frequency. In this regime electron cyclotron emission (ECE) radiometry, an established diagnostic technique widely employed on low-aspect-ratio tokamaks and stellarators, cannot be used to diagnose the electron temperature profile evolution. Electron Bernstein wave emission (EBE) is being studied on NSTX as a possible electron temperature profile diagnostic for plasmas operating in this "overdense" regime. A critical issue for this type of diagnostic is that, unlike ECE, electron Bernstein wave emission must be detected via mode conversion to electromagnetic radiation. Two EBE mode-conversion processes have been investigated on NSTX: conversion to the extraordinary mode at normal incidence to the magnetic field (B-X conversion) and conversion to the elliptically polarized ordinary mode via the slow X-mode at an oblique angle to the magnetic field (B-X-O conversion). Of these two processes, B-X-O conversion appears to be the more promising EBE mode-conversion process for high-temperature plasmas such as those produced on NSTX. B-X-O conversion is less sensitive to variations in the density scale at the mode-conversion layer and does not necessitate a material limiter needed to establish the steep density scale length required for efficient tunneling from the Electron Bernstein Wave to the X-mode.

Initial results obtained using a B-X-O antenna on NSTX were very encouraging and in stark contrast to the poor, fluctuating conversion efficiency measured for the B-X antenna previously installed on NSTX. Fundamental frequency EBW emission EBE from the magnetic axis of low-confinement mode (L-mode) NSTX plasmas was efficiently converted to O-mode electromagnetic waves. Figure 16 shows that the measured time evolution of the Electron Bernstein Wave radiation temperature was in relatively good agreement with modeling predictions that used 3-D ray tracing and a 1-D full-wave mode-conversion model. Measured conversion efficiency for thermal EBE from the plasma magnetic axis was 80 ± 20%. Recently, second harmonic B-X-O conversion experiments were also begun and results from these measurements are still being analyzed. Access to the core plasma at second harmonic is expected to be limited in some NSTX plasmas due to the greater harmonic overlap at higher fre-

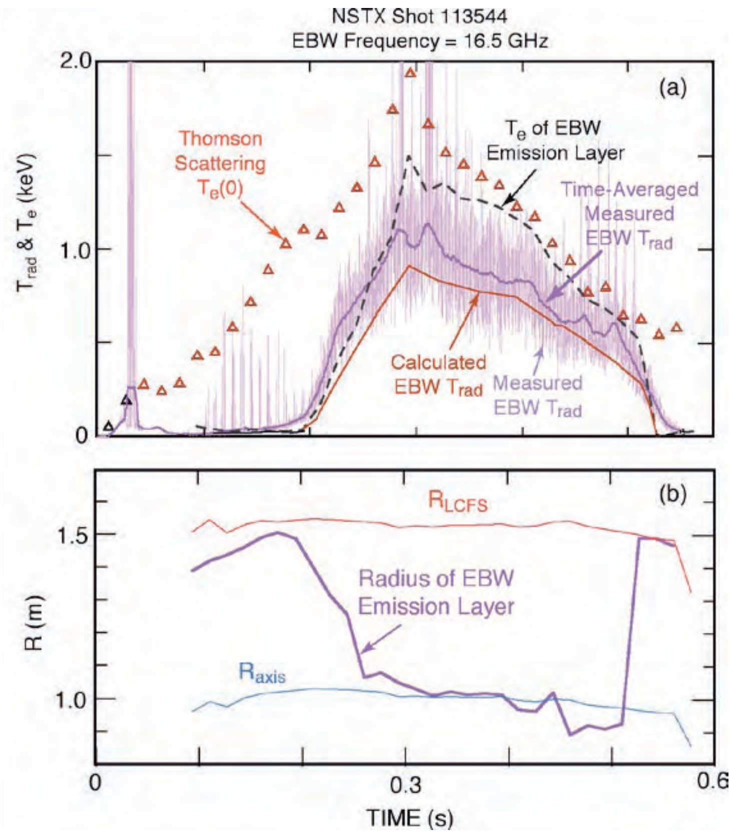

Figure 16. (a) Time dependence of the measured fundamental Electron Bernstein Wave radiation temperature (light purple) and its time-averaged value (dark purple) compared to the calculated radiation temperature (brown) for low-confinement mode NSTX plasma. (b) Calculated radius of the source of the Electron Bernstein Wave emission moves from the last closed flux surface to the axis between 0.2 and 0.25 s, corresponding to the rise in calculated and measured Electron Bernstein Wave radiation temperature.

quencies. Both the fundamental and second harmonic Electron Bernstein Wave radiometers are dual-channel instruments with quad-ridged antennas allowing simultaneous measurement of the emission polarization. Measured EBE polarization at both the fundamental and second harmonic is consistent with near-circular polarization, agreeing with modeling predictions. Further, modeling indicates that the EBE mode-conversion is efficient over a wide range of density gradients at the upper hybrid resonance layer where the EBE mode-conversion occurs.

In FY06, remotely steered fundamental and second harmonic oblique O-mode Electron Bernstein Wave antennas will be installed and tested on NSTX. Until now EBE studies have used either fixed or manually steered B-X-O antennas. These new antennas will allow a detailed mapping of the dependence of the EBE mode-conversion efficiency and emission polarization with antenna pointing direction. The antennas can be steered between plasma discharges allowing a broader range of plasma conditions to be studied during an NSTX experimental run day. Emission data from the remotely steered Electron Bernstein Wave antennas will be used to benchmark modeling predictions.

3-D Microwave Imaging Diagnostic on TEXTOR

Under a strong collaboration between three institutions (PPPL, the University of California at Davis, and the FOM Instituut voor Plasmafysica "Rijnhuizen" in the Netherlands), Electron Cyclotron Emission Imaging (ECEI) and Microwave Imaging Reflectometry (MIR) diagnostics, which simultaneously measure density and temperature fluctuations, have been routinely operated on the TEXTOR tokamak. A logical test of the electron temperature fluctuation measurement for the ECIE system was the m/n = 1/1 mode (sawtooth oscillation) which is a well-established MHD phenomenon in tokamak plasmas. Following successful initial tests on TEXTOR in FY04, improved high-resolution 2-D images of the electron temperature fluctuations measured by the ECEI system were used to study the physics of the m/n = 1/1 mode in TEXTOR in FY05. In the course of this study, the observed 2-D electron-cyclotron emission images were directly compared with the predicted 2-D pattern of the relevant theoretical models of the sawtooth oscillation: the full reconnection, quasi-interchange, and ballooning mode models.

TEXTOR has a circular cross section, a major radius of 175 cm, and a minor radius of 46 cm. The toroidal magnetic field in the present work was in the range 1.9 to 2.4 T and the corresponding plasma current was less than 305 kA. Key plasma parameters were as follows: central electron density and temperature was in the range 1.5 to 2.5 × 10^{19} m^{-3} and from 1.2 to 1.6 keV, respectively. The corresponding peak toroidal beta was approximately 1.0% and the average poloidal beta was between 0.3 to 0.5. The toroidal rotation of the plasma varied from about 1 to 8 × 10^4 m/s. The speed of a thermal electron was approximately 6 ×10^7 m/s. The Alfvén and ion acoustic speeds were 5 × 10^6 and 7 × 10^5 m/s, respectively. Using plasma parameters close to the q ~ 1 surface, the characteristic reconnection time (τ_c) was approximately 700 μs. The system has 16 (vertical) by 8 (horizontal) sampling volumes arranged in a 2-D matrix of 16 cm (vertical) by 7 cm (radial) with a time resolution of about 5 μsec. The fluctuation quantities were relatively calibrated to the averaged value obtained with a long integration time and the intensity of the images is represented by $\delta T_e/\langle T_e \rangle$, where $\langle T_e \rangle$ is the time-averaged electron temperature. A schematic of the coverage areas on the midplane together with the sample imaging data acquired during the sawtooth crash is shown in Figure 17.

In the full reconnection model, the plasma current density in the core region increases [q(0) drops below unity], and the m/n = 1/1 internal kink mode becomes unstable due to the pressure driven instability. In this model, the formation of the island is an indication of the topological change of the magnetic field through reconnection. One of the frames from the simulation results is strikingly similar to the relevant time slice of the 2-D images (island and hot spot) as shown in Figure 18(a). However, in the image of the hot spot, there is no indication of a heat flow until the reconnection through the sharp temperature point (ballooning mode type) takes place in the later stage. This observation suggests that this model has two stages in the reconnection process (weak and strong) or may need an additional physical mechanism.

In the quasi-interchange model, the core plasma having a flat q (~1) profile inside the inversion radius becomes unstable due to a slight change of the magnetic pitch angle. As the hot spot deforms

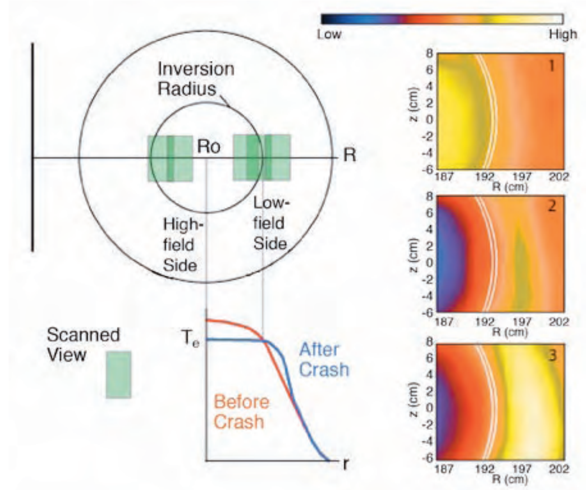

Figure 17. Scanned sampling views are shown with respect to the TEXTOR plasma during the course of the experiment; the range of the sampling view is from the q ~ 2 layer at the low-field side to the q ~ 1 layer at the high-field side. Based on time-averaged images from similar crash phases, composite images are constructed as shown in this figure: (1) heat is inside the inversion radius before the crash, (2) a hint of the heat is shown (greenish color) at the outside of the inversion radius while the growth of the island (blackish blue color) is evident in the intermediate stage of the crash, and (3) heat is accumulated outside the inversion radius after the crash.

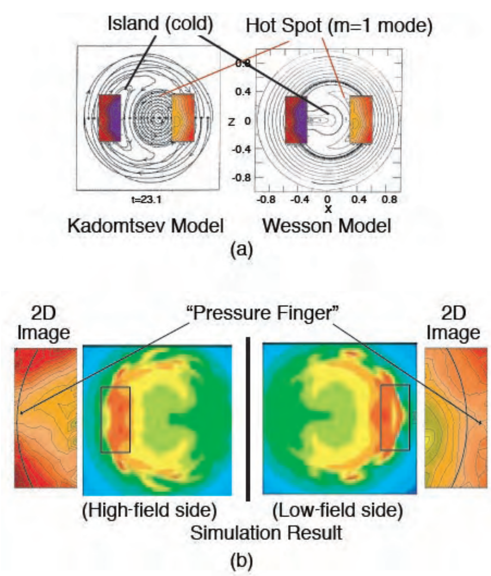

Figure 18. (a) Experimental 2-D images of the hot spot and island formations are overlaid for comparison on the 2-D line patterns from the full reconnection model developed by Kadomstev and the quasi-interchange model developed by Wesson. (b) The 2-D frames of the high- and low-field side of the hot spot with the fully grown ballooning mode from the simulation are directly compared with the relevant experimental 2-D images of "pressure finger" from the high- and low-field side.

into a crescent shape, the cooler outside portion of the plasma is convectively inducted into the core region, resulting in a flattening of the core pressure profile. The 2-D images of hot spot and island do not resemble those from this model as shown in Figure 18(a). Since the occurrence frequency of the pressure-driven reconnection is dominant, the reconnection process based on the pressure instability may be the dominant mechanism compared to the magnetic instability. In plasmas with a moderate beta [β_p ~ 0.4 and $\beta_t(0)$ ~ 1%], where the experiment was performed, the level of the ballooning modes and global stochasticity of magnetic field lines that are strongly coupled with the pressure surfaces is moderate compared to those at high beta plasmas in the ballooning mode model. As shown in Figure 18(b), the sharp temperature point at the low field side is strikingly similar to the ballooning mode in the simulation. Note that the hot spot and island are represented in red and light green color in the simulation, respectively, whereas the greenish yellow represents the hot spot in the 2-D image. At the high-field side, the hot spot is indented toward the center in the simulation, while the observed the 2-D image of the sharp temperature point resembles that of the low-field side as shown in Figure 18(a). While the global stochasticity is dominant in the pressure pattern of the simulation, the experimentally measured heat flow patterns at the high- and low-field sides are highly collective as shown in Figs. 18(a) and 18(b).

X-ray Imaging Crystal Spectrometer

The U.S. Department of Energy grant for the development of an X-ray Imaging Crystal Spectrometer to measure ion-temperature profiles on NSTX was renewed in 2005 and, in preparation for the FY05 experimental campaign, several significant improvements were made to the detector electronics. The software and readout electronics for PPPL's multiwire proportional counters were adapted for delay lines of up to 500 ns, so that it is now possible to record data from the entire 10-cm by 30-cm area of the detector developed by the Brookhaven National Laboratory (BNL) without data overflow. Also, additional electronics were installed to monitor the signals at the ends of the delay lines, in order to measure the actual photon count rate on the detector. With these improvements it was possible to measure the throughput of the processed data from the time-to-digital analyzer, which rejects photon events if the time between such events is less than the characteristic time of the delay line, as a function of the actual photon count rate on the detector.

Using the BNL detector with a 500-ns delay line, it was found that the throughput of the processed data is limited to 150 kHz. This limit is obtained when the actual photon count rate is 500 kHz. If the actual photon count rate is higher than 500 kHz, the throughput of the processed data is reduced; it is zero if the actual count rate is 2 MHz.

These findings explain the observations from the FY04 experimental campaign when only very faint spectra or no spectra at all were obtained in spite of the injection of significant amounts of argon. In fact, it was learned that the amount of argon in the plasma had to be much less than what was used during the FY04 experimental campaign in order to obtain the maximum throughput. The best results were obtained by injecting argon from a 140-cc plenum, with a fill pressure of 300 Torr, for 100 ms at two seconds before a NSTX plasma discharge. Such argon puffs caused only a small tempo-

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rary pressure increase of 10^{-9} Torr, which was measured by a fast-ion gauge. Under these conditions, the amount of argon in the plasma was so low that no argon lines were detected by the SPRED survey spectrometer, which is used to monitor the concentrations of impurities in the plasma.

By monitoring the actual count rate on the detector, it was also learned that the radiation from helium-like argon is significant only at about 150 ms after the beginning of a NSTX plasma discharge. Only then is the electron temperature high enough to produce helium-like argon. Since the typical duration of NSTX discharges with a plasma current of 1 MA is about 500 ms, spectra of helium-like argon can be collected for a time window of about 250 ms. The results are shown in Figure 19.

During the FY05 NSTX experimental campaign, there were only a few plasma discharges with argon injection and those discharges did not have identical parameters, so that the spectrum shown in Figure 19 is only of value for a demonstration of the instrumental performance. A severe impediment is the count rate limit of 150 kHz of the presently used BNL multi-wire proportional counter. A segmented multi-wire proportional counter with a count rate of 800 kHz and a new silicon diode array, the so-called Pilatus II detector, with a count rate capability of 1 MHz per pixel, will be tested during the FY06 NSTX experimental campaign. With an appropriate high-count rate detector, it should be possible to obtain spatially resolved spectra with a time resolution of 10 ms.

Liquid Metal Experiment

The Liquid Metal Experiment (LMX) is a small-scale laboratory experiment focused on the physics of magnetohydrodynamic (MHD) effects on surface waves and turbulence in liquid metals. MHD turbulence has been regarded as an essential element of many intriguing phenomena observed in space and laboratory plasmas, and it has also been a prominent subject of basic plasma physics research. Recent interest in the application of liq-

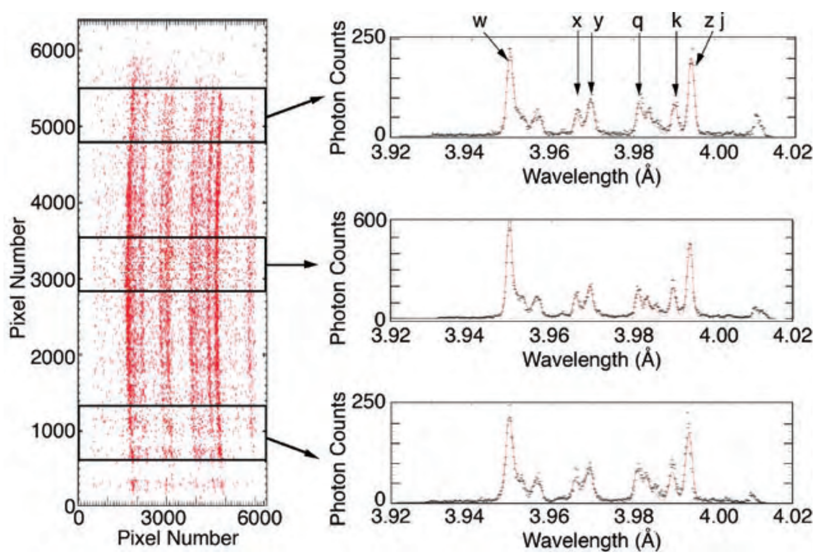

Figure 19. A spatially resolved spectrum of helium-like argon lines w, x, t, and z with the associated dielectronic and inner shell excited lithium-like satellites.The data have been accumulated from several NSTX plasma discharges (discharges: 117848, 117849 and 117853–117857) with ohmic heating to improve the statistics.

uid metal to fusion devices (such as "first walls") adds new demands for a better understanding of the physics of electrically conducting fluids in a magnetized environment. Dynamics of free-surface MHD flows may also have important connections to energetic astrophysical phenomena (such as X-ray bursts), e.g., on neutron stars, where accreted matter is thought to drive free-surface flows within a fluid-like dense plasma ocean. The LMX experiment studies basic physics issues encompassed by such scenarios, with a focus on MHD effects upon free-surface shear flow and fluid turbulence. An alloy of liquid gallium is used that can be well approximated by incompressible MHD.

Three basic physics issues in particular are being addressed in this experiment: (1) How do MHD effects modify surface stability (either in linear regimes or non-linear regimes, such as solitary waves)? (2) How do MHD effects modify shear stability? Is the flow more stable (through suppression of cross-field motions) or less stable (through introduction of new boundary layers)? Can the flow be destabilized by the critical layer instability, where the flow speed matches with the surface wave phase velocity? (3) How do MHD effects modify thermal convection either with a vertical or horizontal temperature gradient? Is the thermal convection enhanced or suppressed?

Previous investigations of this experiment made significant progress in understanding (1) and some of part (2). It was determined that driven surface 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. A linear theory, which takes into account MHD effects, predicted magnetic damping of surface waves that was in good agreement with the experimental results.

Velocity profiles as a function of magnetic field strength were assessed with a prototype small channel flow having a transverse co-planar field up to 1.2 kG. It was seen that the profiles become more peaked with increasing magnetic field, a result which can be understood as an effect due to small channel aspect ratio (depth << width). The effects due to small channel aspect ratios have received only little attention. They could have important implications; i.e., with less influence from the boundaries, different types of instabilities may have a larger role than has been previously appreciated.

To better study all these phenomena, a larger and more refined experiment has been designed which permits a higher flow rate in a stronger magnetic field. The new apparatus, a schematic of which is shown in Figure 20, is being constructed and is nearly complete. The dynamical parameters should allow for a MHD channel flow that is likely to be unstable and turbulent. Studies on stability, turbulence, and transport are anticipated to commence shortly. A particular focus on this next wave of research will be on shear-driven instabilities in MHD. New studies involving heat transport are also planned — these will be taylored to address specific "first wall" convection issues. Overall, the results from this experiment should help fill an important knowledge gap that should prove useful in the general understanding of free-surface MHD flows and their application to both fusion and astrophysics. Active collaboration with broader scientific communities, including experts in astrophysics, computational science, and mechanical engineering, is ongoing.

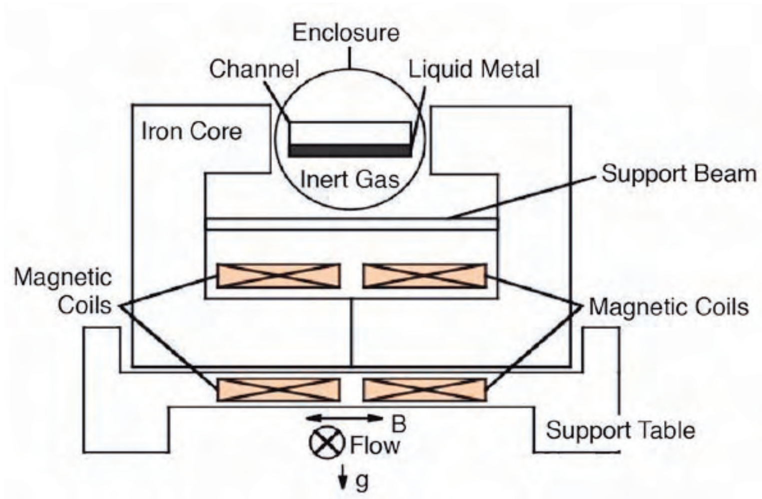

Figure 20. Schematic of a larger, more refined nearly completed Liquid Metal Experiment.

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Engineering and Technical Infrastructure

The Princeton Plasma Physics Laboratory (PPPL) Engineering and Technical Infrastructure Department is responsible for managing the Laboratory's engineering resources. This includes a staff of engineers, technicians, and support personnel organized functionally (Mechanical; Electrical; Computer; and Fabrication, Operations, and Maintenance Divisions) to support the Laboratory's research endeavors. The Department is responsible for the technological infrastructure of the Laboratory's experiments as well as the maintenance and operation of the major C- and D-site experimental facilities.

NCSX Engineering

During FY05, the National Compact Stellarator Experiment (NCSX) Project was focused on completing the final design of stellarator core components and fabrication of the vacuum vessel and modular coils for the device. An U.S. Department of Energy (DOE) Office of Science review was conducted on December 7, 2004 to evaluate the Project's cost and schedule performance subsequent to the approval of Critical Decision 3 (CD-3), "Start of Construction," on September 16, 2004. The Committee had numerous positive findings about the Project Team, such as increased cost contingency, active management involvement, and quick responses to challenges. It recognized, however, the technical complexity of the Project and the need to maintain adequate cost and schedule contingency.

Because of changes in the NCSX funding profile, the DOE Office of Fusion Energy Sciences (OFES) directed a re-baseline of the Project. A series of reviews of the Project's change proposal was held. The DOE Deputy Secretary approved the new baseline on July 27, 2005. As a result of this direction, the Project end date (CD-4 milestone) was delayed 14 months to July 2009. The total estimated cost increased by $6.1 M from $86.3 M to $92.4 M.

NCSX Coil Winding and Component Manufacturing

Fabrication of the modular coil winding forms and vacuum vessel subassemblies proceeded well technically. The NCSX design calls for 18 modular coils, comprised of three coil types designated A, B and C (Figures 1 and 2). The first modular coil winding form (C1) is scheduled to arrive at PPPL from Major Tool and Machine, Inc. in October 2005 (Figure 3). Delivery of winding forms C2 and C3 to PPPL is expected before the end of December 2005. Completion of final design for the Type-A and Type-B modular coils is planned for the first half of calendar year (CY) 2006.

Major Tool and Machine, Inc. is also fabricating the vacuum vessel subassemblies (Figures 4 and 5). Their delivery schedule for the three vacuum vessel subassembly segments is March 27, May 15, and June 16, 2006.

The design of the modular coil assemblies is benefiting greatly from the design, fabrication, and testing of a prototype known as the "Twisted Racetrack Coil" (TRC) shown in Figure 6. The TRC was used to test key aspects of the modular coil designs. It was fabricated using the same coil manufacturing facility that is set up in the former Tokamak Fusion Test Reactor (TFTR) Test Cell

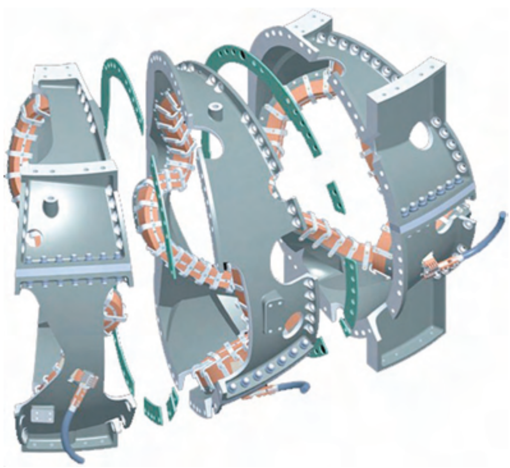

Figure 1. The NCSX will utilize three modular coil types (A, B, and C) which will be bolted together to form a single field-period assembly.

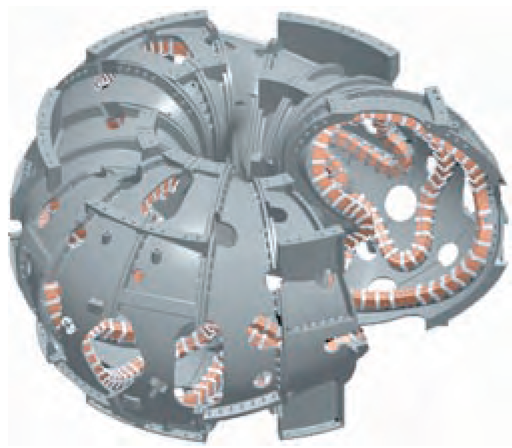

Figure 2. The National Compact Stellerator Experiment shell structure will be formed by bolting together three field-period assemblies.

Figure 3. The first NCSX modular coil winding form is scheduled for shipment to PPPL in October 2005.

Figure 4. The first vacuum vessel subassembly in manufacture at Major Tool and Machine, Inc.

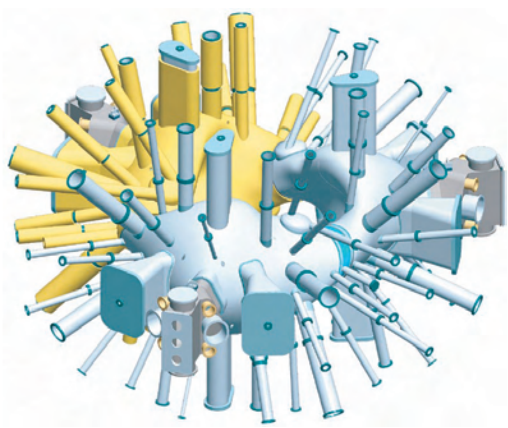

Figure 5. NCSX vacuum vessel assembly showing the ports that will provide diagnostic and heating access to the plasma.

Figure 6. The Twisted Racetrack Coil in the vertical turning fixture which will be used for the winding of NCSX modular field coils.

for the fabrication of the NCSX modular coils.

The TRC is a third representation of a modular coil. It includes many of the modular coil design features such as a winding form with typical machined "tee" profile, identical conductor and insulation, coil leads, cooling scheme, and final coil clamps. The successful manufacturing and testing of the TRC helped finalize tolerance control, manufacturing procedures, tool development, verification of the vacuum-pressure impregnation plan utilizing the autoclave, and training of key personnel. Numerous improvements in the design and manufacturing processes resulted from TRC fabrication.

A coil test facility was set up in the basement of the TFTR Test Cell. The TRC was cooled down to liquid nitrogen temperature and tested at high current (31 kA). Thermally, the coil performed as expected providing increased confidence that the production coils will also perform as expected. Finally, the TRC was Meggared and cut apart for visual inspection. The Side-A ground insulation failed the Meggar Test at 5.5 kV in the lead area, which was redesigned for the production coils. Side-B failed at 10.5 kV, above the 6-kV manufacturing test voltage.

The TRC was sectioned in nine places, allowing close examination of the coil fabrication details. Inspections found good overall epoxy impregnation, validating the mold design and vacuum-pressure impregnation procedure. Modifications needed to address localized issues of incomplete saturation were made for the production coils. Minimal distortion (keystoning) of the conductor cross section was seen and the conductor height was uniform between the first and last layer.

Substantial progress has been made in the design integration of the vacuum vessel with its ancillary components, including heating and cooling lines, port strip heaters, thermocouples, and magnetic diagnostics. Magnetic diagnostics include 160 distinct flux loops for diagnosing stellarator symmetric magnetic fluxes, and a further set of six distinct flux loops for non-stellarator symmetric fluxes. Sixteen pairs of heating and cooling lines have been modeled for each half period of the vessel. The use of flexible cooling lines is being tested at the Oak Ridge National Laboratory (ORNL). All the lines will be routed outside the cryostat through large vertical ports. The heater leads, thermocouple leads, and magnetic diagnostic leads will also exit the cryostat through these same ports.

Final design of the toroidal-field (TF) coils has been completed. The TF design has been modified to preload the TF inner legs in compression through jack-screw devices connected to the coil support structure at the top and bottom of the TF inner legs. This change simplifies the preloading mechanism and reduces peak stresses in the TF winding. The mechanical and fatigue properties of the TF winding pack were tested at ORNL and found to be satisfactory. The copper conductor order for the NCSX TF coils was placed with Outokumpu with delivery expected in November 2005. A Request for Proposals will be issued in early CY06 for the fabrication of completed TF coil assemblies, which include the TF winding and wedge pieces bonded to the winding.

The design of the base support structure was peer reviewed in September 2005. Two options were presented. In the baseline approach, the fixture required to translate and position the field period for final assembly also serves as the permanent support structure. An alternate approach was presented in which the fixture is temporary and permanent supports are located underneath the Type-C coils. The advantages of this alternate approach are numerous, and it was adopted as the new baseline.

Preparations for field-period assembly began in earnest in FY05. The turning fixture for installation of the cooling tubes and magnetic diagnostics on a vacuum vessel period assembly was designed and is being fabricated. Tests were run to determine if it is feasible to assemble the modular coils over the vacuum vessel using rigging instead of a custom-designed modular coil handling fixture. The tests demonstrated the feasibility of the rigging approach, saving several hundred thousand dollars.

A novel method for aligning coils during assembly using mutual inductance measurements was developed. The potential advantage over mechanical methods is that it would align the coils by aligning the magnetic fields, thus more directly targeting the issue of importance to physics performance. A plan is being drafted to show how the proposed methods could be integrated with assembly operations.

NCSX Project Safety

Safety continued to receive due attention on the NCSX Project. In the wake of an unfortunate accident at the Sanford Linear Accelerator Center (SLAC), NCSX undertook the following actions:

- Require Hazard Awareness Training. All NCSX personnel will take Hazard Awareness Training to better appreciate the hazards encountered while performing their jobs, and to learn to make better use of Job Hazard Analysis, which is one of the basic tools for promoting safety.

- Increase use of the Work Planning Form. This form is a simple tool for identifying job issues and control measures, including, though not limited to, safety.

- Improve Visitor Management. Project staff from ORNL, as well as consultants from other organizations, are getting heavily involved in NCSX fabrication activities. PPPL has the responsibility to make sure that every visitor has a host and that hosts meet their responsibilities for visitor safety. Visitors are responsible for following PPPL requirements while on site.

NSTX Engineering Operations

The FY05 National Spherical Torus Experiment (NSTX) experimental run campaign began in April 2005, completing 18 run weeks by mid-September. During this period there were 718 hours of high-power operations with technical subsystems operating at an average availability of 92.9%. There were 2,476 plasma attempts, resulting in 2,221 plasmas.

NSTX operated with enhanced plasma shaping capability with the design, fabrication, and installation of two new axially shorter poloidal-field coils mounted at the upper and lower ends of the central solenoid. Also, optimized gas and microwave power injection points were implemented in conjunction with a more precisely controlled coaxial helicity injection system capacitor bank to investigate solenoid-free plasma initiation.

Six error-field coils proposed for experiments to better characterize the limits of stability of spherical torus plasmas were designed and mounted on NSTX. A new Switching Power Amplifier power supply was installed and commissioned to drive 3 kA, controllable to 7 kHz, in each of three pairs of the error-field coils, and provided initial data for the larger set of resistive wall mode experiments.

Before the start of the experimental run campaign, the toroidal-field coil joints were dismantled and a new technique developed and implemented for the epoxy potting of the joint flags within the upper and lower hub support boxes. This, along with the addition of a commercially available friction coating to enhance the stiffness of the hub assemblies, allowed for toroidal-field operation to 5.75 kG.

Laboratory Power Systems

PPPL continued work with private industry to develop and implement methods to bring older electrical switchgear to current safety standards for arc-flash protection. The Laboratory completed work with Siemens-Westinghouse Corp. on a system to allow remote racking of the 4-kV switchgear, and with General Electric on upgrades to the extensive 480-V D-Site bus system. In addition, PPPL replaced the 45-year-old C-Site emergency diesel generator with a new 820-kW unit manufactured by Caterpillar Corp., and commissioned a new uninterruptible power system for the central computing system.

Princeton University Cyclotron Decommissioning

During the first quarter of FY05, the decommissioning of the Princeton University Cyclotron, located under Jadwin Hall, was completed. The Fabrication, Operations and Maintenance Division, which led the decommissioning of the TFTR at PPPL, generated plans for the Cyclotron decommissioning and selected the contractors for the safing and removal of electrical components, as well as for the removal of more than one million pounds of concrete shielding, 200 tons of lead shielding, and the cyclotron itself. The electrical safing and removals started in late July 2004, and by late September enough had been completed that the mechanical removal contractor could begin work. All removals were completed by the end of December 2004, as scheduled, so the University could begin converting the area into a new physics research facility.

Engineering Work-for-Others

During FY05 two major Work-for-Others projects within the Engineering and Technical Infrastructure Department were in progress.

The first of these projects was the continuation of the development and deployment of the Miniature Integrated Nuclear Detection System (MINDS). MINDS, which is an extension of nuclear detection technologies developed at PPPL in support of the safe decontamination and decommissioning of TFTR, is a real-time radionuclide identification system designed for homeland security applications.

During March of 2005, MINDS technology was licensed to InSitech, a private company with interest in introducing emerging technologies into the marketplace. During FY05, MINDS was deployed in a variety of venues (Figure 7) including a military base, a large commuter rail and bus center in the northeast U.S., in a security vehicle, at a DOE laboratory, and with a large U.S.-based Security Company.

Also during FY05 worked continued in support of the High Average Power Laser Program. This included the development of a silicon/nanocrystalline diamond electron-beam transmission window. The electron-beam transmission window, or "hibachi foil," is the barrier that separates the electron-generating cathode from the high-pressure KrF lasing gas within an excimer laser system. In addition to the continued development of this novel hibachi window, PPPL also developed the conceptual design of a vacuum pumping system for an Inertial Fu-

Figure 7. PPPL's Miniature Integrated Nuclear Detection System (MINDS) deployed at a facility entrance.

sion Energy (IFE) target chamber for the High Average Power Laser Program. The IFE target chamber is anticipated to operate in a pulsed fashion (5–10 Hz) producing a relatively large volume of plasma exhaust gasses. The IFE vacuum pumping system is designed to maintain the target chamber base pressure to required steady-state operational levels in the milli-torr range.

Computing

Business and Financial Computing

PPPL's business computing system consists of Microsoft's Great Plains e-Solutions software running on Microsoft's Windows 2000 Server and a SQL Server 2000 as the database management system. The core system went live on May 1, 2004. In addition to the business operations systems, PPPL's business computing system supports facility maintenance based on Micromain XM. During 2005, this system was expanded to include emergency equipment maintenance scheduling for fire extinguishers and eyewash stations.

The business systems are housed on three Dell servers: one production SQL database server, one Windows IIS web server, and one test/development server running both SQL and IIS. All servers were purchased in July 2001 at the beginning of the project. Dell ceases maintenance on servers over five years old, therefore the production hardware will need to be replaced in FY06.

Scientific and Engineering Computing

PPPL's primary computing resources for scientific and engineering applications are three clusters that utilize "Beowulf" technology to provide cost-effective mid-scale serial and parallel computational capabilities to Laboratory researchers and fusion community collaborators. The clusters were initially built at PPPL in late FY01 and FY02, have not been upgraded, and are now obsolete. A design has been approved to phase in a 400 CPU cluster over two years with 25% to 33% annual refresh thereafter.

In August 2005, a very high-speed interconnect cluster was brought online providing 48 CPU's, an Infiniband interconnect, and 144 GB of memory (the 'kite' cluster). This cluster has been fully booked since it became available.

Off-site researchers are making use of PPPL computing resources, most notably via the FusionGrid TRANSP code run production service, with several thousand jobs run in FY05. Although these serial runs use only a small percentage of the overall capacity of the cluster, the availability of the service is important to its users, introducing an off-site sensitivity to the reliability of the system.

Computing Infrastructure

In FY05, a new 192-terabyte tape library, a 12-terabyte storage array, and a storage area network were brought on-line and have proved to have exceptionally high performance and reliability. This infrastructure opens a new era of computing support at PPPL, as the storage is used by multiple operating systems including VMS (used by NSTX), UNIX/Solaris file servers, Linux servers, and Windows e-mail, domain and operations servers. A dedicated "portal" pool of systems was brought on-line for general purpose login and computation. A key advantage to this approach is the ability to add to the pool with no downtime as demand increases.

Backup of desktop systems is now accomplished in-house using Veritas Netbackup. In previous years, backups were accomplished by using the TSM facility on main campus. Using Netbackup, we have been able to offer daily backups consisting of all data on a disk at a much faster rate. Approximately 400 desktop computers are presently being backed up.

Patch management and the automatic pushing of software updates to domain users were major accomplishments in FY05. A critical patch management scheme was used on the Windows side to patch operating systems while Group Policy was used to install/maintain windows security settings and some application software. For Macintosh users, Apple Remote Desktop is being implemented to centrally manage some software applications and patching.

Cyber Security

Cyber Security at PPPL continues to be a very important and highly visible issue. Staff retirements during FY05 resulted in organizational changes, including appointment of both a new Chief Information Officer and Cyber Security Officer. A new Cyber Security Technical Working Group, chaired by the Cyber Security Officer, was formed. This group holds weekly planning and status meetings that have been very productive in fostering the inter-group communication required to make cyber security improvement efforts as effective as possible.

PPPL had no detected cyber security breaches during FY05, which marks a milestone of five years without a cyber security break-in. A few systems, primarily visitors connecting already-infected personal laptops to our network, were detected with viruses and worms. The effort to keep worms, viruses, trojan horses, spyware, and other malicious software off of PPPL networks continues to be significant. Much effort in the cyber security area has been targeted at addressing cyber security alerts, installing the latest patches, and ensuring that all users have the latest virus protection.

Two U.S. DOE cyber security audits/reviews were performed in FY05, which included detailed external and internal vulnerability scanning and penetration testing. Several areas for improvement were identified and are being addressed, but overall PPPL's cyber security program was found to be in good shape. Policies and procedures required for compliance with the Federal Information Security Management Act (FISMA) and the National Institute of standards and Technology (NIST) regulations were identified by the reviews, and a significant effort is underway to produce the documentation needed to meet those requirements.

The PPPL perimeter firewall continues to operate in default-deny mode and drop numerous attempted connections. This firewall was successfully upgraded in FY05 and can now support up to gigabit-speed wide area network connectivity. An Intrusion Detection and Prevention System was also implemented as part of this upgrade. Users requiring access to our nonpublic computer services from off-site continue to use SecurID-based two-factor authentication, providing a very high level of password security. Our automated firewall virus protection continues to be very busy, detecting and cleaning hundreds of email-attached viruses daily. The visitor/unknown computer systems firewall that was placed in operation during FY05 continues to successfully defend our internal network against possible virus/worm infection. This firewall segregates visitor and PPPL laptops and dial-in computers into an internal virtual network, and systems on this network are monitored for virus/worm infections and other suspicious network traffic. The firewall automatically alerts administrators in real time when an infected machine scans our networks, and blocks these systems if necessary. This firewall successfully detected suspicious computers that connected to our network, and allowed administrators to take corrective action quickly.

Improvements in dial-in modem security were accomplished in several ways. The standard PPPL dial-in modem bank was moved to the segregated, fire-walled network, and dial-in password authentication is now via SecurID only. Local telephone firewalls with ACLs (Accounting Control Lists) were deployed on other computer modems that allow external dial-in access.

To prevent possible embarrassment from inappropriate use of web browsers and to block access to sites that are known to proliferate hacker tools, peer-to-peer software, and malicious code, Enterprise web-filtering software (WebSense) continues to be used. Despite these measures, spyware continues to be a problem on Windows systems. Plans are underway to determine how to best improve spyware prevention.

Increased emphasis on internal cyber security and insider threats have resulted in several initiatives for improvement. Almost all Windows systems now have basic security policy and patch updates managed by the PPPL domain, so that future vulnerabilities can be patched more efficiently. Enforcement of the new policy, which requires all Windows systems at PPPL to be managed by our domain unless specifically exempted by supervisory approval, is increasing. Redhat Linux clusters now boot from a central server allowing for uniform cyber security policy and simple patching. Mac OS systems are starting to be managed via Apple Remote Desktop. PPPL began a program of internal vulnerability scanning using standard software packages. Periodic scans of all computer systems, dial-in modem systems, and wireless networks are done, and known vulnerabilities are identified and addressed.

A new Exchange e-mail system is now fully deployed. This new system provides a third layer of virus protection for all inbound e-mail, and provides a second layer for PPPL internal e-mail. Encrypted protocols for both sending and checking e-mail are now required, and unencrypted protocols are no longer allowed. Password authentication is now required to both send and check e-mail. Attachment file types known to often contain viruses or worms are blocked and quarantined.

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Environment, Safety, and Health

The Princeton Plasma Physics Laboratory (PPPL) and Princeton University enthusiastically support the U.S. Department of Energy's (DOE) commitment to worker safety at the DOE Laboratories. The safety of every one of our staff, faculty, students, and guests is taken very seriously. Safe operation is of paramount importance; PPPL continually works to improve safety performance. The Laboratory supports the challenging goals that the DOE Office of Science has established, and is implementing strategies to accomplish them.

During FY05, the Laboratory experienced a dramatic decrease in its key worker safety metrics compared with FY04. The FY05 Total Recordable Case (TRC) and Days Away, Restricted, Transferred (DART) case rates were 0.93 and 0.23, respectively, compared with 1.63 and 1.02 in FY04. This represents a 43% drop in recordable injuries and a 75% decrease in accidents that prevented workers from fulfilling their normal job duties.

Safety initiatives previously begun were continued or expanded in FY05. Activities being performed to increase employee safety awareness and to reduce work-related injuries and illnesses are discussed below.

Hazard Analysis

A formal Hazard Awareness course initiated in FY04 was continued in FY05. This training focuses on identifying and mitigating job hazards using classroom training and field exercises. The class size is limited to a maximum of 16 staff to allow for direct interaction with the participants. The course is recommended for all employees and has already been given to diverse groups within the Lab, including senior managers, graduate students, and off-site collaborators. Twenty sessions were held in FY05 involving 290 employees. Additional training sessions are scheduled for FY06. Other activities in this area in FY05 include:

- Provided dedicated and in-depth industrial hygiene, health physics, and electrical and construction safety engineering support to the National Spherical Torus Experiment (NSTX) operations and upgrades and to the National Compact Stellarator Experiment (NCSX) coil fabrication and testing activities.
- Performed a safety evaluation review of the Advanced Lithium Wall Coatings Experiment.
- Defined actions required by the National Environmental Policy Act (NEPA) for the U.S. ITER Project.

Workplace Improvements

Workplace improvement activities for FY05 include:

- Completion of workplace safety improvements using the Occupational Safety Health and Administration

(OSHA) inspection punch list, well within the 24-month timeframe established by the DOE.

- Continued to promote and respond to safety items identified via the web-based ES&H Safety and Suggestions (SOS) Box. Twenty-four suggestions or comments were received from PPPL employees and were followed up on in FY05. Results were posted on the web, accessible from the PPPL Employee Services home page.
- Conducted 26 management safety walkthroughs to review the safety of Laboratory areas and to assign responsibilities and schedules for corrective actions. Experimental, laboratory, and shop areas are visited annually and all other areas every two years. Participants in the walkthroughs included senior lab management, line managers, DOE staff, ES&H professionals, and workers. Additionally, ES&H action items are generated based on frequent (usually twice per week) DOE-Princeton Site Office reports on surveillances of PPPL areas.
- Held the Fourth Annual Safety Forum for the PPPL staff.

Worker Safety and Performance Awareness

Safety information and issues were shared with the PPPL staff throughout the year:

- An ES&H Newsletter was issued periodically that provided timely information on topical safety issues.
- PPPL's electrical safety program was reviewed and revised in response to the lessons learned from the October 2004 Stanford Linear Accelerator Center (SLAC) arc flash event. A special team from the DOE Office of Science reviewed PPPL's program and found among other things that "line management support of electrical safety initiatives has led to a strong safety culture at PPPL." Recommendations by the team for further improvement of

Carl Potensky (left) and Shawn Connolly accepting one of three "NJ Governor's Safety Awards" given to PPPL during 2005.

the electrical safety program were implemented.

- Monthly reports were issued to the staff on safety performance and related ES&H issues.
- Shared internal and external lessons-learned reports with the PPPL staff.
- Submitted "Safety Bulletins" to the PPPL staff to provide reminders for specific aspects of electrical safety, e.g., the PPPL energized electrical work permit and the safety requirements for electrical testing, troubleshooting, and voltage measurements.
- Continued to work on an application to obtain a DOE Voluntary Protection Program endorsement. Acceptance into the Voluntary Protection Program is DOE's official recognition of the outstanding efforts of employers and employees who have achieved exemplary occupational safety and health.

Outreach

A team of three PPPL staffers traveled to the University of Wisconsin at Madison to perform requested safety reviews of the Madison Symmetric Torus (MST) and PEGASUS experiments and facilities, and to provide training to University of Wisconsin fusion personnel on radiation safety, electrical safety, and confined space entry.

Safety Awards

During FY05, PPPL, the Maintenance and Operations Division, and the NSTX Project received safety awards from the State of New Jersey for performance in Calendar Year 2004. These awards were:

- PPPL — *"Recognition Award"* for having a low rate of away-from-work lost time injury/illness cases.
- Maintenance and Operations Division — *"Citation of Merit Award"* for having no away-from-work lost time injury/illness cases.
- NSTX Project — *"Commissioner of Labor and Workforce Development Continued Excellence Award"* for having gone four consecutive years without an away-from-work lost time injury/illness case.

These awards were presented at a New Jersey Governor's Occupational Safety and Health Awards Program Area dinner in May 2005.

The ES&H Division, with strong support from senior Laboratory management, works aggressively and proactively to keep workers safe while allowing them to perform their jobs efficiently and effectively. There is a strong worker safety culture at PPPL and we are committed to making it even stronger.

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Applications Research and 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 working with a number of partners in scientific research and technology development. These collaborations are Cooperative Research and Development Agreements (CRADAs) or Work for Others (WFOs) projects, and primarily involve applications of science and technology developed for PPPL's fusion program. In addition to CRADAs and WFOs, the Laboatory also uses Licensing Agreements, Personnel Exchanges, and Technology Maturation Projects to promote the transfer of PPPL technology.

A CRADA, which is a contractual agreement between a federal laboratory and one or more industrial partners, enables industry and PPPL researchers to work on programs of mutual interest. Costs and project results are generally shared between PPPL and the partner. Work for Others arrangements may involve either federal or non-federal partners. The partners pay for the work performed at PPPL. In the Personnel Exchange Program, researchers from industry assume a work assignment at the Laboratory, or PPPL staff may visit the industrial setting. In a Technology Maturation Project, a Laboratory researcher may work on technologies of interest to industry, 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.

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.

CRADA Projects

Data Grids for Large-scale Fusion Simulations

In this Phase II, Small Business Innovation Research CRADA project funded during FY05, Tech-X Corporation is implementing a FusionGrid Service for data transfer and access with PPPL collaboration. The service will connect heterogeneous data collections and provide transparent Interactive Data Language and AVS/Express client interfaces with the MDSplus and HDF5 application interfaces. The service will allow for pluggable network protocols (MDSip, GridPST, and GridFTP).

The Princeton Plasma Physics Laboratory is uniquely qualified to collaborate on this project based on its experience in fusion simulations, fusion experiments, and visualization along with its expertise in grid computing. The PPPL Computational Plasma Physics Group, which is the primary PPPL party in this CRADA, has experience in developing data grids for large-scale fusion simulations from its work on the National Fusion Collaboratory Project.

Flowing Liquid-lithium Walls using Engineered Surfaces

The objective of this CRADA project is to demonstrate flowing liquid-lithium walls using engineered surfaces. Liquid metal walls have been identified as a promising solution to magnetic fusion energy first-wall problems. Among the liquid metals, lithium has unique properties which make it a promising material for the first wall in a fusion reactor. It is the only candidate liquid metal that offers the possibility of a low-recycling wall. In this project, Plasma Processes, Inc. is fabricating samples of engineered surfaces for testing with liquid lithium utilizing the Advanced Lithium Wall Coatings facility at PPPL.

WFO Projects

Micro-air Vehicles Project

This project is conducted in support of the U.S. Naval Research Laboratory's (NRL) Micro-air Vehicles (MAV) Program, which involves fundamental research and development of aerodynamics and airframes for novel concepts in unconventional miniature aircraft design. (Figure 1) MAVs generally have a wingspan of less than two feet and weigh less than a pound. These aircraft are expected to perform useful surveillance missions.

The FY05 effort continued the development of the Samara aircraft concept.

Figure 1. Dave Cylinder tests the ornithopter at PPPL. The ornithopter is a micro-air vehicle being developed in collaboration with the Naval Research Laboratory under the Survivable Autonomous Mobil Platform, Long Endurance (SAMPLE) Project. Micro-air vehicles generally have a wingspan of less than two feet and weight less than a pound. These aircraft are expected to perform useful surveillance missions.

The Samara is a stop-rotor aircraft that combines the vertical ascent/descent capabilities of a helicopter with the speed and aerodynamic efficiencies of a fixed-wing airplane. Enhanced performance of this type of aircraft is being explored with the development of Samara II. The improvements include controlled-hover ability, simplified stability controls, and a more compact geometry. Samara II began first flight tests near the close of FY05.

During FY05, efforts continued in the development of a more robust, controllable, and reliable version of the Biplane Insectoid Travel Engine (BITE-Wing) aircraft. During FY05 prototypes were tested using vectored thrust on the lower rear wing, increasing control authority. The addition of a small amount of wing dihedral has dramatically increased flight stability. The construction of new BITE-Wing air vehicles that began in FY05 incorporated these improvements with more power and more damage resistance. Tests of these newer versions will begin in FY06.

The Samara, BITE-Wing, and other new vehicle efforts are part of the ongoing NRL Survivable Autonomous Mobile Platform, Long Endurance (SAMPLE) Project. These vehicles must be able to move in two or more modes of locomotion, including flight, crawling, hopping, and swimming. They are also expected to carry out extended missions in a variety of environments.

Hibachi Window Project

This effort involves the development of an electron beam transmission window for use in a KrF laser system in support of direct-drive inertial fusion energy. This project includes the study, design, and production of thin "hibachi" windows fabricated from silicon wafers (~100 micron thick) coated with a ~1.2-micron thick nano-crystalline diamond coating. The effort in FY05 involved the development of a 24-window hibachi prototype with edge cooling (Figure 2). This design incorporates an aluminum frame with internal channels for active cooling. Bench testing of the silicon windows during FY05 indicated that they can withstand differential pressure and pulsed pressure cycling consistent with those required for the laser to work in an extended 5-Hz rep rate. Work on the window develop-

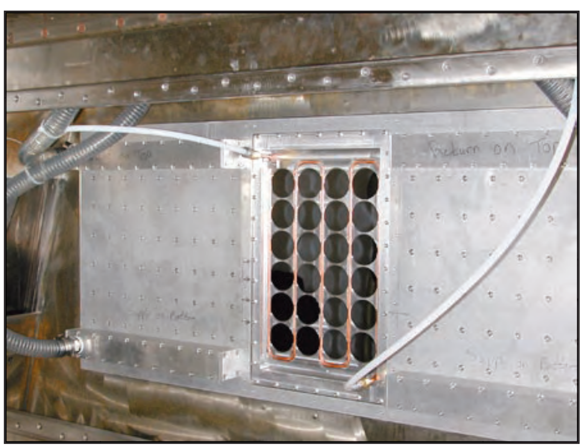

Figure 2. Anode insert with 24 hibachi windows installed for testing at NRL's Electra Laser Facility. The 24 round objects are the silicon wafers. The copper tubes provide edge cooling so when the electrons pass through the windows heat can be removed from the edges of the frame.

ment is expected to optimize mounting and cooling configurations. The fabrication of this hibachi prototype will focus on a design that supports an economical configuration and that provides ease for changing-out individual windows while maintaining the frame parameters and operational considerations.

Miniature Integrated Nuclear Detection System

During FY05, PPPL scientists continued development of the Miniature Integrated Nuclear Detection System (MINDS), which is designed to detect and identify specific radionuclides for homeland security applications. The MINDS, which was funded under three WFO projects for Picatinny Arsenal during FY04, has application for use by police, security personnel, the National Guard, the Coast Guard, and other agencies involved in homeland security, national security, or transportation rule compliance. In March 2005 Princeton University and InSitech, a small business located at the Picatinny Arsenal in New Jersey, signed a licensing agreement for the commercialization of MINDS.

The MINDS is configured to detect potential nuclear threats from a weapon of mass destruction or from nuclear contamination, such as a "dirty bomb." The objective is to detect and identify nuclear material in transit, such as entering a site, passing through a tollbooth, placed inside of a shipping container, or hidden in other ways, under realistic conditions. A major feature is the ability to compare the energy spectrum of the detected radionuclide with the spectrum of particular radiological materials that might be used in weapons. MINDS, which is designed to respond to nuclear signatures at levels slightly above normal background radiation, can be programmed to respond to specific signatures (Figure 3), thus eliminating false positive alarms resulting from the movement and transportation of approved radionuclides, such as in medical shipments. The possibility of false positives is a major concern of security personnel.

An initial proof-of-principle demonstration was performed in August 2002 in which MINDS detected small quantities of radionuclides in a stationary cargo-type shipping container. Additional demonstrations in FY03 showed MINDS' ability to detect similar material in a moving vehicle. In FY04, the MINDS system was improved with the introduction of a new neural-network-based detection algorithm. Also in FY04,

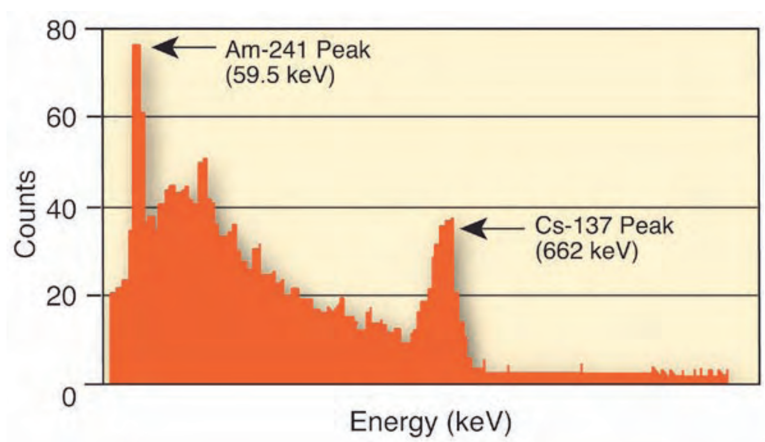

Figure 3. Energy spectra showing the presence of the radioactive elements Americium and Cesium.

a mobile configuration of MINDS was developed and demonstrated for law enforcement agencies.

In FY05, the MINDS library was expanded to include a wider array of radionuclides and improvements were made to the detection algorithms. Also, MINDS was positioned at two locations off-site from PPPL to collect data from the field.

Other WFO Projects

Title: Sterilization of Liquid Foods

Sponsor: U.S. Department of Agriculture

Scope: The purpose of this project is to develop new pasteurization methods that use radio-frequency (rf) waves and microwave heating. These heating techniques used to warm plasma in a fusion device, are being tested for pasteurizing raw liquid foods such as eggs, fruit juices, and milk.

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

Title: Magnetic Reconnection Experiment

Sponsor: National Aeronautics and Space Administration

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

Title: Korean Superconducting Tokamak Advanced Research, Phase II

Sponsor: Korean Basic Science Institute

Scope: The Princeton Plasma Physics Laboratory is coordinating a U.S. team in supporting the design of the Korean Superconducting Tokamak Advanced Research (KSTAR) device. KSTAR is the flagship project of the Korean National Fusion Program that was launched officially in January, 1996. The KSTAR device will be built at the National Fusion Research and Development Center at the Korean Basic Science Institute in Taejon, Republic of Korea.

Title: Raman Pulse Compression of Intense Lasers

Sponsor: Defense Advanced Research Projects Agency

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

PPPL are assessing the practical realization of the plasma-based pulse compression schemes. Preliminary experimental results show apparent amplification of the counter-propagating wave.

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

Sponsor: National Aeronautics and Space Administration

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

Title: Pre-eruption Coronal Magnetic Fields and Coronal Mass Ejections

Sponsor: National Aeronautics and Space Administration

Scope: A typical manifestation of coronal mass ejection (CME) consists of formation and expansion of a CME loop and eventual opening up of the magnetic field lines. Since the field opening is a spontaneous energy-releasing process, the energy of the pre-eruption field of a closed configuration must be greater than the open field energy. The objective of this effort is to investigate the energetics and dynamics of the magnetic fields involved. This study will not only provide an understanding of CME physics, but also information about the observable conditions associated with CMEs.

Title: Current Sheet Structure in Near-Earth Plasma Sheet during Substorm Growth Phase

Sponsor: National Aeronautics and Space Administration

Scope: The purpose of this effort is to study the 3-D current sheet structure in the near-Earth plasma sheet region during the substorm growth phase by combining the 3-D modeling with observations of magnetic field and plasma pressure from the POLAR satellite.

Title: Accretion onto Massive Black Holes in Low-luminosity Galactic Nuclei

Sponsor: National Aeronautics and Space Administration

Scope: Most galaxies in the universe contain supermassive black holes at their centers; yet most galactic nuclei emit very little radiation indicative of active accretion. The purpose of this work is to investigate this issue using low-radiative efficiency accretion flow models including advection-dominated and convection-dominated accretion flows.

Title: Low-power Cylindrical Hall Thruster

Sponsor: Air Force Office of Scientific Research

Scope: This project focuses on the study of Hall thrusters of cylindrical, rather than annular design, with new features such as emissive segmented electrodes and central localizing of the cathode neutralizer. The key cylindrical thruster concepts were invented and tested at Princeton, but the physics remains far from sufficiently understood. Many phenomena key to the operation of this thruster concept, and incidentally of general importance to the science of insulating plasma flows, are simply not understood at all. In a cylindrical geometry Hall thruster, including a cusp magnetic field, any optimization requires an understanding of electron transport, ionization, electric potential distribution, waves and instabilities, and discharge stability.

Title: Electromagnetic Full-particle Simulations of the Structure and Stability of the Magnetopause with Velocity Shear

Sponsor: National Aeronautics and Space Administration

Scope: Two-dimensional,electromagnetic particle simulations of the Earth's magnetopause are being performed to study the formation and stability of the magnetopause current layer in regions where there is substantial flow along the magnetopause interface (on the dayside and tail flanks). In particular, geometries considered unstable to the Kelvin-Helmholtz instability are being considered. The results obtained from the simulation model will be compared with space observations in order to improve understanding of the formation and stability of the magnetopause and its boundary layers.

Title: Laboratory Study of Magnetorotational Instability in a Gallium Disk

Sponsor: National Aeronautics and Space Administration

Scope: The importance of magnetic fields has been widely recognized in a class of astrophysical objects called accretion disks. An accretion disk consists of gas, dust, and plasmas rotating around and slowly accreting onto a central point-like object, which can be a star in formation, collapsed stars in binary systems, or supermassive black holes in active galactic nuclei. Rapid angular momentum transport in accretion disks has been an outstanding problem in astrophysics for more than three decades. The magneto-rotational instability has been identified as a powerful mechanism to transport angular momentum. The objective of this project is to demonstrate and study this instability in the laboratory for the first time. This work is being performed in close collaboration with the Princeton University Department of Astrophysical Sciences.

Title: Schlumberger Analyses

Sponsor: Schlumberger-Princeton Technology Center

Scope: PPPL is providing chemical and trace tritium analysis services and diagnostic services including non-destructive and destructive analysis to determine physical and chemical properties. The Laboratory is also providing instrument calibration and bio-assay analysis germane to health physics requirements.

Title: Developing the Procedure and Initial Code for Charge-changing Ion-atom Collisions

Sponsor: Tech-X Corporation

Scope: This project involves the development of the code structure and the procedure for evaluating charge-changing ion-atom collisions based on the Classical Trajectory Monte Carlo method.

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Patents and Invention Disclosures

Patent Issued

Method and Apparatus for Diamond Wire Cutting of Metal Structures
— *Robert Parsells, Geoff Gettelfinger, Erik Perry, and Keith Rule*

Invention Disclosures

Alpha Channeling in Mirror Machines
— *Nathaniel Fisch*

"Barber-Pole" Helical Anisotropic Resistive Conductor Magnet Windings
— *Robert D. Woolley and Charles L. Neumeyer*

Collisionality Control of Electron Thermal Transport in Fusion Reactors
— *Martha Redi, Jessica Baumgaertel, Gregory Rewoldt, Robert Budny, and Dan Stutman*

Device for Joining Fiberglass Tape to Kapton Tape
— *John Trafalski and Christopher Hause*

Ferromagnetic Annular Flux Channel
— *Charles L. Neumeyer and Robert D. Woolley*

Flex Bus Removal/Insertion Tool
— *John DeSandro, Mike Anderson, Frank Terlitz, and Tom Meighan*

Method to Cool Atoms and Molecules using Asymmetric One-way Barriers
— *Mark G. Raizen, Qian Niu, and N.J. Fisch*

Self-cooling Liquid Metal Target for Dissipating High Heat Loads
— *Robert Kaita, Richard Majeski, and Leonid Zakharov*

Software for MINDS Detector Analysis
— *Bill Davis, Dana Mastrovito, and Ken Silber*

Universal Networked Timer
— *P. Sichta, G. Oliaro, J. Lawson, and J. Wertenbaker*

Vessel Eddy Current Measurement for NSTX
— *David A. Gates, Jon E. Menard, and Robert J. Marsala*

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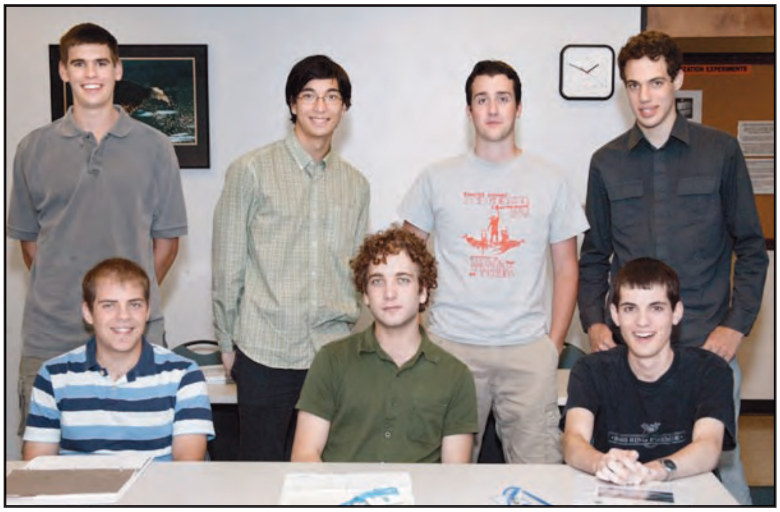
Graduate Education

Program in Plasma Physics graduate students for academic year 2004–2005. Standing back row (l-r): Nikolai Yampolsky, Jeremy Olson, Mikhail Dorf, Andrey Zhmoginov, Xiaoyan Ma, Sterling Smith, Laura Berzak, Peter Norgaard (Mechanical and Aerospace Engineering), Prateek Sharma, Tom Jenkins, Nate Ferraro, Artem Smirnov, Wei Liu, and Adam Sefkow. Seated on couch (l-r): Dan Lundberg, Josh Kallman, Seth Dorfman, Abe Fetterman, Austin Roach, and Daniel Fong. Seated on floor (l-r): Jong-kyu Park, Mahmood Miah, and Patrick Ross.

Graduate Education at the Princeton Plasma Physics Laboratory (PPPL) is supported through the Program in Plasma Physics and the Program in Plasma Science and Technology. Students in these programs receive advanced degrees from Princeton University. In the Program in Plasma Physics, Doctoral (Ph.D.) degrees are given through the Department of Astrophysical Sciences, while in the Program in Plasma Science and Technology, Masters (M.S.E.) or Doctoral (Ph.D.) degrees are given through the Departments of Astrophysical Sciences, Chemical Engineering, Chemistry, Civil Engineering, Computer Science, Electrical Engineering, Mechanical and Aerospace Engineering, and Physics.

Program in Plasma Physics

With more than 225 graduates since 1959, the Program in Plasma Physics has had a significant impact on the field of plasma physics, providing many of today's leaders in the field of plasma research and technology in academic, industrial, and government institutions.



First-year graduate students. Standing (l-r): Austin Roach, Daniel Fong, Dan Lundberg, and Abe Fetterman. Seated (l-r): Josh Kallman, Jeremy Olson, and Seth Dorfman.

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 FY05, there were 38 graduate students in residence in the Program in Plasma Physics, holding between them one U.S. Department of Energy Magnetic Fusion Energy Science Fellowship, one U.S. Department of Energy Computational Science Graduate Fellowship, one National Science Fellowship, and one Princeton University Honorific Fellowship.

Seven new students were admitted in FY05, one from Canada, and six from the United States (Table 1). Six students graduated in FY05, accepting positions at Los Alamos National Laboratory, Naval Research Laboratory, Novaphotonics, Inc., Massachusetts Institute of Technology, Princeton University, and the University of Wisconsin at Madison (Table 2).

Program in Plasma Science and Technology

Applications of plasma science and technology meld several traditional scientific and engineering specialties. The Program in Plasma Science and Technology (PPST) provides strong interdisciplinary support and training for graduate students working in these areas. The scope of interest includes fundamental studies of the plasmas, their interaction with surfaces and surroundings, and the technologies associated with their applications. Plasmas are essential to many high-technology applications, such as gaseous lasers, in which the lasing medium is plasma. X-ray laser research is prominent in the PPST. Another example is fusion energy for which the fuel is a high-temperature plasma. Lower-temperature plasmas are used for a growing number of materials fabrication processes including the etching of complex patterns for micro-electronic 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

Table 1. Students Admitted to the Program in Plasma Physics in Fiscal Year 2005.

Student	Undergraduate Institution	Major Field
Seth Dorfman	Massachusetts Institute of Technology	Physics
Abe Fetterman	Caltech	Physics
Daniel Fong	Dalhousie University	Physics
Joshua Kallman	Stanford & Rutgers Universities	Physics
Daniel Lundberg	Cornell University	Physics
Jeremy Olson	Harvard University	Physics
Austin Roach	Massachusetts Institute of Technology	Physics

Table 2. Recipients of Doctoral Degrees in Fiscal Year 2005.

Dodin, Ilya
Thesis: Nonlinear Dynamics of Plasmas under Intense Electromagnetic Radiation
Advisor: Nathaniel J. Fisch
Employer: Princeton University

Foley, Elizabeth
Thesis: Development of the Motional Stark Effect with Laser-induced Fluorescence Diagnostic
Advisor: Fred Levinton
Employer: Novaphotonics, Inc., Princeton, NJ

Kuritsyn, Alexey
Thesis: Experimental Study of the Effects of Boundary Conditions and Guide Field on Magnetic Reconnection
Advisors: Masaaki Yamada and Fred Levinton
Employer: University of Wisconsin at Madison

Landsman, Alexandra
Thesis: Single Ion Dynamics Inside the Magnetic Field-reversed Configuration
Advisor: Samuel A. Cohen
Employer: Naval Research Laboratory, Washington, D.C.

Son, Seunghyeon
Thesis: Reaction Rates and Other Processes in a Dense Plasma
Advisor: Nathaniel J. Fisch
Employer: Los Alamos National Laboratory

Stowell, Ronald
Thesis: Kinetic Theory for Antihydrogen Recombination Schemes
Advisor: Ronald C. Davidson
Employer: Massachusetts Institute of Technology

of toxic wastes, chemical synthesis, space propulsion, control system theory and experiment, solar cell fabrication, and advanced-design particle accelerators.

The PPST 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, Mechanical and Aerospace Engineering, and Physics. In FY05, nine graduate students received support from the PPST during the academic year and/or summer. They co-authored more than a dozen refereed publications. Three PPST-supported students received Ph.D. degrees from their respective departments.

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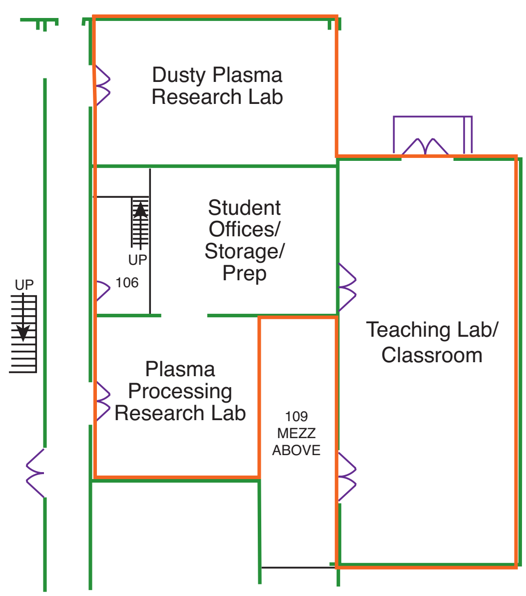
Science Education

The goal of the Science Education Program (SEP) at the Princeton Plasma Physics Laboratory (PPPL) is to become a model for how a U.S. Department of Energy (DOE) laboratory can combine its core research activities with science education innovations to create a center of excellence. An education strategy is employed that uses as its bases the fact that studying plasmas generates questions, stimulates curiosity, and increases personal relevance of learning for students of all ages.

To achieve its goals, the SEP strives to: (1) contribute to the training of the next generation of scientists and engineers, (2) collaborate with K–12 teachers on ways to improve science teaching using an inquiry-based approach to learning, and (3) improve the scientific literacy of the community at large. These initiatives, led by SEP staff in conjunction with PPPL volunteers, master teachers, and local education experts create significant learning opportunities for undergraduate college students and K–12 teachers and students.

The center of all SEP activities is the new Plasma Science Education Laboratory (PSEL). A fusion of research between education and plasma science, this unique facility includes a teaching laboratory/classroom, two research labs, and student offices/storage/prep room. The research performed in the PSEL is centered upon dusty plasmas and plasma processing and is primarily student-centered.

Undergraduate and advanced high school students plan all work, formulate research goals, assemble all apparatus, collaborate with scientists and engineers, critique and evaluate each other's work, write papers, and make oral and poster presentations. Simultaneously, the PSEL's open layout for educational workshops fosters communication between participants, master teachers, and student researchers to create a unique learning environment for teachers and students of all abilities. In FY05, construction of the new center was completed. Activities will



Schematic of the new Plasma Science Education Laboratory (PSEL) that was completed in FY05.

begin using the new space in the early part of FY06.

Elle Starkman, PPPL's staff photographer, and Andrew Post-Zwicker, Head of PPPL's Science Education Program, collaborated to create "Plasma Table," a photograph of a dust cloud of silica microspheres illuminated by laser light and suspended in a plasma. "Plasma Table" was submitted to the "Art of Science Competition" at Princeton University in the Spring of 2005 and was awarded the first-place prize. More than 200 entries were received. Princeton students and faculty from many departments launched the competition, seeking entries of images that came directly from research in science and engineering or works by artists incorporating tools and concepts from science.

Undergraduate Research Programs

PPPL staff continued the tradition of training the next generation of scientists and engineers as 39 students participated in the Laboratory's undergraduate research programs during FY05. This was the largest number of students accepted by these programs. Eleven students from the Science Undergraduate Laboratory Internship (SULI) program, two from the Pre-Service Teacher Program, and 26 from the National Undergraduate Fellowship (NUF) program completed their summer research at PPPL, other DOE Laboratories, and U.S. Colleges and Universities including, Massachusetts Institute of Technology, Caltech, University of California (UC)-Davis, University of Colorado, UC-Irving, Los Alamos National Laboratory, General Atomics, and Lawrence Livermore National Laboratory. The U.S. DOE Office of Science Workforce Development and Office of Fusion Energy Sciences support these programs. The nine-week research project is preceded by a one-week introductory course at PPPL in the basic elements of plasma physics, after which the stu-

A dust cloud of silica microspheres is illuminated by laser light and suspended in a plasma. The dust cloud is approximately 0.5 inches high and floats in a conical shape between the dust tray and an electrode as long as the plasma is maintained. Fundamental dust cloud properties and dynamics have applications ranging from plasma processing to space plasmas.

National Undergraduate Fellowship (NUF) and Summer Undergraduate Laboratory Internship (SULI) participants, summer 2005.

dents travel to the sites of their research projects.

Two NUF students were recognized for their posters/research at the annual American Physical Society's Division of Plasma Physics Meeting in 2005. Nova Daniels of the University of Montana, Missoula, did her research with Dr. R.J. Groebner at General Atomics. Her poster was titled, "Analytic Electron Density Barrier Model, Including Edge Transport Barrier." Parthiban Santhanam of the University of California, Berkeley, did research with Dr. Paul Bellan at Caltech. His poster was titled, "Simulation of Single-Particle Motion in Spheromak Geometries."

Two-hundred and ninety-nine students have received a National Undergraduate Fellowship from 1992 through 2005. Of those, many are currently American Physical Society members. The list also includes professors of physics at the University of California at Los Angeles and the University of Colorado, researchers at DOE National Laboratories and private industry, and graduate students at Princeton University and other schools throughout the country.

Pre-College Activities

High School Research Internships

Each year, opportunities exist for motivated high school students to perform independent laboratory work in plasma physics. This year, talented students from the Princeton area worked on a variety of research topics. They include:

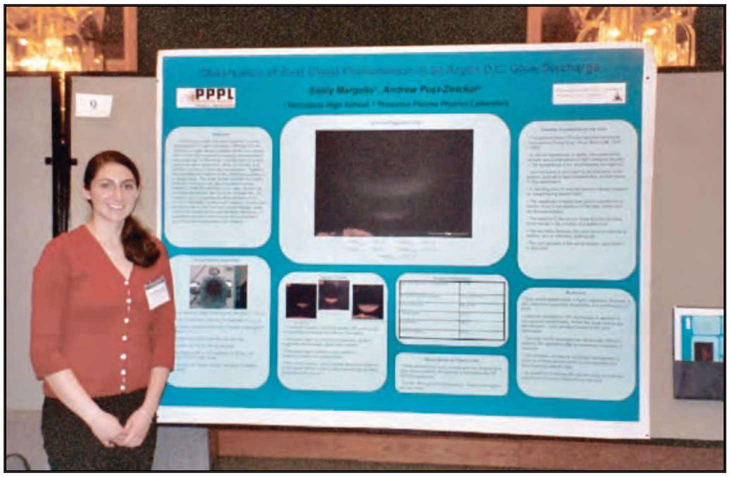
Will Fisher, The Dalton School, New York City, NY — *Integrating Command Line Programs with Java Clients.*

Everett Schlawin, West Windsor-Plainsboro High School, Plainsboro, NJ — *Investigation of Fluorescent Dusty Plasmas.*

Emily Margolis, Pennsbury High School, Pennsbury, PA — *Observation of Dust Acoustic Waves and Bifurcating Voids in a Low Temperature Direct Current Discharge Dusty Plasma.*

Marc Osherson, Princeton High School, Princeton, NJ — *Integrating SCOPE with ElVis.*

Karan Khanna, West Windsor-Plainsboro High School, Plainsboro, NJ — *LabView Control of a Wafer Handling System for Plasma Processing.*



High School Research Intern Emily Margolis in front of her poster at the American Physical Society Division of Plasma Physics Meeting in Denver, Colorado.

David Ponton, (Trenton High School, Trenton, NJ) — *Development of a Classroom Plasma Source.*

In addition to their research projects, Emily Margolis presented her work at the 2005 American Physical Society Division of Plasma Physics Meeting while Will Fisher and Marc Osherson gave PPPL seminars about their work.

High School Science Bowl

The National Science Bowl® is a high school team competition which was initiated in 1991 to encourage the study of mathematics and science. Since its inception, more than 60,000 high school students from every region of the country have participated. PPPL joined the national competition by hosting the New Jersey Regional Science Bowl in February 1992.

In February 2005, PPPL hosted its 14th regional competition; 31 teams from 21 schools from across the state participated. More than 40 volunteers helped facilitate the event. East Brunswick High School won, West Windsor-Plainsboro North placed second, Bergen County Academies placed third, and High Technology High School placed fourth. Teams that did not advance to the later rounds were given a tour of the PPPL facility.

As winner of the regional competition, East Brunswick High School received an all-expense paid trip to Washington, D.C. and the right to compete in the National Science Bowl® which is usually held in May. At the national competition the team competed against 67 teams from around the country, placing eighth overall, for the second year in a row,. The team received a trophy and a $1,000 check for their school's science department.

Middle School Science Bowl

In FY05, PPPL sponsored the second Middle School Science Bowl with students from the Trenton, NJ school district. This DOE-sponsored nation-wide program is based upon the successful National Science Bowl® for high school students. Seven teams of five students each participated in an academic competition and a hydrogen fuel cell car challenge. The hydrogen fuel cell competition asks each team to design, build, and race a model car powered by hydrogen.

The winning team from Joyce Kilmer Middle School received an all expenses paid trip to Denver for the national competition where they made it to the third round (of ten) in the academic competition and placed eighth in the fuel cell challenge.

Science-on-Saturday Lecture Series

Now in its 21st year, Science-on-Saturday consists of eight lectures geared toward high school students, but open to everyone. Scientists and other professionals who are leaders in their respected fields present the talks. The program drew more than 2,500 students, teachers, parents, and community members. It has evolved from a narrow focus on high school students to become a valuable resource to people of all ages who wish to be exposed to the intellectual stimulation of new scientific ideas. Overall, the lectures are an excellent, low-cost way to involve students in science, provide peer support for their involvement, and encourage students to think about science as a career. The FY05 lectures were:

The Idea of a Moduli Space, by Professor Jordan Ellenberg, Princeton University

A Quantum Chemist Looks Under the Hood: What Makes Molecules do the Things They Do?" by Professor Michelle M. Francl, Bryn Mawr College

The Body Synthetic: Biomaterials in You, by Dr. Michele Marcolongo, Drexel University

Glass, the Canvas for Science: From the Scientific Glassblower's Perspective, by Mr. Michael Souza, Princeton University

Linking Perception to Action: Mechanisms of the Brain that Give Rise to Qualities of the Mind, by Professor Joshua Gold, University of Pennsylvania

Invading the Virus World: Detective Stories in Infectious Diseases, by Professor Joseph B. McCormick, University of Texas at Houston

The science bowl team from East Brunswick High School (East Brunswick, New Jersey) won the 2005 New Jersey Regional Science Bowl competition held at PPPL.

More Perfect than We Imagined: A Physicist's View of Life, by Professor William Bialek, Princeton University

High Power Lasers: Another Path to Fusion Energy, by Dr. John D. Sethian, Naval Research Laboratory

What is the Value of Continued Long-term Research on Wild Mountain Gorillas? by Dr. H. Dieter Steklis, Rutgers University

The Lewis School Collaboration

An ongoing collaboration for special-needs students of The Lewis School was formalized with the goal of supplementing their existing physical science curriculum with new topics taught at PPPL in the Plasma Science Education Laboratory including solar and fusion energy. In FY05, the 11th grade physics class visited the PSEL throughout the school year designing and building solar-powered devices and learning about renewable energy. In addition, a new physics curriculum was designed and will be piloted at PPPL in FY06.

Plasma Camp

Since 1998, the Plasma Science and Fusion Energy Institute ("Plasma Camp") has brought high school physics teachers from around the country (and Canada) to PPPL for an intensive workshop on plasma physics, fusion energy, and curriculum writing. Plasmas are ideal to illustrate many concepts in high school physics curricula including waves, atoms, nuclear reactions, relativity, electricity and magnetism. An integral part of the Institute is the development of new plasma-based lesson plans, student-led investigations, and demonstrations.

In FY05, work continued on plasma-centered curricula development with participants from the 2004 program. For example, a new curriculum developed in fiscal year 2005 includes one for a high school in New York City that uses the portrayal of fusion energy in Hollywood movies as an entry point into the study of non-fossil-fuel energy sources for both general and Advanced Placement physics classes. After the pilot curriculum is completed during the 2005–2006 school year, it will be made available for distribution on the Plasma Camp web page.

During its history, Plasma Camp has concentrated on helping high school physics teachers. However, multiple studies have shown that there is a critical need for improvement in science instruction at the middle school level. Thus, during FY05, a pilot program was begun to determine how to best take the Plasma Camp model and use it to help middle school teachers. The pilot program consisted of two days of program development with two master teachers (one high school and one middle school) and then a single day workshop on energy for approximately 30 middle school teachers.

Young Women in Science, Mathematics, and Technology Mini-conference

In FY05, PPPL hosted its fourth "Expand Your Horizons Mini-conference for Young Women in Science, Mathematics, and Technology." Approximately 237 young women in the eighth through twelfth grades participated. The conference included presentations by women in the sciences, breakout sessions, exhibits, and lunch. The two keynote guest speakers were Donna Fontana, a forensic anthropologist from the New Jersey State Police, and Aisha K. Lawery, an electrical engineer from the New Jersey Institute of Technology.

Nearly 240 young women attended the fourth "Expand Your Horizons Mini-conference for Young Women in Science, Mathematics, and Technology." The conference was hosted by PPPL's Science Education Program.

Bergen Academy for Math, Science, and Technology Partnership

Since 2003, the Laboratory has had a partnership with this science magnet high school in northern New Jersey. Juniors from the school spend a week each summer at PPPL working through an advanced Plasma Academy agenda. Beginning in the 2004-2005 school year, the school is offering a concentration for students in "Energy Engineering." This program offers a unique curriculum and innovative scheduling, allowing students to work of-campus for large blocks of time. Students study current and future sources of energy from a scientific, sociologic, and political perspective. In FY05, 33 students from the school participated in the summer program at PPPL.

Students from the Bergen Academy for Math, Science, and Technology participated in the "Plasma Academy," a summer academic program at PPPL. The students study current and future energy sources from a scientific, sociologic, and political perspective.

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Awards and Honors

Representatives of the U.S. Small Business Administration (SBA) present PPPL Director Rob Goldston with an "Award of Distinction" in recognition of the Laboratory's "Outstanding Public Service" in providing subcontracting opportunities and assistance to small business. At the award ceremony at PPPL are (from left) SBA's Allison Randolph, Princeton University's Michelle Christy, PPPL's Arlene White, SBA's William Manger (presenting the award), PPPL's Rodney Templon and Rob Goldston, SBA's Larry Hansen and Janette Fasano, PPPL's Ed Winkler, and U.S. Department of Energy's Greg Pitonak.

Individual Honors

Chio Z. "Frank" Cheng
Award for Excellence in Plasma Physics Research
American Physical Society

David Cylinder
President's Achievement Award
Princeton University

Ronald Davidson
Particle Accelerator Science and Technology Award
Institute of Electrical and Electronics Engineers (IEEE)

Nathaniel Fisch
E.O. Lawrence Award
Spencer Abraham, U.S. Secretary of Energy

Hantao Ji
Fellow
American Physical Society

John Krommes
Graduate Mentoring Award
McGraw Center for Teaching and Learning, Princeton University

Wei Liu
Thomas H. Stix '54 Plasma Physics Prize
Princeton University

Robert Marsala
PPPL Distinguished Engineering Fellow
Princeton Plasma Physics Laboratory

Dale Meade
Distinguished Associate Award
U.S. Department of Energy
and
Distinguished Career Award
Fusion Power Associates
and
Fellow
American Association for the Advancement of Science

Andrew Post-Zwicker
Art of Science Competition First Place Award
Princeton University

Hong Qin
Presidential Early Career Award for Scientists and Engineers
President George Bush
and
Early Career Scientist and Engineer Award
U.S. Department of Energy, Office of Science

Martha Redi
Outstanding Mentor Award
U.S. Department of Energy, Office of Science

Ned Sauthoff
Fellow
American Association for the Advancement of Science

John Schmidt
Distinguished Associate Award
U.S. Department of Energy

Elle Starkman
Art of Science Competition First Place Award
Princeton University

King-Lap Wong
Award for Excellence in Plasma Physics Research
American Physical Society

Laboratory Honors

Recognition for PPPL's "Noteworthy Practices"
for Pollution Prevention and Environmental Stewardship
Department of Energy, Office of Science

Award of Distinction
U.S. Small Business Administration
In recognition of the Laboratory's "Outstanding Public Service"
in providing subcontracting opportunities and assistance to small business.

PPPL physicist Hong Qin received the Presidential Early Career Award for Scientists and Engineers and the DOE's Office of Science Early Career Scientist and Engineer Award during two ceremonies on June 13. Qin (left) is with DOE Office of Science Director Ray Orbach during the DOE Award ceremony.

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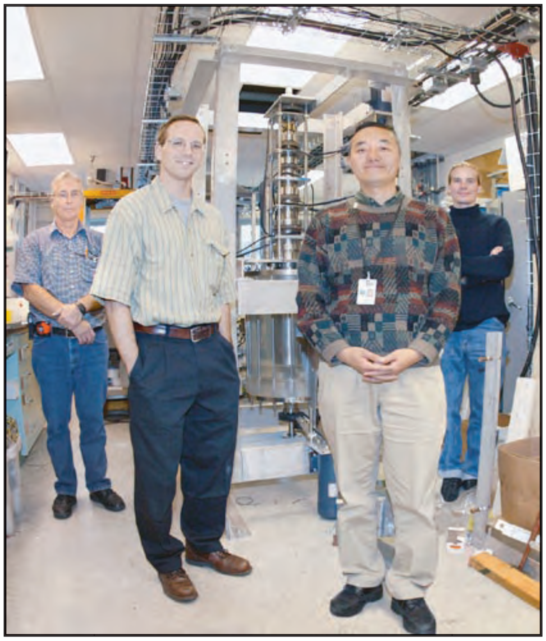
The Year in Pictures



The Magnetorotational Instability (MRI) experiment began in November at PPPL with the goal of shedding light on star and planet formation. At the MRI experiment are, from left, Bob Cutler, Michael Burin, Hantao Ji, and Ethan Schartman.

Think Green: PPPL offered ways to celebrate America Recycles Day during the fall, including setting up a 20-cubic-yard dumpster for staff to recycle paper items. Margaret Kevin-King (left) and Tom McGeachen, the PPPL recycling "chefs," dropped materials into the Lab's special recycling dumpster. Other events were a Lab-wide Office Clean-up Day and an America Recycles Day Celebration for staff with a presentation titled, "How All PPPL'ers Can Reduce Energy Usage and Trash Generation, Save the Lab $$$, and Prevent Pollution."

PPPL Director Rob Goldston delivered his annual "State-of-the-Lab" address to staff on November 23, telling the standing-room-only crowd in the Gottlieb Auditorium, "We are taking on big challenges — and our people are up to them, our program is succeeding, and our prospects are exciting."

PPPL designed and built a 41,000-pound electromagnet for the Jupiter II Project at the University of California at Los Angeles (UCLA). The PPPL team involved included, from left (standing), Tom Meighan, Red Delany, Charlie Sands, Fred Simmonds, Bob Clark, and Bob Woolley, and (kneeling) Mike Kalish, Manuel Fernandez, Joe Bartzak, and Bob Horner. Not pictured are Steve Kemp and Mike Messineo. Behind the team is the magnet. After completing final assembly in January, the magnet was shipped to California for installation in the Thermo-Fluids Laboratory of UCLA's Fusion Science and Technology Center. Engineering experiments will be conducted there to study how the strong magnetic fields in future fusion reactors would affect the heat transfer properties of proposed fusion blanket coolants, using a 3.5-inch diameter transparent pipe carrying a flowing liquid.

Sheila Widnall delivered the keynote talk, "Lessons Learned from the Columbia Accident Investigation and How They Apply to the R&D Environment," at PPPL's Fourth Annual Safety Forum on February 18. Widnall is a professor of aeronautics and astronautics at the Massachusetts Institute of Technology. The ES&H and Infrastructure Support Department hosted the forum, which included a series of presentations aimed at improving workplace safety.

Nearly 200 eighth through 12th graders came to PPPL on March 11 for the fourth "Expand Your Horizons Mini-conference for Young Women in Science, Mathematics, and Technology." The conference included talks by various women in the sciences, exhibits, and lunch. West Windsor-Plainsboro High School South student Sumona Bhattacharya (right) watches Becky Barak, of the Princeton Environmental Institute at Princeton University, make "clouds in a bottle" to demonstrate that cloud formation is based upon changes in temperature and pressure.

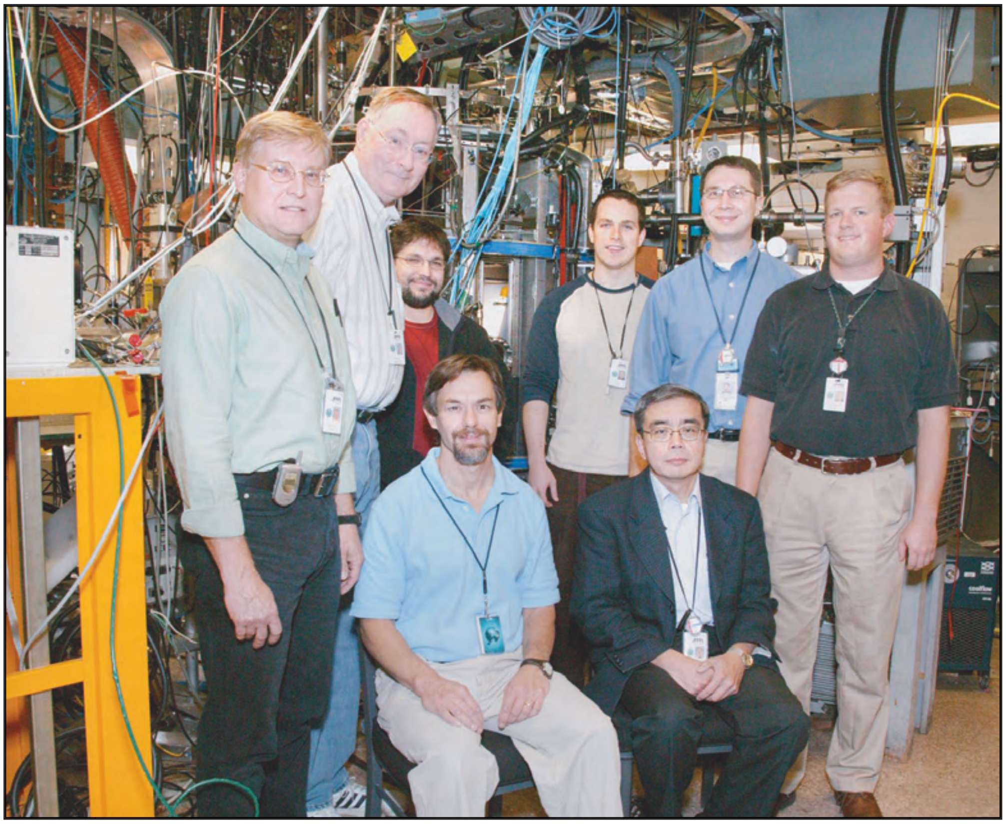
During the past year, PPPL began fully operating its upgraded business computing system, which includes budget, accounting, procurement, and property management components. The new system was adapted using Great Plains Enterprise Resource Planning software — an up-to-date commercial product. The team members who implemented the new system are (front row) Ed Winkler, Emma Torres, Steve Baumgartner, Jim MacTaggart, Jerry Siminoff; (second row), John Wheeler, Jo Lumberger, Connie Cummings, Magdalena Liebnitz, Penny Neuman, Fran Cargill, Spence Holcombe; (third row) Larry Sutton, Sharon Warkala, Jackie Pursell, Sallie Meade, Skip Schoen, Theresa Gillars, Kathleen Lukazik, Kevin Ranahan; and (back row) Rod Templon, Matt Lawson, Marie Iseicz, Arlene White, John Luckie, Tony Bleach, and Madeline McMullen.

Princeton University and InSitech, Inc. have signed a licensing agreement for InSitech to commercialize an anti-terrorism device developed by PPPL. The device, the Miniature Integrated Nuclear Detection System (MINDS), would have applications in transportation and site security. MINDS would be used to scan moving vehicles, luggage, cargo vessels, and the like for specific nuclear signatures associated with materials employed in radiological weapons. At a meeting at PPPL to discuss upcoming MINDS deployments for homeland security applications are, from left, PPPL's Lewis Meixler; Picatinny Arsenal's Tom McWilliams; PPPL's Kenny Silber, Bill Davis, Steve Langish, and Charles Gentile; Advanced Logic Systems' Kaydon Stanzione and Michael Fisher; and InSitech's Roger Adams.

PPPL applauded the news of June 28: a site for ITER had been selected and the project would proceed. In Moscow, the ministers representing the six ITER parties announced the international fusion reactor would be located at the European Union site in Cadarache, France. PPPL Director Rob Goldston (left) and U.S. ITER Project Office Manager Ned Sauthoff stand in front of the ITER poster in the Lobby

In June, the Laboratory honored 18 inventors for fiscal year 2004 during the annual Patent Awareness Program Recognition Dinner at Princeton University's Prospect House. Those attending the dinner and receiving awards were, from left, (front row) Ernest Valeo, Richard Majeski, David Cylinder, and Hironori Takahashi; (back row) Lewis Meixler, Nathaniel Fisch, Richard Hawryluk, Charles Skinner, Ilya Dodin, and Masayuki Ono.

PPPL provided a small plasma lab to Goshen College in Indiana to serve as a teaching tool for undergraduate students at the college. The tabletop lab is the first PPPL has created specifically for use by undergraduates outside of PPPL. Surrounding the tabletop plasma lab (from left) are Goshen College Professor Carl Helrich and PPPL's Stewart Zweben, Lane Roquemore, and Mike Dimattia. Zweben designed the experiment, DiMattia built it, and Roquemore helped locate equipment and diagnostics.



The conversion of the Current Drive Experiment-Upgrade (CDX-U) machine to a new device, the Lithium Tokamak Experiment (LTX), began in the late summer. The LTX will continue promising, innovative work started on CDX-U in 2000, involving the use of liquid lithium on surfaces facing or contacting the plasma. Members of the LTX team are (standing, from left) Tom Kozub, John Timberlake, Jeff Spaleta, Tim Gray, Vlad Soukhanovskii, and Craig Priniski; (sitting, from left) Richard Majeski and Robert Kaita.

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PPPL Financial Summary by Fiscal Year
(Thousands of Dollars)

	FY01	FY02	FY03	FY04	FY05
Operating Costs					
Fusion Energy Sciences					
NSTX	$20,538	$19,894	$25,604	$27,203	$27,944
NCSX	3,156	3,608	3,109	621	368
Theory and Computation	5,757	6,201	6,749	6,993	7,086
Off-site Collaborations	7,722	7,601	9,121	7,656	7,474
Off-site University Research Support	871	742	819	710	750
CDX-U/LTX	771	822	743	865	230
MRX/MRX Frontier Science Center	513	462	673	885	867
Heavy Ion Fusion	1,078	1,191	1,410	1,307	1,211
Next-step Options	771	749	589	536	272
ITER	–	–	705	647	2,606
Science Education Programs	593	624	667	685	641
TFTR	17,402	14,936	717	–	–
Waste Management*	3,086	2,790	–	–	–
Other Fusion	1,369	1,442	1,700	2,509	3,016
Total Fusion Energy Sciences	$63,627	$61,062	$52,606	$50,617	$52,465
Environmental Restoration and Waste Mgt	$95	$123	–	–	–
Advanced Scientific Computing Research	72	547	437	231	536
Basic Energy Sciences	391	161	79	–	–
High Energy Physics	316	341	181	354	182
Safeguards and Security	1,670	1,617	1,623	1,907	1,875
Science Laboratories Infrastructure	–	710	679	1,237	420
Other DOE	120	185	87	86	141
Total DOE Operating	$66,291	$64,746	$55,692	$54,432	$55,619
Work for Others					
Federal Sponsors	$1,111	$1,424	$1,958	$1,661	$1,394
Nonfederal Sponsors	596	130	170	523	598
Other DOE Facilities	425	235	103	51	386
TOTAL OPERATING COSTS	$68,423	$66,535	$57,923	$56,667	$57,997
Capital Equipment Costs					
NSTX	$2,393	$1,995	$976	$2,365	$2,168
NCSX	–	–	4,796	11,392	16,410
Off-site Collaborations	1,714	2,187	1,817	740	1,291
LTX	–	–	–	75	817
TFTR	870	34	–	–	–
All Other Fusion	917	966	200	850	439
All Other DOE	177	–	–	68	57
TOTAL CAPITAL EQUIPMENT COSTS	$6,071	$5,182	$7,789	$15,490	$21,182
Construction Costs					
General Plant Projects - Fusion	$1,533	$2,170	$738	$1,696	$2,129
General Plant Projects - S&S	–	–	49	1,265	237
Other DOE Construction	77	64	28	47	258
TOTAL CONSTRUCTION COSTS	$1,610	$2,234	$815	$3,008	$2,624
TOTAL PPPL	$76,104	$73,951	$66,527	$75,165	$81,803

*Waste Management transferred to an indirect-funded activity in FY03.

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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

Susan E. Murphy-LaMarche
Head, Human Resources

PPPL Director's Cabinet

Robert J. Goldston
Director

Richard J. Hawryluk
Deputy Director

William M. Tang
Chief Scientist

A.J. Smith
Chair, Princeton University Research Board

Departments

National Compact Stellarator Experiment
G. Hutch Neilson, Project Manager

Off-Site Research
J.R. Wilson, Head
R. Nazikian, Deputy

Plasma Science and Technology
Philip C. Efthimion, Head

National Spherical Torus Experiment
Martin Peng, Program Director*
Masayuki Ono, Project Director
Michael D. Williams, Deputy Proj. Dir.

Theory
J. Manickam, 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

	FY01	FY02	FY03	FY04	FY05
Faculty	3	3	3	3	3
Physicists	97	95	94	90	83
Engineers	82	82	77	78	73
Technicians	210	166	157	170	161
Administrative	73	72	73	69	73
Office and Clerical Support	20	18	16	17	14
Total	485	436	420	427	407

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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 biannually and reports to the University President through the Provost. Members listed below served in fiscal year 2005.

Dr. Norman R. Augustine
Lockheed Martin Corporation

Professor John N. Bahcall
Institute for Advanced Study

Dr. Jonathan M. Dorfan
Stanford Linear Accelerator Center

Dr. Edward A. Frieman (Chair)
Scripps Institution of Oceanography

Mr. Robert I. Hanfling

Professor Richard D. Hazeltine
University of Texas at Austin

Professor Thomas R. Jarboe
University of Washington, Seattle

Dr. William Kruer
Lawrence Livermore National Laboratory

Dr. Ants Leetmaa
NOAA Geophysical Fluid Dynamics Laboratory

Professor Sir Chris Llewellyn-Smith
United Kingdom Atomic Energy Agency
Culham Division

Mr. Bruce Mehlman
Computer Systems Policy Project
Mehlman Strategies

Dr. Barrett Ripin
Research Applied

Retired Admiral Richard Truly
National Renewable Energy Laboratory

Professor Michael S. Turner
University of Chicago

Professor Friedrich Wagner
Max-Planck-Institut für Plasmaphysik

Professor Ellen G. Zweibel
University of Wisconsin at Madison

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Abbreviations, Acronyms, and Symbols

1-D	One-dimensional
2-D	Two-dimensional
3-D	Three-dimensional
AFOSR	(U.S.) Air Force Office of Scientific Research
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 Program (a U.S. Department of Energy Program)
AMP	Adaptive Mesh Refinement
AMR	Adaptive Mesh Refinement
AMTEX	American Textile Partnership
APEX	Advanced Power Extraction Program (a U.S. Department of Energy Program)
ARIES	Advanced Reactor Innovation Evaluation Studies
ARL	Army Research Laboratory
ARSC	Arctic Region Supercomputing Center
AS	Advanced Stellarator
ASDEX	Axially Symmetric Divertor Experiment (at the Max-Planck-Institut für Plasmaphysik, Garching, Germany)
ASDEX-U	ASDEX-Upgrade (went into operation in 1990)
AT	Advanced Tokamak
B_t	Toroidal Magnetic Field
BES	Beam Emission Spectroscopy
BEST	Beam Equilibrium Stability and Transport Code
BPAC	Burning Plasma Assessment Committee (under the National Research Council
BPX	Burning Plasma Experiment
CAD	Computer-aided Design
CADD	Computer-aided Design and Drafting
CAE	Compressional Alfvén Eigenmodes
CAIP	Center for Advanced Information Processing at Rutgers University, New Jersey
CCD	Charge-coupled Device
CD	Current Drive

CD-2	Critical Decision 2
CDR	Conceptual Design Review
CDX-U	Current Drive Experiment-Upgrade at the Princeton Plasma Physics Laboratory now the Lithium Tokamak Experiment
CEMM	Center for Extended MHD Modeling
CER	Charge-exchange Recombination system on DIII-D at General Atomics in California
CFC	Carbon Fiber Composite
CHE	Coaxial Helicity Ejection
CHERS	Charge-exchange Recombination Spectrometer
CHI	Coaxial Helicity Injection
CIEMAT	Centro de Investigaciones Energéticas, Medioamblentales y Tecnológicas
CIT	Compact Ignition Tokamak
cm	Centimeter
C-Mod	A tokamak in the "Alcator" family at the Plasma Science and Fusion Center at the Massachusetts Institute of Technology
CME	Coronal Mass Ejection
CPPG	Computational Plasma Physics Group at the Princeton Plasma Physics Laboratory
CRADAs	Cooperative Research and Development Agreements
CTF	Component Test Facility
CY	Calendar Year
DIII-D	A tokamak at the DIII-D National Fusion Facility at General Atomics in San Diego, California
D-D	Deuterium-deuterium
D-T	Deuterium-tritium
D&D	Decontamination and Decommissioning
DARPA	Defense Advanced Research Projects Agency
DART	Days Away, Restricted, Transferred (case rates)
DBM	Drift Ballooning Model
DE	Differential Evolution
DND	Double-null Divertor
DOE	(United States) Department of Energy
DWC	Diamond Wire Cutting
EAEs	Ellipticity-induced Alfvén Eigenmodes
EBE	Electron-Bernstein (Wave) Emission
EBW	Electron-Bernstein Wave (Heating)
ECCD	Electron Cyclotron Current Drive
ECE	Electron Cyclotron Emission
ECEI	Electron Cyclotron Emission Imaging (Radiometer)
ECH	Electron Cyclotron Heating
ECR	Electron Cyclotron Resonance
ECRH	Electron Cyclotron Resonance Heating

EDA	Enhanced D_α Mode
EFC	Error Field Correction
EFDA	European Fusion Development Agreement
EFIT	An equilibrium code
E-LHDI	Electrostatic Lower-hybrid Drift Instability
ELMs	Edge Localized Modes
ELVS	Graphics Program
EPM	Energetic Particle Mode
ER	Expansion Region
ER/WM	Environmental Restoration and Waste Management
ERD	Edge Rotation Diagnostic
ERP	Enterprise Resource Planning
ES&H	Environment, Safety, and Health
ESC	Earth Simulator Center in Japan
ESC	Equilibrium and Stability Code
ESnet	Energy Science Network
ET	Experimental Task
ETG	Electron-temperature Gradient Mode
eV	Electron Volt
FAC	Field-aligned Current
FCC	Fusion Computational Center
FCPC	Field Coil Power Conversion
FEAT	Fusion Energy Advanced Tokamak
FEM	Finite Element Method
FES	Fusion Energy Sciences
FESAC	Fusion Energy Sciences Advisory Committee
FIR	Far-infrared
FIRE	Fusion Ignition Research Experiment (a national design study collaboration)
FIReTIP	Far-infrared Tangential Interferometer and Polarimeter
FISMA	Federal Information Security Management Act
FLC	Federal Laboratory Consortium (for Technology Transfer)
FLR	Field-line Resonance
FPT	Fusion Physics and Technology, Inc.
FRC	Field-reversed Configuration
FREP	Fast Reciprocating Edge Probe
FTP	File Transfer Protocol
FUV	Full Ultraviolet
FW	Fast Wave
FY	Fiscal Year
GA	General Atomics in San Diego, California
GAE	Global Alfvén Eigenmodes
GDC	Glow Discharge Cleaning
GEM	Gas Electronic Multiplier

GFDL	Gas Fluid Dynamics Laboratory (on Princeton University's James Forrestal Campus)
GPI	Gas Puff Imaging
GPS	Gyrokinetic Particle Simulation (Center)
GTC	Gyrokinetic Toroidal Code
H-mode	High-confinement Mode
HCX	High Current Experiment at the Princeton Plasma Physics Laboratory
HFS	High-field Side
HHFW	High-harmonic Fast-waves
HIT-II	Helicity Injected Torus II at the University of Washington, Seattle, Washington
HRMIS	Human Resources Management Information System
HTX	Hall Thruster Experiment at the Princeton Plasma Physics Laboratory
HXR	Hard X-Ray
HYM	Hybrid and MHD Code
I-coil	Radial Field Coil
I_p	Plasma Current
I/O	Input/Output
IBW	Ion-Bernstein Wave
IBX	Integrated Beam Experiment
ICE	Ion Cyclotron Emission
ICF	Inertial Confinement Fusion
ICRF	Ion Cyclotron Range of Frequencies
ICW	Ion-cyclotron wave
IDSP	Ion Dynamic Spectroscopy Probe; an optical probe used to measure local ion temperature and flows during magnetic reconnection
IGNITOR	Ignited Torus
IMF	Interplanetary Magnetic Field
IPP	Institut für Plasmaphysik, Garching, Germany
IPR	Institute for Plasma Research, Gujarat, India
IR	Infrared
IRE	Integrated Research Experiment at the Princeton Plasma Physics Laboratory
IRE	Internal Reconnection Event
ISS	International Stellarator Scaling
ITB	Internal Transport Barrier
ITER	"The Way" in Latin. Formerly interpreted to stand for International Thermonuclear Experimental Reactor, although this usage has been discontinued.
ITG	Ion-temperature Gradient (Mode)
ITP	International Tokamak Physics Activity

JAERI	Japan Atomic Energy Research Institute
JET	Joint European Torus (JET Joint Undertaking) in the United Kingdom
JET-EP	Joint European Torus Enhancement Program
JFT-2M	A small Japanese tokamak
JHU	Johns Hopkins University
JT-60U	Japanese Tokamak at the Japan Atomic Energy Research Institute
kA	Kiloampere
KAM	Kolmogorov-Arnold-Mosher
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
L-mode	Low-confinement Mode
LBNL	Lawrence Berkeley National Laboratory
LFS	Low-field Side
LH	Lower-hybrid
LHCD	Lower-hybrid Current Drive
LHD	Large Helical Device; a stellarator operating in Japan
LHDI	Lower-hybrid Drift Instability
LIF	Laser-induced Fluorescence
LLNL	Lawrence Livermore National Laboratory
LMX	Liquid Metal Experiment at the Princeton Plasma Physics Laboratory
LPDA	Laboratory Program Development Activities at the Princeton Plasma Physics Laboratory
LPI	Lithium Pellet Injector
LSN	Lower Single Null
LTOA	Long Torus Opening Activity (on the DIII-D at General Atomics)
LTX	Liquid Tokamak Experiment (formerly the CDX-U) at the Princeton Plasma Physics Laboratory
MA	Megampere
MAST	Mega-Ampere Spherical Tokamak at the Culham Laboratory, United Kingdom
MAV	Micro Air Vehicle
MCWF	Modular Coil Winding Form
MHD	Magnetohydrodynamic
MHz	Megahertz
MINDS	Miniature Integrated Nuclear Detector System
MIR	Microwave Imaging Reflectometer

MIT	Massachusetts Institute of Technology in Cambridge, Massachusetts
MLM	Multilayer Mirror
MNX	Magnetic Nozzle Experiment at the Princeton Plasma Physics Laboratory
MPI	Message Passing Interface
MPP	Massively Parallel Processor
MPTS	Multi-point Thomson Scattering
MRI	Magnetorotational Instability 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)
MST	Madison Symmetric Torus at the University of Wisconsin at Madison
MW	Megawatt
NASA	National Aeronautics and Space Administration
NBCD	Neutral-beam Current Drive
NBI	Neutral Beam Injection (Heating)
NCSX	National Compact Stellarator Experiment (a Princeton Plasma Physics Laboratory-Oak Ridge National Laboratory fabrication project)
NDCX	Neutralized Drift Compression Experiment at the Lawrence Berkeley National Laboratory
NEPA	National Energy Policy Act
NERSC	National Energy Research Supercomputer Center
NIFS	National Institute of Fusion Science (Japan)
NIFS	National Institute of Standards and Technology
NJTC	New Jersey Technology Council
NNBI	Negative-ion-based Neutral-beam Injection
NPA	Neutral Particle Analyzer
NRC	National Research Council
NRC	Nuclear Regulatory Commission
NRL	Naval Research Laboratory
NSF	National Science Foundation
NSO	Next-step Option
NSO-PAC	Next-step Option Program Advisory Committee
NSST	Next-step Spherical Torus
NSTX	National Spherical Torus Experiment at the Princeton Plasma Physics Laboratory
NTCC	National Transport Code Collaboration
NTM	Neoclassical Tearing Mode
NTX	Neutralized Transport Experiment at the Lawrence Berkeley National Laboratory
NUF	(DOE) National Undergraduate Fellowship

OFES	Office of Fusion Energy Sciences (at the U.S. Department of Energy)
OH	Ohmic Heating
ORNL	Oak Ridge National Laboratory, Oak Ridge, Tennessee
ORPA	Office of Research and Project Administration at Princeton University
OS	Optimized Shear
OSHA	Occupational Safety and Health Administration
PAC	Program Advisory Committee
PBX	Princeton Beta Experiment, predecessor to PBX-M at the Princeton Plasma Physics Laboratory (no longer operating)
PBX-M	Princeton Beta Experiment-Modification at the Princeton Plasma Physics Laboratory (no longer operating)
PDC	Pulse Discharge Cleaning
PDR	Preliminary Design Report
PDR	Preliminary Design Review
PDX	Poloidal Divertor Experiment, predecessor to PBX and PBX-M at the Princeton Plasma Physics Laboratory (no longer operating)
PEGASUS	A toroidal experiment at the University of Wisconsin at Madison.
PF	Poloidal Field
PFC	Plasma-facing Component
PFRC	Princeton Field-reversed Configuration (Experiment) at the Princeton Plasma Physics Laboratory
PIC	Particle-in-Cell
PICSciE	Princeton Institute for Computational Science and Engineering
PLT	Princeton Large Torus at the Princeton Plasma Physics Laboratory (no longer operating)
PPPL	Princeton Plasma Physics Laboratory (Princeton University, Princeton, New Jersey)
PPST	Program in Plasma Science and Technology
PSACI	Plasma Science Advanced Scientific Computing Initiative
PSEL	Plasma Science Education Laboratory at the Princeton Plasma Physics Laboratory
PSFC	Plasma Science and Fusion Center at the Massachusetts Institute of Technology in Cambridge, Massachusetts
PTSX	Paul Trap Simulator Experiment at the Princeton Plasma Physics Laboratory
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
QH-mode	Quiescent High-confinement Mode

R&D	Research and Development
REs	Reconnection Event(s)
rf	Radio-frequency (Heating)
RFA	Resonant Field Amplification
RGA	Residual Gas Analyzer
RI	Radiative-improved Confinement Mode
RMF	Rotating Magnetic Field
RSAEs	Reversed-shear Alfvén Eigenmodes
RTAE	Resonant TAE
RWM	Resistive Wall Modes
SAMPLE	Survivable Autonomous Mobile Platform, Long Endurance (Project)
SBIR	Small Business Innovative Research (Program)
SciDAC	(The Department of Energy Office of Science's) Scientific Discovery through Advance Computing Program
SEP	Science Education Program at the Princeton Plasma Physics Laboratory
SF	Shaping field
SLAC	Stanford Linear Accelerator Center (in California)
SOL	Scrape-off Layer
SSX	Swarthmore Spheromak Experiment located at the Department of Physics and Astronomy, Swarthmore College, Swarthmore, Pennsylvania
SSX-FRC	Swarthmore Spheromak Experiment-Field-reversed Configuration
ST	Spherical Torus
START	Small Tight Aspect Ratio Tokamak at Culham, United Kingdom
STTR	Small Business Technology Transfer (Program)
SULI	(DOE) Science Undergraduate Laboratory Internship
SXR	Soft X-ray
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
TFC	Topical Computing Facility
TFTR	Tokamak Fusion Test Reactor (1982-1997), at the Princeton Plasma Physics Laboratory (no longer operating)
TJ-II	A "flexible" Heliac (stellarator) located at the CIEMAT Institute in Madrid, Spain
Tore Supra	Tokamak at Cadarache, France
TRACE	Transition Region and Coronal Explorer (satellite)
TRC	Total Recordable Case
TRC	Twisted Racetrack Coil

TSC	Transport Simulation Code
TWC	Tandem Wing Clapper
UC Davis	University of California at Davis
UCLA	University of California at Los Angeles
UCSD	University of California at San Diego
UKAEA	United Kingdom Atomic Energy Agency
ULF	Ultra-low Frequency
USDA	United States Department of Agriculture
USDOE	United States Department of Energy
UV	Ultraviolet
VPP	Voluntary Protection Program (An U.S. Department of Energy Program — a reinforcement of Integrated Safety Management which promotes worksite-based safety and health.)
W7-AS	Wendelstein-7 Advanced Stellarator, an operating stellarator in Germany
W7-X	A stellarator being built in Germany
WFOs	Work For Others
WVU	West Virginia University
XP	Experimental Proposal
Y2K	Year 2000

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