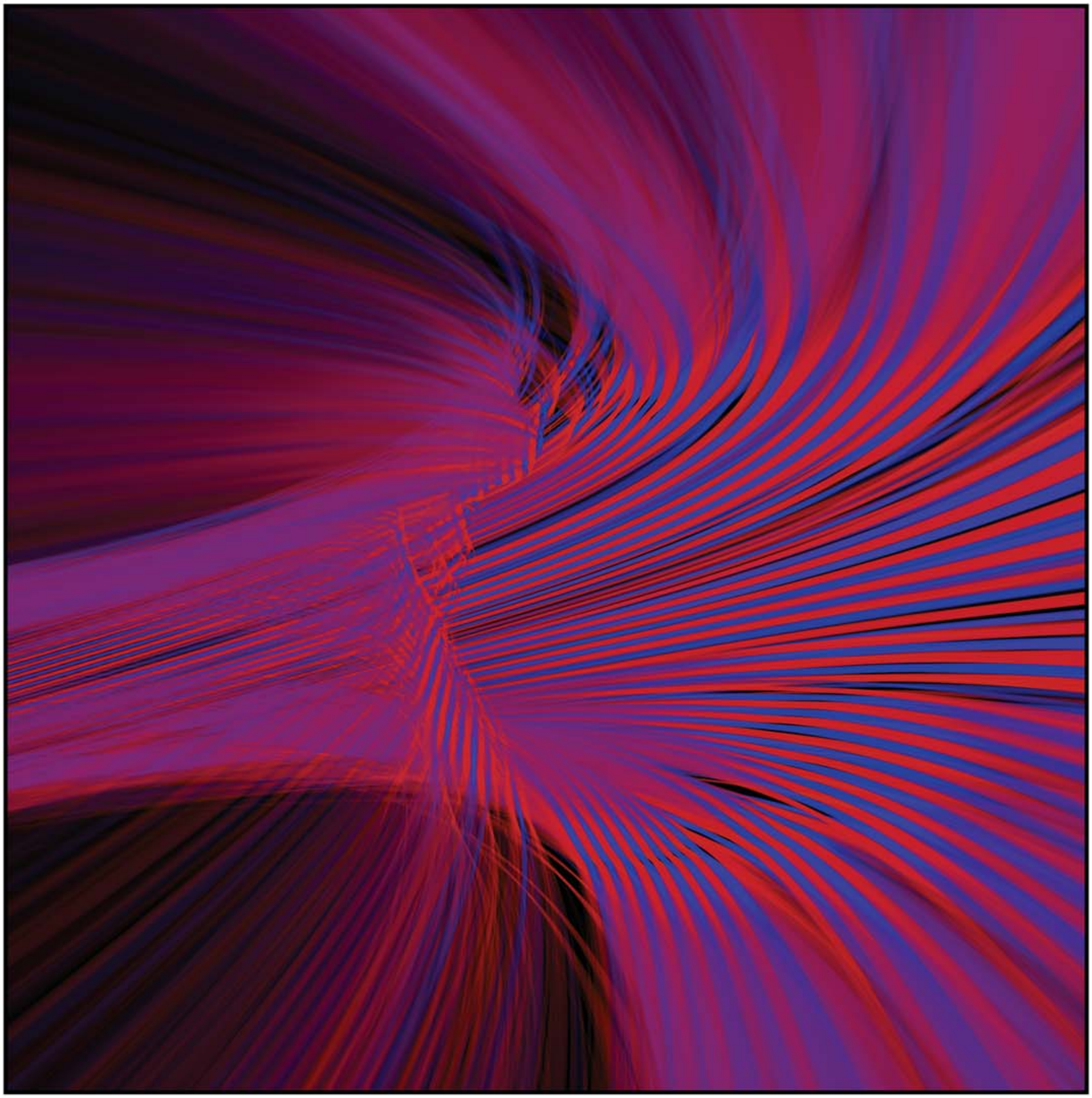
Princeton Plasma Physics Laboratory
Highlights for Fiscal Year 2004



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. It was the site of the Tokamak Fusion Test Reactor that completed a historic series of experiments using deuterium-tritium fuel in April 1997. A new innovative facility, the National Spherical Torus Experiment, came into operation in 1999, ahead of schedule and on budget.

Princeton University manages PPPL under contract with the U.S. Department of Energy. The fiscal year 2004 budget was approximately $77.8 million. The number of full-time regular employees at the end of the fiscal year was 407, not including approximately 30 subcontractors and limited duration employees, 35 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. In addition, PPPL scientists and engineers are applying knowledge gained in fusion research to other theoretical and experimental areas including the development of plasma thrusters and propagation of intense beams of ions. The Laboratory's Office of Technology Transfer assists industry, other universities, and state and local government in transferring these technologies to the commercial sector.

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

On The Cover

Advanced volume visualization of microturbulence data generated by PPPL's Gyrokinetic Toroidal Code. The field-line following perturbed electrostatic potential inside the tokamak is shown in red (positive) and in blue (negative), and higher transparency depicts low absolute values of potential.

Image provided by Professor Kwan-Liu Ma's group at the University of California-Davis as part of the U.S. Department of Energy, Office of Science, "Scientific Discovery through Advance Computing" Program's Gyrokinetic Particle Simulation Project.

This publication highlights activities at the Princeton Plasma Physics Laboratory for fiscal year 2004 — 1 October 2003 through 30 September 2004.

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-class research along the broad frontier of plasma science and technology, and providing the highest quality of scientific education.

Vision

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

Advantages of Fusion Energy

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

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From the Director

Fiscal year 2004 (October 2003 – September 2004) was a year of excellent advances in the understanding of fusion plasmas and progress in the negotiations towards the implementation of the ITER Project. We at the Princeton Plasma Physics Laboratory (PPPL) are particularly pleased that the National Spherical Torus Experiment (NSTX) had a banner year with 21 weeks of experimental operations; the National Compact Stellarator Experiment (NCSX) passed both Department of Energy (DOE) Critical Decision 2 and Critical Decision 3 allowing the start of construction; and PPPL, partnering with the Oak Ridge National Laboratory (ORNL), was selected through a broad competition to host the U.S. ITER Project Office.

The FY04 campaign on NSTX was very successful, leading to deeper understanding of fusion plasmas, scientific information of importance for ITER, and development of long-pulse high-beta operating scenarios for a future Spherical Torus Component (ST) Test Facility and ultimately a power plant. Advances were made in the understanding of resistive wall modes, plasma kinks which grow up on the resistive diffusion time of the conducting walls, including for the first time detection of toroidal mode number n=3 components of the perturbed fields. New resistive wall mode control coils were exercised for the first time and shown to have a favorable effect on locked modes. Confinement trends in ST's were elucidated, and transport barriers were observed in plasmas calculated to have reversed shear. New insight was gained into the nonlinear behavior of fast particle modes, and a new class of edge localized modes was discovered, which has minimal impact on the divertor.


Robert J. Goldston

The NCSX passed a number of tough DOE reviews, the Critical Decision 2, project baselining, and also Critical Decision 3, construction authorization. Contracts were let to industry for critical items: the vacuum vessel subassembly and the modular coil winding forms. These contracts were optimized by a risk-reduction process in which multiple vendors performed construction R&D, and then those with the best results and most attractive bids were selected for fixed-price construction contracts.

This year DOE selected the host for the U.S. ITER Project Office through a broad competition among the National Laboratories. PPPL, with ORNL as a partner, submitted a bid to host the Project Office at PPPL, and after an arduous review we were selected. This means that PPPL, with support from ORNL, will have responsibility for managing the construction of the U.S. components for the international ITER Project. This is a major responsibility for the Laboratory, which we accept with enthusiasm. As Princeton University President, Dr. Shirley Tilghman, pointed out in her letter of support, this is fully consistent with Princeton's motto: "In the nation's service, and the service of all nations." PPPL is continuing to support the ITER negotiation process, as it moves towards the selection of a site for the Project. ITER is a very important project for the U.S. and the world. It will demonstrate for the first time production of near-industrial levels of fusion power. Results from ITER will be directly applicable to the spherical torus (NSTX) and to the compact stellarator (NCSX), as well as the tokamak, because of the close similarity in physics across these three plasma configurations.

The PPPL Theory Department continued to make very important advances. Two of particular interest were in the areas of the nonlinear physics of energetic particles and the nonlinear physics of plasma turbulence. In the area of energetic particles, simulations were completed in which the plasma was treated as a fluid, but the energetic particles were treated fully kinetically. The observed nonlinear frequency shift of the modes in NSTX with amplitude was nicely reproduced. This is a critical step towards physics understanding in ITER. In the area of plasma turbulence, there has been a long-standing question as to the locality of turbulent transport. Does the turbulence and transport at a given location depend only on the local sources of free energy (e.g., density and temperature gradients) or does it depend on more global plasma parameters? For the first time the effect of turbulence spreading was shown conclusively in simulations, allowing this topic to move from debate to quantifying the magnitude of the effect and including it in the analysis of data.

Computational efforts continued to grow, as the PPPL Computational Plasma Physics Group (CPPG) plays a key role in the Fusion Collaboratory by putting the TRANSP data analysis code "on the Grid," making it available both nationally and internationally. The approach of maintaining this large code on a single architecture and making it available through the Grid has been very successful. The CPPG also continues to advance theory at the Lab by porting the most advanced codes to the most advanced new platforms and by implementing the most advanced algorithms, such as Adaptive Mesh Refinement, in theory codes.

The PPPL Off-Site Research effort has flourished in FY04. On the DIII-D tokamak we implemented a high-precision poloidal rotation diagnostic, based on experimental techniques and analysis developed on the Tokamak Fusion Test Reactor. We also observed for the first time a "sea" of Alfvén modes in DIII-D, which appear in reversed-shear discharges. We are implementing the very challenging motional Stark effect diagnostic on Alcator C-Mod, and helping the Massachusetts Institute of Technology group bring online a lower hybrid wave launcher. At the Joint European Torus (JET) we are implementing a set of diagnostics for lost alpha particles, based on the tools we developed and implemented on the Tokamak Fusion Test Reactor, and we are working with ORNL on a high power prototype ion cyclotron range of frequencies (ICRF) antenna to help optimize the new JET ICRF system. PPPL has provided critical insight into the physics of negative ion neutral beams in support of both JT-60U and the Large Helical Device (LHD) in Japan.

In our smaller experiments and Work for Others, we have also made fast progress. Some examples include the Current Drive Experiment-Upgrade experiment, which won a competition to be modified to the Lithium Tokamak Experiment (LTX), not in small part because of its demonstration that liquid lithium surfaces in contact with high temperature plasmas result in dramatic reduction in plasma recycling. Another example is the Magnetic Reconnection Experiment, which has recently been upgraded, and for the first time has demonstrated the expected difference between parallel and perpendicular resistivity as predicted by Lyman Spitzer, the Laboratory's first director, in his classic treatise on the physics of ionized gases. Plasma neutralizers for heavy ion beams, developed at PPPL, have successfully improved the focus of these beams in experiments at the Lawrence Berkeley National Laboratory. The Hall Thruster experiment has extended its research to very low power thrusters, which might be used for small satellites traveling in coordinated groups, as needed for a number of applications. Our plasma sterilization effort is successfully using an innovative technique to kill microbes.

In summary, this has been a busy and successful year. Our experiments and theoretical efforts are advancing the understanding of fusion plasmas; PPPL, partnering with ORNL, has been selected to host the U.S. ITER Project Office; and our efforts across the broader frontier of plasma science are meeting with success. With luck, at the end of FY05 we will be able to report that a site has been selected for the ITER Project, negotiations are underway towards an ITER agreement, and the domestic fusion program at PPPL and elsewhere will be strengthened to assure that the U.S. is able to take advantage of the advances that ITER will provide.

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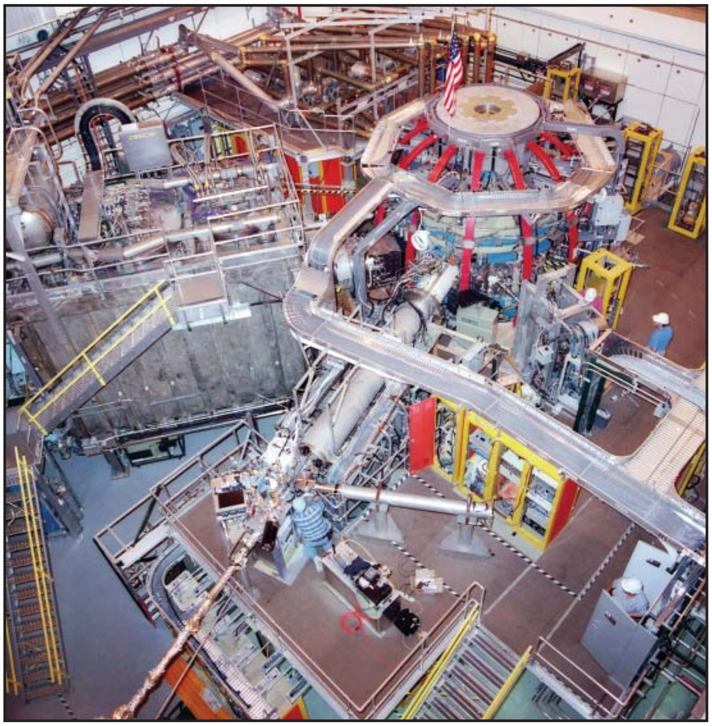
National Spherical Torus Experiment



National Spherical Torus Experiment

The National Spherical Torus Experiment (NSTX) at the Princeton Plasma Physics Laboratory (PPPL) is being used to explore a novel magnetic fusion concept — the Spherical Torus (ST) — that may lead to practical fusion energy at reduced cost. The ST is also particularly well suited for an important step along the path to fusion development, a Component Test Facility. Finally, NSTX broadens the scientific base of fusion research and provides important data for ITER. A national team comprised of 24 U.S. fusion research institutions is performing the experiments. Scientists from the United Kingdom, Japan, Russia, Korea, France, Germany, and Canada also participate.

Physics Research

The FY04 experimental campaign of NSTX began in January 2004 with a programmatic goal to complete 20 weeks of experiments. By the end of the campaign in mid-August, the NSTX had completed 844 hours of high-power operations, or 21 effective run weeks, with 2,701 plasma attempts resulting in 2,460 plasmas. Of the plasma discharges, 2,166 achieved currents greater than 0.2 MA, 1,310 of them with neutral-beam injection (NBI) only, 260 with high-harmonic fast-wave (HHFW) heating only, and 214 with combined NBI and HHFW heating. A total of five Machine Proposals, devoted to operational development, and 42 Experimental Proposals, devoted to physics research, received run time. Plasma operation during this campaign was reliable, with many extended run days and few unplanned stoppages, and it was interrupted only for a three week opening in March to perform diagnostic tasks and install optical dumps for the Charge-exchange Recombination Spectroscopy (CHERS) diagnostic.

The integrated performance goal for the year, which was to produce high-performance, long-duration plasma discharges sustained by significant amounts of noninductive current drive, was accomplished. A specific example of such an integrated high-performance discharge is shown in Figure 1. This 1-MA discharge was heated by 7 MW of NBI, and had a current flattop time of 0.8 s, which is approximately four current relaxation times. According to model calculations, the current profile remained approximately constant for the last 300 ms of the discharge (>1 current relaxation time). The stored energy of the plasma plateaued at 280 to 300 kJ with toroidal beta greater than 20% for approximately 0.5 s, which is more than ten energy confinement times. Toroidal beta (β_T) exceeded 5% of the normalized current (I_p/aB_T), and the energy confinement time was 70% above the predicted low-confinement mode (L-mode) value for the same duration. The line-averaged density exhibited only a modest increase after 0.3 s, and was then held constant at 80% of the Greenwald limit by edge-localized mode (ELM) activity, with no confinement degradation at these high densities.

In this and similar discharges, the loop voltage remained low (<0.5 V) through the duration of the current and energy flattop, indicative of a significant amount of noninductive driven current. Approximately 60% of the total current was driven noninductively by NBI (10%) and

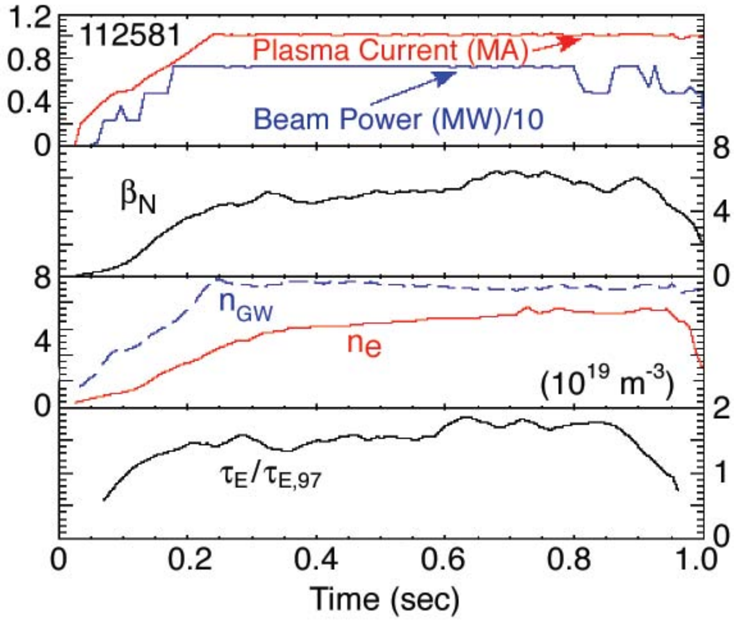


Figure 1. Integrated high-performance plasma discharge with significant non-inductive current.

bootstrap current (50%), as calculated by the TRANSP code. In order to develop this type of plasma discharge, progress and understanding was required in individual areas of research, as will be described below.

Macroscopic Plasma Behavior

The reduced time response of the plasma control system improved the feedback control for vertical stability, and this led to routine operation at higher elongation, κ, triangularity, δ, and pulse lengths than those achieved in previous years. The control system improvement permitted operation over an extended range of elongation; κ values exceeding 2.6 at low plasma inductance l_i (~0.5) and δ up to 0.8 were achieved. An approximate 20% increase over the previous maximum elongation, and a 30 to 40% increase over previous pulse lengths were obtained.

The ability to access more routinely higher elongation benefits most operational scenarios in NSTX. In particular, the greater shaping allowed higher plasma current at otherwise fixed conditions, leading to higher values of normalized current I_p/aB_T [where I_p (MA) is the plasma current and aB_T (m·T) is the minor radius times the toroidal magnetic field] and higher values of toroidal beta. Shown in Figure 2 is a plot of peak toroidal beta as determined from the EFIT magnetic reconstruction code. Values of the normalized beta (β_N) of up to 6.2 %·m·T/MA at the time of peak toroidal beta were attained over the full range of normalized current. A maximum value of β_N = 6.8 %·m·T/MA was achieved at peak poloidal beta, β_{pol} (1.8). The benefit of being able to achieve higher elongation and thus higher normalized current is evidenced by significantly more high-toroidal-beta (>30%) discharges during the 2004 experimental campaign than in previous years.

The high-toroidal-beta discharges were limited by the growth of low toroidal mode number (low-n) internal modes, which is shown in Figure 3. The red traces in the figure show the evolution of the toroidal magnetic field, toroidal beta, and the magnetic fluctuation amplitude in the high-toroidal-beta discharge. The black

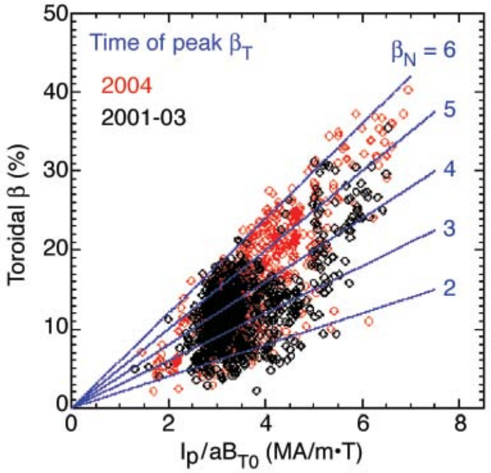


Figure 2. Toroidal β versus normalized current I_p/aB_T for the 2004 experimental campaign (red) and earlier years (black).

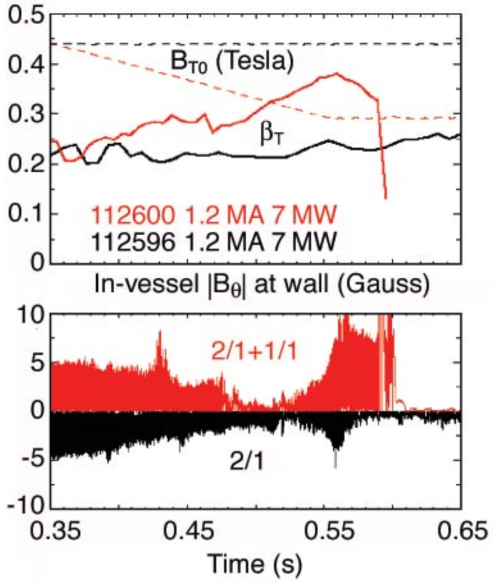


Figure 3. Comparison of MHD activity for two NSTX plasma discharges.

traces are taken from a similar discharge in which the toroidal field was held steady and, therefore, which had lower toroidal beta (~20%). A long-duration m/n = 2/1 (where m is the poloidal mode number) MHD tearing mode in the mid-radius region existed in both discharges. An m/n = 1/1 mode became unstable in the high-toroidal-beta discharge, as reflected by the increase in the amplitude of the magnetic fluctuations, at about 560 ms. The toroidal beta started to decrease as the modes coupled and the rotation decreased (Figure 4, top panel), gradually at first, but then it collapsed as the rotation frequency decreased through a critical value of 2 kHz. The plasma rotation remained high in the discharge with no toroidal field ramp-down (Figure 4, bottom panel).

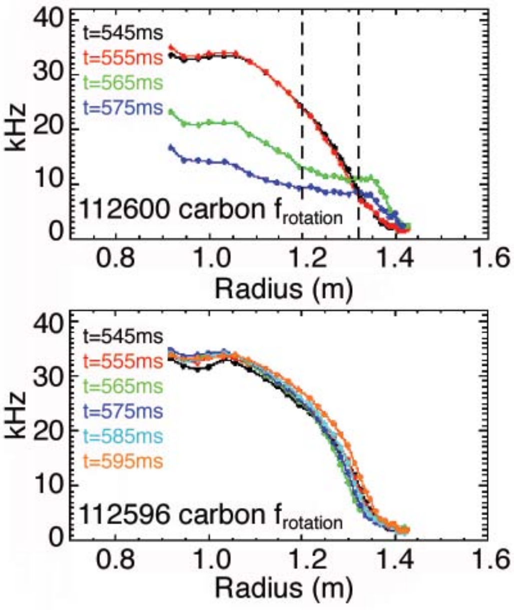


Figure 4. Evolution of rotation profiles for the two discharges shown in Figure 3.

Resistive wall modes (RWM) were prevalent and often were the toroidal-beta-limiting mechanism at low safety factor. Internal magnetic sensors show nearly simultaneous growth of n = 1 to 3 modes, consistent with the DCON stability code result which shows unstable n = 1 to 3 RWM components. Visible light emission from the plasma during a RWM is shown in the left panel of Figure 5, and it is compared to the DCON-computed perturbed magnetic field normal to the surface exterior and interior to the plasma in the middle and right panels of Figure 5. The computation uses an EFIT experimental equilibrium reconstruction, and the illustration includes the sum of the n = 1 to 3 components. The fast camera images (left panel) confirm the toroidal asymmetry and macroscopic scale of the mode.

In order to expand the NSTX operating space and allow for further increases in toroidal beta, it was essential to explore means by which performance-limiting MHD modes could be stabilized. This was done using the first of three pairs of error field compensation/RWM control

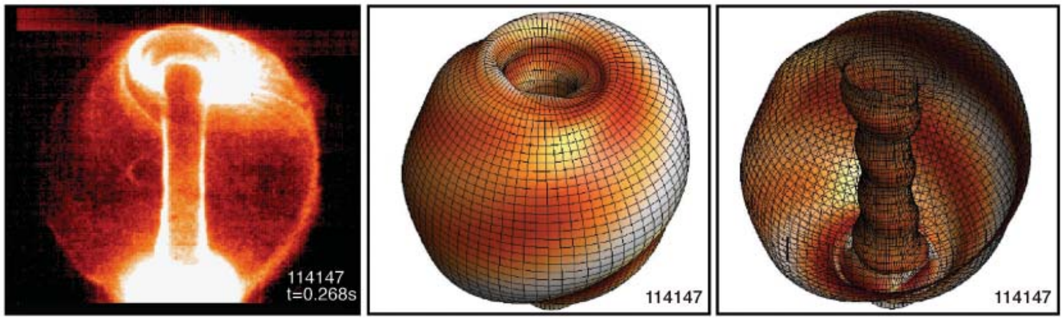


Figure 5. Fast camera image of NSTX plasma during a resistive wall mode (left) along with computed perturbed surfaces observed from outside (middle) and inside (right) the plasma.

coils. The other two pairs will be commissioned for the 2005 experimental campaign. The first active control coil pair was used to eliminate low-density locked modes which could otherwise limit the potential for achieving high-performance plasmas, as well as to understand the effect of the applied radial magnetic fields on modes at higher density and toroidal beta. With these coils, the density threshold for avoiding locked modes was reduced from 1.2 to 0.5–$0.6 \cdot 10^{19}$ m^{-3}. The reduction of the locked mode at low density by use of this coil expands the NSTX operating space, aids high-harmonic fast-wave (HHFW) operation at low density and allows for the study of possible performance-limiting modes at higher density and toroidal beta. Experiments during the next experimental campaign will focus on using the error field compensation/RWM control coil to suppress the low-density locked modes and the RWM simultaneously.

Noninductive operation will be essential for future spherical tori because of space and neutron loading limitations. Consequently, this is a critical area of research on NSTX. Several techniques of non-solenoidal plasma start-up were explored on NSTX. In initial experiments in one technique, plasmas were preionized using HHFW and electron cyclotron heating (ECH) in the outside region near the radio-frequency antenna. Poloidal-field coil currents were initially adjusted to establish a field null over a substantial portion of the plasma, and then they were ramped to produce a toroidal loop voltage of 5 to 15 V near the antenna. Currents up to 20 kA were produced. The goal for future work using this technique is to control the radial position of the nascent plasma to confine it to the region where the loop voltage is high, and thus achieve higher current.

Another technique that was tested is transient coaxial helicity injection (CHI), in which a pulse of voltage lasting for only a few milliseconds was applied between the inner and outer vessel segments, causing plasma breakdown and generating a toroidal current which was propelled into the main chamber. The transient CHI technique has the benefit of reduced power to the walls, since the CHI is on for only a short time. With this technique, plasma currents up to 140 kA with amplification factors (I_p/I_{CHI}) of up to 40 were achieved. This amplification is a factor of two greater than that obtained previously with longer duration CHI application. Ion and electron temperatures of up to 25 eV were measured, indicating the possibility of closed flux surfaces. Future experiments will focus on maintaining plasma current beyond the duration of the injector current in order to couple the seed current to other current drive sources, both inductive and noninductive.

Transport

High-confinement mode (H-mode) operation in NSTX resulted in the highest performance plasmas, with stored energies reaching 400 kJ in 1-MA plasmas with about 7 MW of NBI heating power. An experiment to study the L-H (low-to-high confinement mode) threshold power was conducted as part of an NSTX/MAST identity experiment. (MAST is the acronym for the Mega-ampere Spherical Tokamak device at Culham Laboratory in England.) The threshold in NSTX was found to be low, P_{NBI} ~ 350 kW (where P_{NBI} is injected neutral-beam power), in balanced double-null divertor (DND) plasmas at 0.5 MA and 0.45 T, with the threshold increasing to between 1 and 2 MW in lower single-null (LSN) plasmas (with the ∇B drift towards the X-point), consistent with MAST results for similar configurations and parameters. Ohmic H-modes were often observed, most reproducibly at toroidal magnetic field greater than 0.4 T, and these exhibited a gradual decrease in the edge rotational shear and radial electric field E_r, as measured by the edge spectrometer, starting up to 30 ms before the drop in D_α emission that signified the L-H transition.

The confinement trends in NSTX were similar to those at conventional aspect ratio in some respects, but differed in others. Systematic scans of lower single-null H-mode plasmas at fixed power and toroidal magnetic field indicated a linear increase in both the global and thermal energy confinement time (τ_E) as a function of plasma current (0.6 to 1.2 MA). Figure 6 shows the results of this scan; the linear increase of total stored energy (W_{MHD}) with plasma current (I_p) is seen as an increase in the electron stored energy (W_e) as measured by the Thomson scattering diagnostic. The electron density (n_e) was seen to vary by approximately 30% over the range of currents, but the electron temperature (T_e) remained constant. The “ears” on the density profile reflect the buildup of carbon at the edge during the early and mid H-mode phases.

Results taken from these systematic scans, as well as from other discharges with similar operating parameters, indicate that at fixed current and toroidal magnetic field, the global and thermal energy confinement times were found to have a slightly weaker power degradation than at higher aspect ratio. Contrary to conventional aspect ratio, however, a toroidal magnetic field dependence was observed. This trend in the global and thermal energy confinement times is shown in Figure 7. The left panel shows the global energy confinement time normalized to the ITER97 L-mode scaling, and the right panel shows the thermal energy confinement time normalized to the H-mode ITER98pby,2 thermal energy confinement time scaling. The figures show that

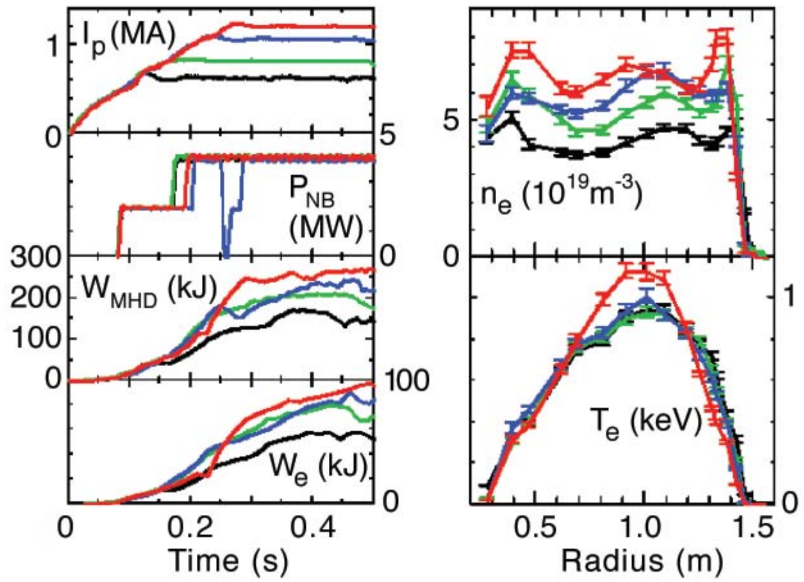


Figure 6. Plasma current (top left) and electron stored energy (bottom left) evolutions for discharges from a systematic current scaling experiment at fixed neutral-beam power. Also shown are the electron density (top right) and temperature (bottom right) profiles for these plasma discharges at the time of maximum electron stored energy.

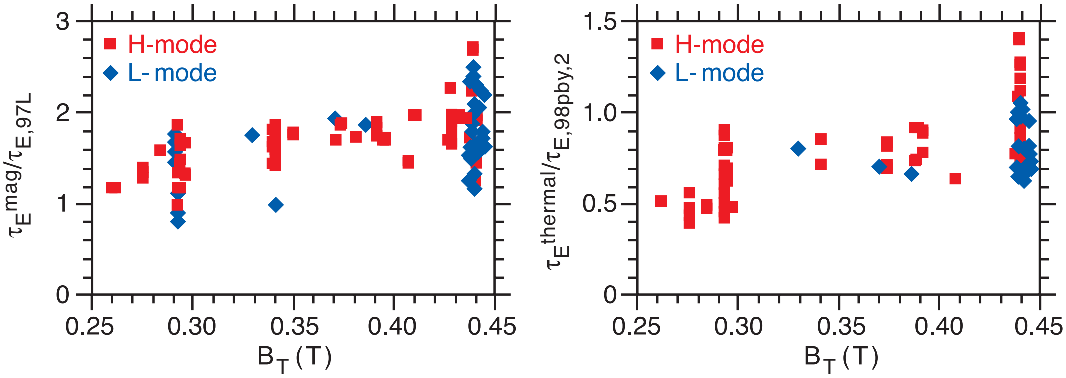


Figure 7. Global energy confinement time normalized to the 97L L-mode scaling value (left) and thermal energy confinement time normalized to the 98pby,2 scaling (right) plotted as a function of toroidal field.

the global energy confinement time values are enhanced over the L-mode value, with enhancement factors of close to 2.8 at the highest toroidal magnetic field for both L- and H-mode plasmas. The thermal energy confinement enhancement factors are more modest, reaching 1.4 at the highest toroidal magnetic field for H-mode plasmas. A reduction in confinement enhancement at the lowest toroidal magnetic field (<0.3 T) is seen for both the global and thermal values.

Insight into the possible toroidal magnetic field dependence and processes causing transport can be gained by examining turbulence measurements using fixed-frequency (30, 42, and 49 GHz) quadrature and swept-frequency (26 to 40 GHz) homodyne correlation reflectometry systems. For the first time in an ST, quantitative long-wavelength turbulence measurements have been made in the core (r/a = 0.2 to 0.7) of beam-heated L-mode plasma discharges. Correlation reflectometry data indicate radial correlation lengths (L_c) ranging from 2 to 25 cm with significantly smaller values observed in the outer plasma (r/a ~ 0.65). The correlation lengths measured in the outer plasma at r/a = 0.7 (where ion-temperature gradient turbulence can exist) are illustrated in Figure 8 as a function of local total magnetic field |B| during a fixed-edge safety factor scan. As can be seen, correlation lengths are observed to increase with decreasing field, reaching values of approximately 8 cm at the lowest field. Reflectometer measurements taken for a similar set of discharges show a reduction in the measured reflectometer phase fluctuation level, and associated reduction in the density fluctuation levels, as the magnetic field is increased.

The determination of the transport properties of NSTX plasmas by the TRANSP code has benefited greatly by the increased number of spatial points of the CHERS diagnostic. The calculations

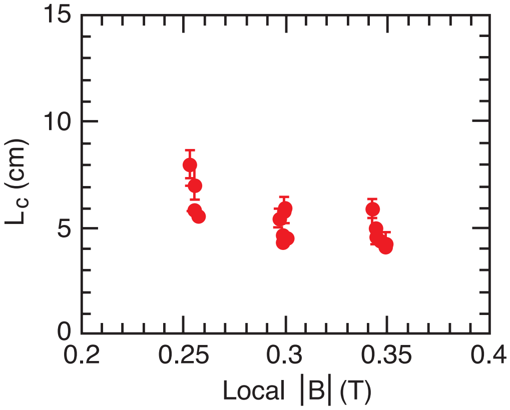


Figure 8. Reflectometer fluctuation radial correlation length (L_c) as a function of local total magnetic field (|B|).

indicate that the electron thermal diffusivity (χ_e) dominates the transport loss in most H-modes ($\chi_e \sim 10$ to 20 m^2/s), with the ion thermal diffusivity (χ_i) near or above the NCLASS code neoclassical value in many cases ($\chi_i \sim 1$ to 5 m^2/s). However, the NCLASS code neoclassical values do not take into account possible enhancements to the neoclassical diffusivity by up to a factor of 2 due to finite gyro-orbit effects. In the L-mode, $\chi_i \sim \chi_e$ (1 to 10 m^2/s) for line-averaged densities less than $4 \cdot 10^{19}$ m^2, but $\chi_i < \chi_e$ for higher densities.

The local transport properties of NSTX plasmas appeared to be sensitive to variations in magnetic shear, as is shown by comparing two plasma discharges with different safety factor profiles. The safety factor profiles of these discharges were varied by changing the current ramp rate and the NBI timing in low-density ($n_{e0} \sim 2 \cdot 10^{19}$ m^{-3}) L-mode discharges. In a discharge with a fast current ramp and early NBI, the electron and ion temperature exhibited much stronger gradients near r/a = 0.5 than in a discharge with a slower current ramp and later NBI, signifying the formation of an internal transport barrier. The electron and ion temperature profiles from these discharges at times of comparable density and rotation velocity profiles are shown in Figure 9; the sharper temperature profile gradients can be seen in discharge 112989, which had the faster current ramp and earlier NBI. The safety factor profiles for these two discharges, as determined in the TRANSP code, are shown in the top panel of Figure 10. The modeling for the slow current ramp/late NBI discharge (112996) shows a monotonic safety factor profile, while that for the fast current ramp/early NBI discharge (112989) exhibits a magnetic shear reversal from r/a = 0.2 to 0.5. The effects of the possible reversed shear are seen in the bottom panels of Figure 10, which show a reduction by a factor of 3 to 7 in the thermal diffusivities of both the electrons and ions in the region of reversed and low shear, respectively. The ion thermal diffusivities equal the electron diffusitivies outside this region. Because of uncertainties in the electron temperature, ion temperature, and their gradients, the thermal diffusivities are highly uncertain in the shaded regions, r/a < 0.2 and r/a > 0.7.

Reflectometer measurements indicated both longer turbulence correlation lengths and higher estimated density fluctuation levels in the plasma discharge with monotonic shear than in the one with calculated reversed shear. GS2 gyro-

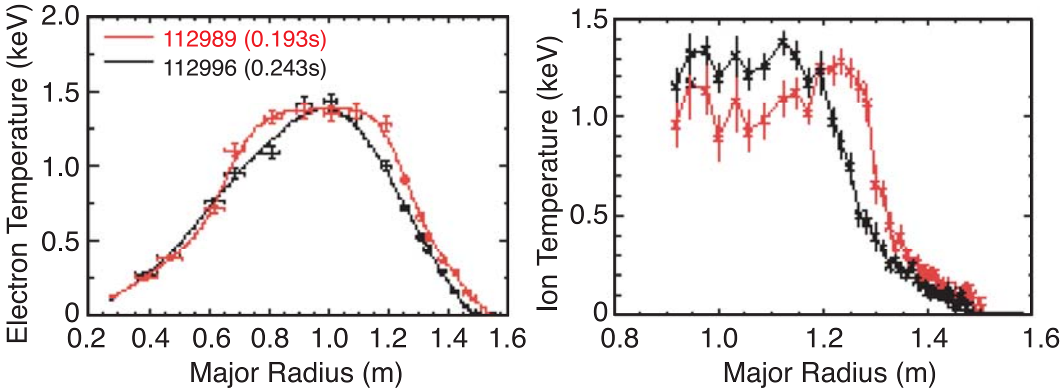


Figure 9. Electron and ion temperature profiles for two comparison plasma discharges at times of comparable density and rotation.

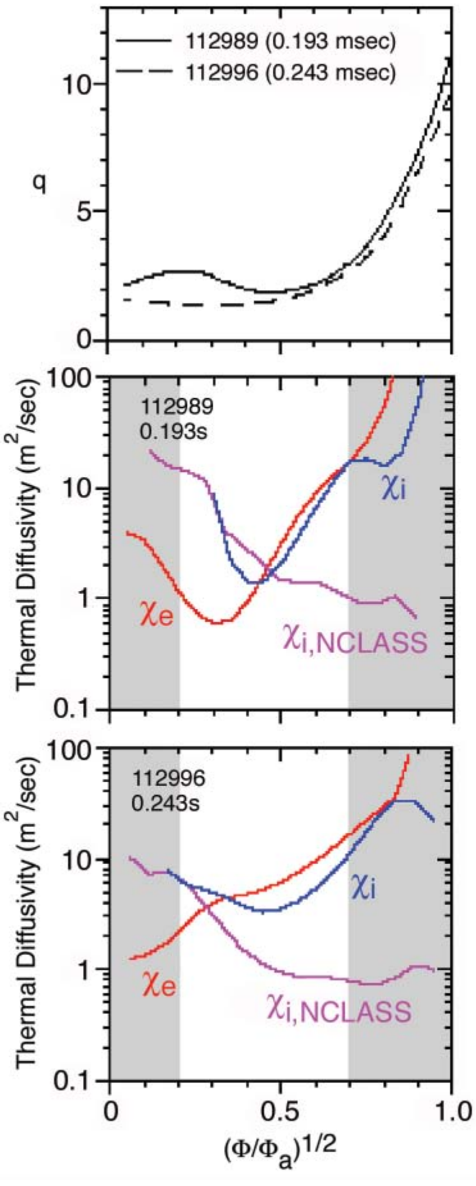


Figure 10. Safety factor profiles and thermal diffusivities calculated by the TRANSP code for comparison discharges. The thermal diffusivity values have the least uncertainty in the unshaded region.

kinetic code calculations indicate linear growth rates for microinstabilities near r/a = 0.45 which are significantly higher in the monotonic than in the reversed-shear case. Nonlinear gyrokinetic calculations are underway to confirm these results and to study the stabilizing effect of sheared rotation.

Waves and Energetic Particles

The 30-MHz system (9th deuterium cyclotron harmonic frequency, $f_{c,D}$, on axis) provides the potential for heating electrons selectively to reduce ohmic flux consumption and for providing noninductive current drive directly. The twelve-strap HHFW antenna has the capability to launch waves over a range of wavenumbers ($k_{||}$ = 3 to 14 m^{-1}) and directions. While significant electron heating has been observed in low-density deuterium and helium plasmas, the actual power absorption of the electrons was found to depend sensitively on the spectrum of launched waves, with greater absorption at higher toroidal wavenumbers. Electron heating profiles are consistent with model calculations which predict broader heating profiles for higher toroidal wavenumbers, but the increment in electron stored energy is less than what would be expected for pure electron heating.

Heating of the edge thermal ions during HHFW was measured by the edge rotation diagnostic. This heating is being considered as a possible explanation for the apparent deficit in electron heating. This edge measurement indicates that the edge ions could be described as a two-temperature component plasma, with a significant hot component whose temperature scaled with the HHFW power, and which could reach 0.6 keV. The edge ion heating was associated with parametric decay of the launched HHFW wave as measured by a radio-frequency probe. A frequency spectrum of the probe signal is shown in Figure 11; the fundamental wave at 30 MHz is seen along with sidebands separated by $f_{c,D}$, indicative of a decay into an ion-Bernstein wave (IBW) wave. More ion-Bernstein wave sidebands are observed with increasing HHFW power. It

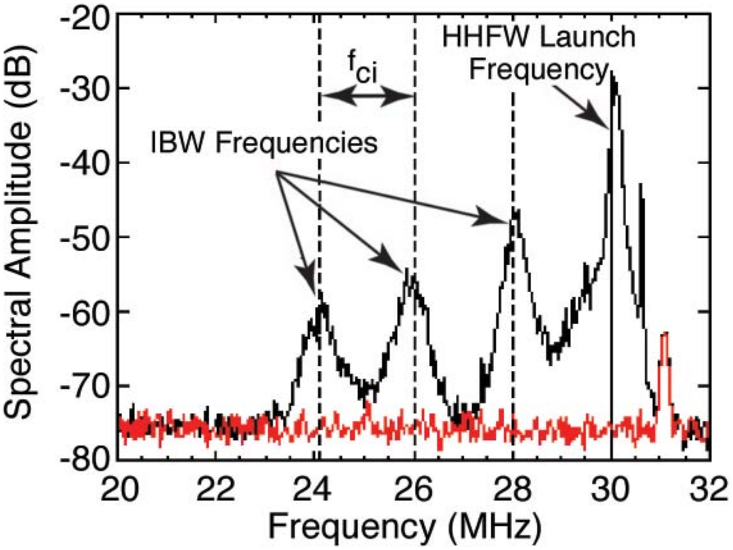


Figure 11. Evidence for parametric decay of high-harmonic fast-wave (HHFW) into ion-Bernstein wave (IBW) waves as measured by a radio-frequency probe. The red curve is the background signal.

is also noted that a significant amount of HHFW power could be absorbed by fast ions in HHFW plus neutral-beam-injection experiments.

The reduced HHFW power absorption limited the current driven by the HHFW, especially for the fastest wave, $k_{TOR} = 3\ m^{-1}$, where the driven current is predicted by theory to be maximal.

Because of the importance of noninductive current drive in STs, other techniques to accomplish this must be developed. The electron-Bernstein wave (EBW) is one candidate. In this approach, an ordinary-mode wave is launched into the plasma, and it is converted to an EBW, which then heats the electrons locally at the cyclotron layer in the perpendicular direction. The key to making this a viable technique is to have a greater than 80% conversion efficiency from ordinary-mode to the EBW. Assessments of EBW emission and estimates of mode-conversion efficiency in NSTX support this requirement, and plans for developing a high-power EBW system are underway.

The NSTX, and STs in general, are particularly susceptible to fast-ion-driven instabilities due to the intrinsically low toroidal magnetic field, and this area is a particularly useful test bed for ITER. The super-Alfvénic 80-kV neutral-beam ions have similar dimensionless parameters to 3.5-MeV alpha particles from deuterium-tritium fusion reactions in proposed magnetic fusion reactors. In NSTX, neutral-beam-heated plasmas typically exhibited a broad spectrum of instabilities excited through a resonant interaction with fast ions, from compressional and global Alfvén eigenmode waves (CAE and GAE, respectively) at frequencies $0.3 < \omega/\omega_{ci} < 1$, to toroidal Alfvén eigenmodes (TAE) at frequencies approximately 100 kHz. While there was no observed degradation in performance correlated with the appearance of compressional Alfvén eigenmode wave activity, enhanced fast-ion losses were correlated with both the toroidal-Alfvén-eigenmode-wave-like and fishbone-like modes; this could be relevant to ITER in the super-Alfvénic regime.

Plasma-boundary Interface

The exploration of improved particle control and plasma fueling benefited from the implementation of several new techniques and capabilities. Boronization during bakeout at 350 degrees Centigrade, deposition of 1 to 2 grams of trimethylboron prior to certain experimental run days, and interspersing plasma and helium conditioning discharges all helped to maintain good wall conditions and led to better density control. Initial experiments were successfully performed using a lithium pellet injector developed for particle control and a supersonic gas injector for localized and efficient fueling. The use of these capabilities and techniques will be expanded in future operation.

Because of the compact nature of the ST, it is important not only to account for the power escaping from the plasma, but to reduce the power to the material surfaces. It is also the case that STs form a very good test bed for studying high power density operation for ITER. Power accountability in both lower single-null and double-null divertor plasmas was found to be good, with up to 70% and 90% of the power accounted for in the two configurations, respectively. The largest fraction of the power loss (35%) was deposited on the divertor plates, with an out-in ratio of up to 5:1. Inner divertor detachment was found to reduce the power loading of the inner divertor plates to below 1 MW/m^2. Inner divertor detachment was observed in both L- and H-mode NBI-heated plasmas at densities greater than $2 \cdot 10^{19}$ m^{-3}. The outer divertor in all experiments remained attached, with heat fluxes up to 10 MW/m^2, greater than that anticipated in ITER.

A variety of edge-localized modes (ELMs), which can cause increased divertor power loading, was observed in H-mode plasmas. An apparent new type of ELM, Type V, was identified. This ELM is small amplitude with minimal energy loss and minimal resulting power loading, and it occurs when the normalized electron collisionality frequency (ν_e^*) is greater than one, where ν_e^* is evaluated at the top of the pedestal. At lower normalized electron collisionality frequency, this small ELM was interspersed between large Type I ELMs. Type I ELMs often exhibited low toroidal mode number external kink-like structures on the fast camera images, while structures associated with Type II/III/V ELMs were higher toroidal mode number (Figure 12). The

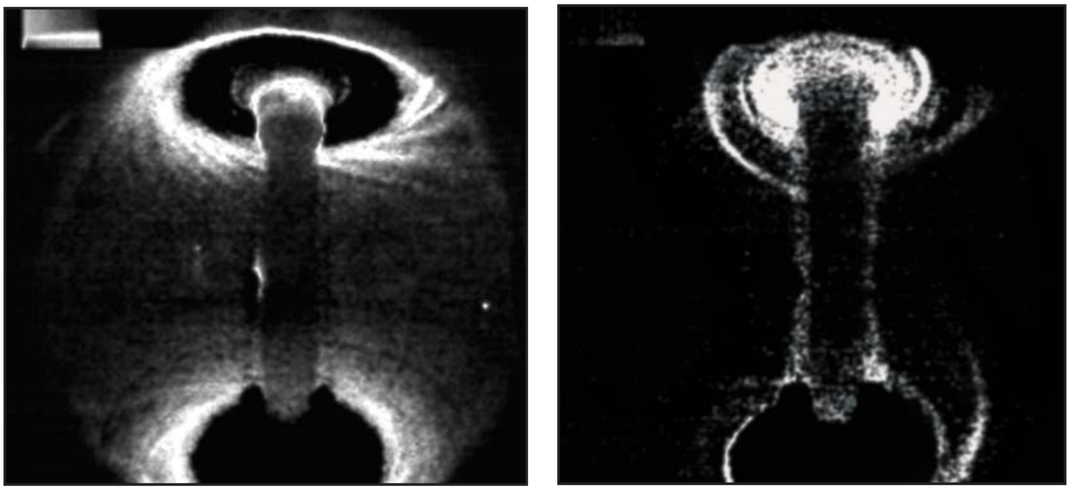


Figure 12. Fisheye camera images of contrast-enhanced, unfiltered light during a large, Type V edge-localized mode (left) and a small, Type I edge-localized mode (right).

severity of ELMs that affect the plasma stored energy was found to depend sensitively on plasma elongation. Future work will focus on understanding the underlying ELM stability properties and their dependence on shape, using high-spatial-resolution edge diagnostics in order to utilize them for control of both density and power loading.

The two-dimensional structure of edge plasma turbulence was measured by viewing the emission of D_α or helium spectral lines enhanced by gas puffing using an ultra-high speed CCD camera. Transitions from L-mode to H-mode could appear as a continuous evolution from a turbulent "blob-like" or intermittent state to a quiescent state over 0.1 ms, apparently without any new spatial features or flows. Transitions from H-mode to L-mode appeared as high toroidal mode number poloidal perturbations which evolved into radially moving blobs. The ELMs normally were associated with an increase in blob-like activity, although sometimes ELM-free H-modes had intermittent blob-like turbulence.

Maintenance Activities and Upgrades

A redesign of the NSTX demountable toroidal-field (TF) assembly was implemented before the start of the FY04 experimental run. This new design provided an increase in the strength of the hub assemblies, utilizing steel boxes with epoxy filling rather than shims to restrain the joint flags. Voltage difference probes were added at all 72 toroidal-field joints to provide high-resolution real-time measurements of the joint resistances, and a fiber-optic-based instrumentation system was installed to take strain, temperature, and displacement measurements at selected joints. During the first four months of the experimental run, a small but gradual upward drift of the resistances of some of the more highly stressed TF joints was measured, and a TF operating limit of 3 kG was imposed while joint performance was analyzed. Toroidal-field joint performance remained stable at 3 kG, and the FY04 experimental run was successfully completed.

A number of other important facility and diagnostic upgrades were performed during the past year. The experimental run began with new technical system capabilities to allow for boronization of the vacuum vessel walls using trimethylboron while at vessel bakeout temperatures, and to provide rapid daily boronization to meet experimental needs. A 400-pellet lithium pellet injector and new shoulder gas valve controls were implemented to support particle control experiments. A supersonic gas injector for localized and efficient fueling was installed and commissioned. The microwave reflectometer diagnostic system was upgraded to measure long-wavelength turbulence in the plasma core through correlation reflectometry. Edge fluctuations were measured with an upgraded reciprocating edge probe, a new fast camera for gas puff imaging measurements, a divertor visible camera, and edge channels in the far-infrared interferometer system (FIReTIP). Additionally, the motional Stark effect diagnostic was installed and operated with up to eight channels to determine the plasma current profile. Results from a plasma equilibrium reconstruction using motional Stark effect data as a constraint are shown in Figure 13.

A facility upgrade critical to the success of the majority of experiments run in the past year was an upgrade to the SKYBOLT real-time control computer, resulting in reduced latency in the plas-

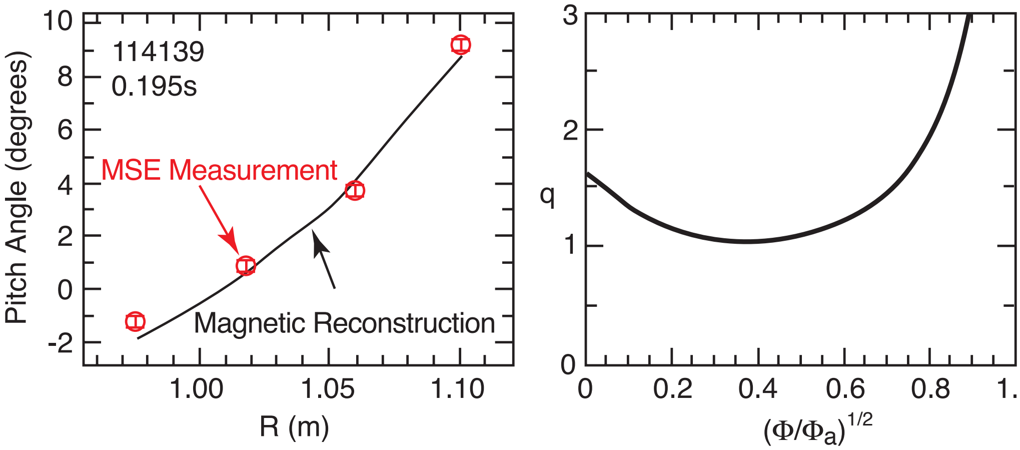


Figure 13. Measured and reconstructed magnetic pitch angle (left) and reconstructed safety factor profile (right) using motional Stark effect data as a constraint.

ma control system from several milliseconds to under one millisecond, improving the real-time plasma control. Continued development of the real-time EFIT code led to its successful use in experiments that required fine boundary control. Other control system upgrades this year include a real-time phase control system for HHFW and a radio-frequency filtering system for the magnetic diagnostic system to allow real-time plasma control during high-power HHFW operation. In support of ongoing experiments on techniques to achieve solenoid-free plasma initiation, poloidal-field coil #4 on NSTX was commissioned for operations this year, and a new capacitor bank to provide transient coaxial helicity injection capability was designed and installed. The first of three pairs of ex-vessel control coils for error field compensation and ultimately for control of resistive wall modes was installed and operated.

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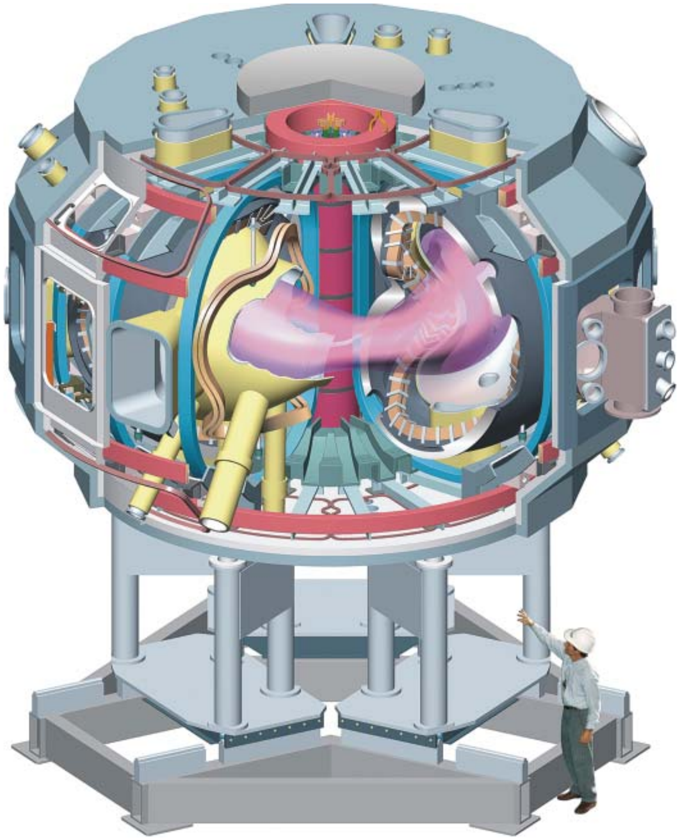
National Compact Stellarator Experiment



National Compact Stellarator Experiment

A key goal for fusion science research is to develop physics solutions for practical magnetic fusion power plants. Stellarators, a family of three-dimensional (3-D) toroidal magnetic configurations, are of interest because they solve major problems — achieving steady-state operation and avoiding disruptions. There is a substantial effort in stellarator research worldwide, including Japan's Large Helical Device (operating) and Germany's Wendelstein-7X (under construction), large facilities that use superconducting magnets. United States researchers have focused on a new variant, the compact stellarator, which shares the attractive properties of existing stellarators but also has additional advantages.

The compact stellarator is a result of major advances in plasma physics understanding and computation over the past decade. For the first time, researchers are able to design stellarator configurations that are stable without active feedback control or current drive, have low aspect ratio ($A \leq 4.5$, where A is the ratio of the torus radius to plasma radius) compared to previous stellarator designs ($A \leq 10$), and have a quasi-symmetric magnetic field structure. A quasi-symmetric magnetic configuration has, in spite of its three-dimensional geometry, an approximate symmetry direction in the field strength, as experienced by charged particles drifting along magnetic field lines in the system. In a quasi-*axi*symmetric stellarator (QAS) such as the National Compact Stellarator Experiment, the single particle trajectories and plasma flow damping are similar to those in tokamaks, which are axisymmetric in both geometry and magnetic structure. Based on this fundamental similarity, quasi-axisymmetric stellarators are expected to share the tokamak's good confinement performance. Their physics link with tokamaks should enable compact stellarators to 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.

A new experimental device, the National Compact Stellarator Experiment (NCSX), is being constructed at the Princeton Plasma Physics Laboratory (PPPL) in partnership with the Oak Ridge National Laboratory (ORNL) as the centerpiece of a national program to develop compact stellarators. During FY04, the NCSX completed major design and project management milestones and, with the placement of contracts for manufacture of major components, moved into fabrication. Technical advances in design, research and development, and manufacturing process development for NCSX are discussed in the Engineering and Technical Infrastructure section of this report. In this section, the key milestones in the project's transition from a design to a fabrication activity in FY04 are highlighted.

NCSX Mission

The NCSX is an integral part of the U.S. Department of Energy's (DOE) Office of Fusion Energy Sciences program. Its mission is to acquire the physics knowledge needed to evaluate compact stellarators as a fusion concept, and to advance the physics understanding of 3-D plasmas for fusion and basic science. In addition, the technological innovations and developments that are produced in the course of the fabrication project are making important contributions to fusion technology, including publication at major conferences. The NCSX device is designed to test compact stellarator physics in a high-beta ($\beta > 4\%$), low aspect ratio ($A = 4.4$) QAS plasma configuration which obtains about one-fourth of its edge rotational transform from the self-generated bootstrap current. Modular coils (Figure 1) provide the externally generated 3-D stellarator magnetic fields for the three-period configuration. The QAS concept was chosen for NCSX because its connection with the tokamak enables it to build on the tokamak as well as the stellarator databases.

NCSX Machine Design

The NCSX design is built upon the robust machine concept that was documented in the 2002 NCSX Conceptual Design Report. At the core of the device are the modular coils and the vacuum vessel, the two most critical components. The eighteen modular coils will be fabricated at PPPL on steel winding forms manufactured in industry to precise shape

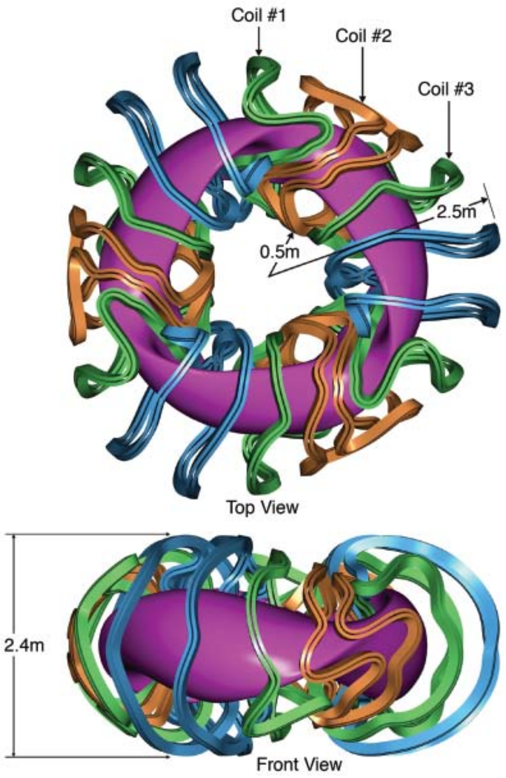


Figure 1. The NCSX will use three-dimensional modular coils to produce a three-dimensional plasma shape.

specifications. The finished coils will be assembled over segments of the vacuum vessel, also manufactured in industry, to form three identical field-period subassemblies. These components and assembly steps are illustrated schematically in Figure 2. In final assembly, the field periods will be joined together on a support base to form a vacuum-tight vessel surrounded by a toroidal shell structure, made up of the eighteen winding forms, that will permanently support the modular coils. Additional control coils, associated structures and services, and a cryostat will then be installed to complete the stellarator core assembly.

Establishing the Project Baseline

The NCSX fabrication project began in April 2003. By the start of FY04, six months into the project, the design had reached a level of maturity sufficient to establish the cost and schedule baseline for execution. Four industrial teams were already under contract, developing manufacturing processes for the major components. The teams, two for the vacuum vessel and two for the modular coil winding forms, had submitted cost and schedule estimates for production and were preparing to fabricate full-scale prototypes of these components.

The project's designs, work plans, and estimates were documented in a detailed report and reviewed on October 7–9, 2003 at a NCSX Preliminary Design Review, the first of several project milestones accomplished in FY04. Carl N. Strawbridge, Deputy Director of the Spallation Neutron Source Project at Oak Ridge National Laboratory, chaired a committee of thirteen experienced engineers from fusion and other science communities. They found the NCSX design to be technically sound, the management plans and budget to be adequate, and the project ready to be baselined. The report included numerous recommendations, one of which was to make the vacuum vessel capable of being heated to a temperature of 350 degrees C, so that future plasma-facing components, which may require bakeout to that temperature, can be accomplished through simple attachments to the vacuum vessel. This change improves the economics and reliability of such plasma-facing components and thus will be a significant benefit to research operations.

The Preliminary Design Review was followed by two DOE reviews that were held jointly November 18–20, 2003. The Performance Baseline Review, chaired by Daniel Lehman of the DOE Office of Science (SC), examined the project's technical basis, risk mitigation plans, cost and schedule estimates, and management plans. The External Independent Review by the DOE Office of Engineering and Construction Management validated the project's estimating basis and compliance with performance baseline prerequisites. The two reviews satisfied key baseline readiness requirements, as specified in DOE Manual M413.3, "Project Management for the Acquisition of Capital Assets," which governs the management of the NCSX project. The reviews concluded that the project was responding appropriately to the Preliminary Design Review and was ready to be baselined. Key project changes resulting from these reviews included decisions to budget additional tooling to increase coil winding capacity at PPPL, to power test all modular coils individually at cryogenic temperature, and to test the completed coil assembly at cryogenic temperature prior to operation.

Based on the results and project responses to these three reviews and an updated DOE funding plan, the project baseline was approved (Critical Decision 2, or CD-2) on February 4, 2004 by the Associate Director for Fusion Energy Sciences, DOE SC. Criteria for project completion, including production of "first plasma" with coils at cryogenic temperatures, were set. A budget of $86.3 million and a completion date (CD-4) of May 2008 were established. The Work Breakdown Structure (WBS), including contingency of 26% on the work remaining at CD-2, is summarized in Table 1. The schedule, including over five months of contingency, is summarized in Figure 3. The funding profile adopted at CD-2 is provided in Table 2.

Moving into Construction

Throughout FY04, the project progressed in its technical activities toward the goal of awarding the two largest fabrication contracts, for the vacuum vessel subassemblies and for the modular coil

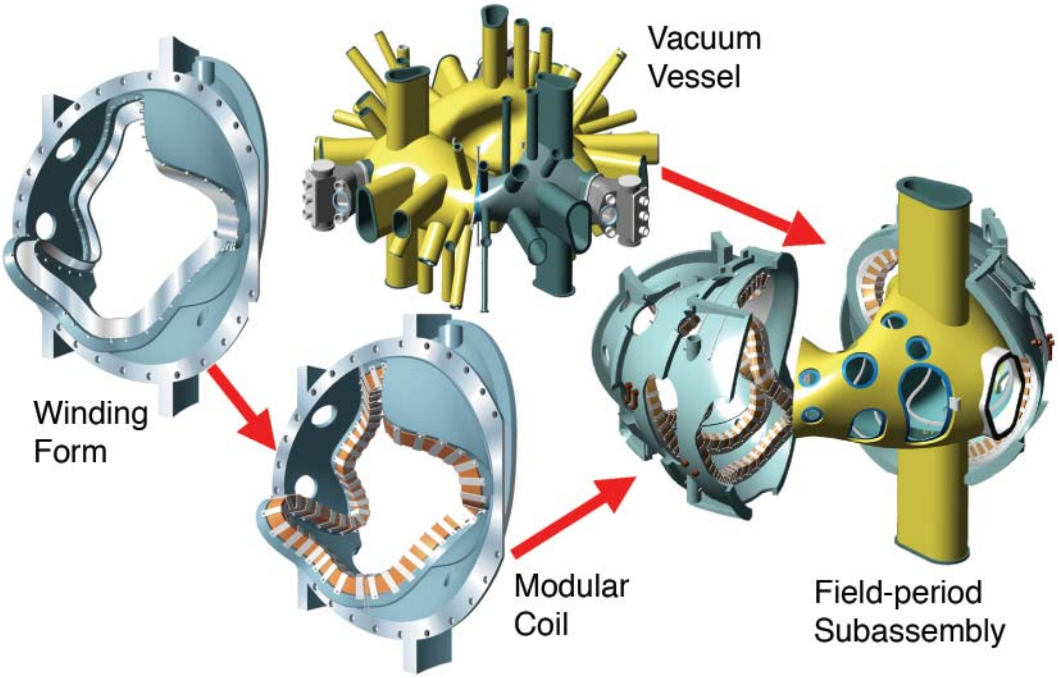


Figure 2. Manufacture and assembly of the NCSX modular coils and vacuum vessel into field-period subassemblies.

Table 1. The National Compact Stellarator Experiment Project Budget.

WBS	Work Package	Budget ($M)
1	Stellarator Core	42.3
2	Heating, Fueling, and Vacuum	1.6
3	Diagnostics	1.7
4	Electrical Power	5.3
5	Central I&C and Data Acquisition	2.6
6	Facility Systems	2.0
7	Test Cell Preparation and Machine Assembly	4.3
8	Project Management and Integration	10.6
	Subtotal	**70.4**
	Contingency (26% of work remaining at CD-2)	15.9
	Total Estimated Cost	**86.3**

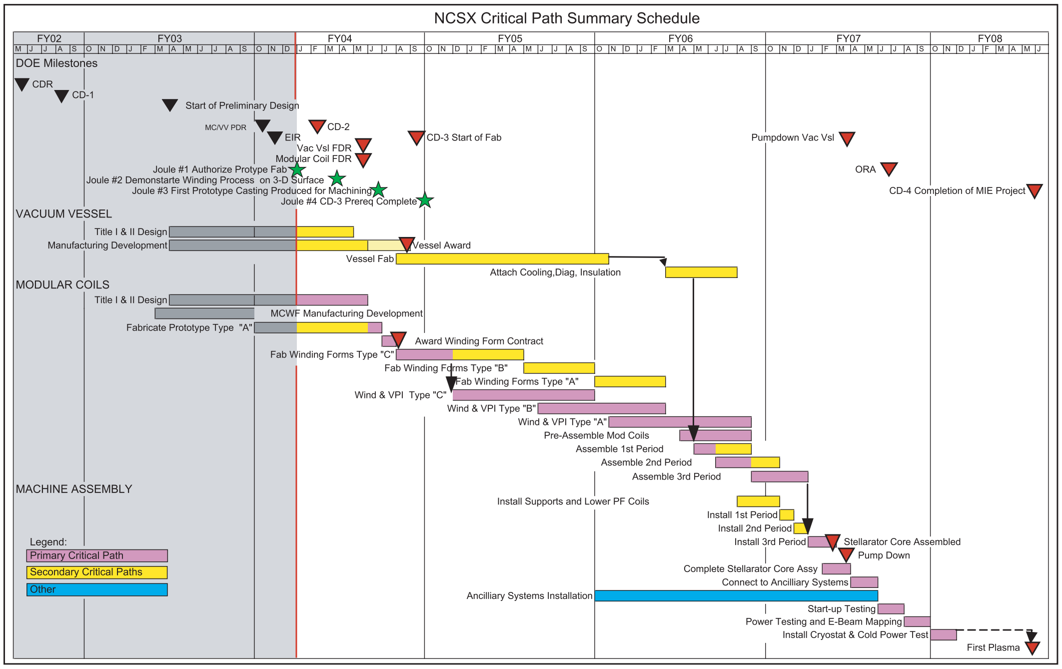


Figure 3. The National Compact Stellarator Experiment Project Schedule.

Table 2. The NCSX Funding Profile at Critical Decision-2.

Fiscal Year	2003	2004	2005	2006	2007	2008	Total
Funding ($M)	7.9	15.9	15.9	22.1	19.4	5.1	86.3

winding forms by the end of the fiscal year. Documents produced include complete fabrication specifications for those components, reports documenting the design description and supporting analysis and research and development, procurement plans, contract statements of work, and source selection criteria. A successful Final Design Review held May 19–20, 2004, again chaired by Carl Strawbridge of ORNL, confirmed the project's technical readiness to proceed with procurement and fabrication.

After incorporating review recommendations, the project sent requests for proposals to the four industry teams who were participating in the project's manufacturing development program. Production proposals were received from all four teams in early August 2004. After evaluating the proposals, two subcontract procurement evaluation boards recommended the awardees for the production program. Major Tool and Machine, Inc. of Indianapolis, Indiana, was selected to fabricate the vacuum vessel subassemblies (Figure 4). Energy Industries of Ohio, Inc., of Independence, Ohio, was selected to fabricate the modular coil winding forms (Figure 5), leading a team including C.A. Lawton Company of De Pere, Wisconsin, for pattern making; MetalTek International of Pevely, Missouri, for casting; and Major Tool and Machine, Inc. for machining.

Two DOE Office of Science project reviews, one on June 8–9, 2004 (before issuance of the request for proposals) and the second on September 1, 2004 (after source selection), were held to assess the project's readiness for fabrication. Based on their positive recommendations, Start of Fabrication (CD-3) was approved on September 16, 2004. Immediately afterwards, the project awarded the contracts, achieving its final goals for FY04 on schedule.

Summary and Project Status

In FY04, the NCSX project made the transition from a design-dominated to a fabrication-dominated activity. Following the approval of the performance baseline in February, formal cost

Figure 4. A full-scale 20-degree prototype section of the NCSX vacuum vessel produced by the Major Tool and Machine, Inc., team.

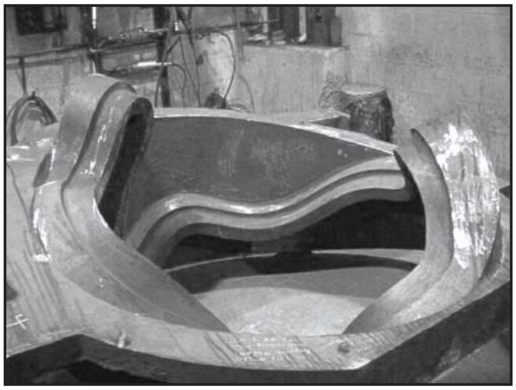


Figure 5. An actual full-scale NCSX prototype modular coil winding form produced by the Energy Industries of Ohio team.

and schedule performance tracking began. The earned value of accomplished work was updated each month and reported to DOE. Schedule and cost performance indices, ratios of earned value to scheduled work and to costs, respectively, were computed and used to assess project performance. These indices remained between 0.9 and 1.1 as required by DOE performance standards, and improved with time. With the placement of its two major component fabrication contracts, about half the project's effort moved to industry. Because of the success of the manufacturing development program, and the continuity of the selected contractors' efforts from that program to production, the fabrication activities were able to make a rapid and efficient start following contract award.

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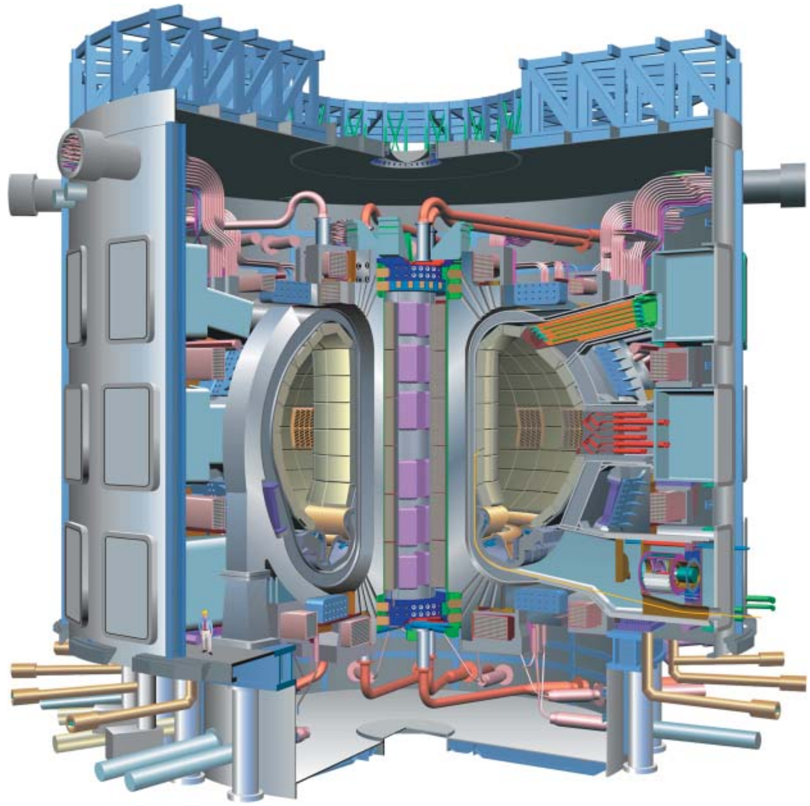
U.S. ITER Project Office



ITER

The study of burning plasmas has been identified as the next major step in the world fusion program. The worldwide community of fusion researchers has reached a consensus that the scientific and technological basis is sufficient to proceed to a burning plasma experiment — one in which the plasma is heated predominantly by alpha particles produced in deuterium-tritium fusion reactions.

An unprecedented international collaboration of scientists and engineers has performed needed research and development (R&D) and has designed a burning plasma experiment called ITER, which in Latin means “the way.” The fusion power produced by ITER will be ten times greater than the external power delivered to heat the plasma. In January 2003, President Bush announced that the U.S. would join in negotiations for the siting and construction of this project, whose mission is to demonstrate the scientific and technological feasibility of fusion power. If successful, these deliberations could lead to the operation of ITER around the middle of the next decade.

In FY04, ITER emerged as a significant component of PPPL's program. In February 2004, the U.S. Department of Energy (DOE) Office of Science unveiled its *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 the DOE selected the partnership of the Princeton Plasma Physics Laboratory (PPPL) and the Oak Ridge National Laboratory to host 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." The U.S. contributions will take the forms of in-kind contributions, staff, and cash.

In FY04, worldwide ITER activities transitioned from a period of technical and administrative preparations for construction to one characterized by high-level inter-governmental negotiations, along with continued R&D and design. The U.S. ITER activities focused on the two major scopes: (1) technical support of the on-going ITER negotiations and (2) technical activities focused on the U.S.'s in-kind contributions.

Technical Support of Negotiations

The January 2003 presidential decision for the U.S. to engage in ITER negotiations followed an extensive U.S. fusion community assessment of the scientific and technological benefits of the study of burning plasmas, of the technical readiness to proceed to the study of burning plasma, and of the range of approaches to such studies. The *Snowmass 2002 Fusion Energy Sciences Summer Study* at Snowmass Village, Colorado, during which 250 fusion scientists and engineers performed a uniform technical assessment of approaches to burning plasma, was used by the Fusion Energy Sciences Advisory Committee as the technical basis for the development of a strategy for the U.S. to conduct burning plasma studies. This strategy was reviewed by the National Research Council, which recommended that the U.S. should enter into ITER negotiations. These preparations served as the scientific and technological basis for community support of the U.S. negotiators for participation in ITER. In February 2003, a PPPL research manager was asked to serve as the U.S. ITER Planning Officer and to organize and coordinate technical activities aimed at preparing the nation for engagement in ITER. A series of 2003 meetings of the ITER Negotiators Standing Sub-Group explored possible arrangements for the management and execution of the international ITER project, including a provisional allocation of responsibilities for supplying the major components of ITER, which was achieved in September 2003 and was endorsed by the governmental negotiators as a suitable basis for further planning.

At the beginning of FY04, a meeting of the Negotiators' Standing Sub-Group was held in Beijing, China, at which the U.S. ITER Planning Officer and the PPPL Director participated as members of the U.S. delegation. Discussions addressed further refinement of staffing regulations, resource management regulations, risk management, intellectual property regulations, procurement allocations, the decommissioning fund, and drafting of the International ITER Agreement. In the staffing area, significant progress was made in making most ITER organization positions accessible to U.S. staff as either ITER secondees or direct employees of the ITER organization. Risk management continued to be an area of U.S. emphasis and attention, with an increasing level of support from several parties. In procurement regulations, compensation for design changes imposed by the ITER Project Organization remained a significant issue.

At the end of calendar 2003, Vice Ministers from the six ITER parties gathered in Reston, Virginia, to seek agreement on the ITER site. Unfortunately, the site-decision could not be made and homework was assigned in two areas: more detailed technical assessments of the two sites (in Cadarache, France, and Rokkasho, Japan) and technical discussions of a broader approach, described below. In January 2004, two meetings were held, one in Garching, Germany, and the other in Naka, Japan, at which technical representatives of the parties met to discuss these two topics. The U.S. ITER Planning Officer and the Director of the U.S. Virtual Laboratory for Technology participated in these meetings. Technical assessments generated a greater understanding in each party of the strengths of the two sites and led to a subsequent meeting in Vienna, Austria, at which the potential hosts answered questions regarding their proposed sites. The discussions on the broader approach focused on opportunities for distributing parts of the ITER Project and the associated ITER program in a way that might achieve a win-win configuration for the two potential host parties. The information from the site studies and broader approach discussions were made available to the parties as input to further judgments and negotiations.

Cost Estimates for U.S. In-kind Contributions

Beginning in October 2003, the U.S. ITER Planning Officer, at the request of the Department of Energy, initiated an independent assessment of the costs for U.S. performance of the requested and provisionally allocated in-kind contributions. The U.S. contributions are currently "provisional" because negotiated details need to be finalized after an agreement on ITER siting and other details are concluded. Area coordinators, mostly from the Virtual Laboratory for Technology, examined the relevant procurement packages from the 2001 "ITER Final Design Report" and performed their own estimates based on U.S. labor rates, commodity prices, etc. The estimate included all costs for the U.S., not just those categories included within the ITER cost estimate sheets from 2001. In particular, the U.S. cost estimate included remaining research and development, remaining design work, engineering oversight of the procurements, contingency, and escalation, in addition to the industrial fabrication activities estimated in the 2001 "*ITER Final Design Report*." In early December 2003, the group convened at DOE headquarters to discuss and refine their findings.

Project Office Selection

Early in FY04, the Department of Energy issued a request for proposal to DOE laboratories to host the U.S. ITER Project Office, which would be responsible for the coordination of the nation's activities on ITER. These activities would include not only the arrangements for the United States provisionally allocated contributions, but also supply of cash to the international ITER organization for common expenses and the arrangements for U.S. staff to the ITER organization. Three DOE laboratories submitted proposals, which were evaluated by a Department of Energy team centered at the Chicago Operations Office. In July 2004, PPPL in partnership with the Oak Ridge National Laboratory was awarded the host responsibility. The U.S. ITER Project Office formalized activity in the research and development and design of the U.S. contributions and began work with the Department of Energy on preparations for project activities specified within the DOE Project Management Order.

Technical Activities Focus on In-kind Contributions

The partnership between the U.S. Virtual Laboratory for Technology and the U.S. ITER planning activities continued to address R&D and design for the provisionally allocated U.S. in-kind contributions (Figure 1).

Central Solenoid Magnet: The provisionally allocated magnet contribution by the U.S. includes four of the seven modules of the central solenoid, which is the flexible set of coils in the inner stack of ITER, which will not only drive ohmic current but also enable flexible shaping of the plasma cross section to allow both enhanced performance and experimental flexibility. R&D issues addressed by the United States included the development of higher capacity superconducting strand by potential U.S. vendors, the characterization of the surrounding jacket material which provides structural support for the superconducting strands and their wraps, studies of joints, and overall design of the central solenoid by both domestic and seconded work.

Shield/Blanket: U.S. contribution of 10% of the plasma-facing surface will be implemented by our supplying 36 mod-

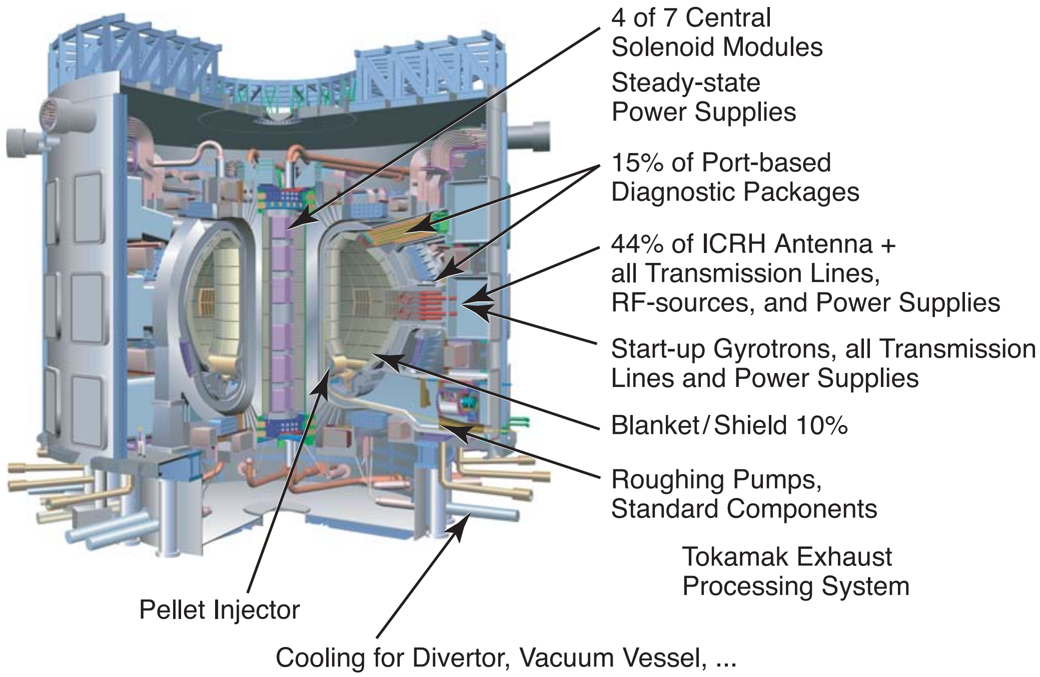


Figure 1. U.S. provisional "in-kind contributions."

ules in the lower half of the machine near the divertor. R&D and design issues addressed included the bonding of beryllium plasma-facing materials to a copper heat sink and bonding of the copper heat sink to a stainless steel support structure. Design activity addressed not only the thermohydraulics of the cooling, but also the electromagnetic loads from plasma disruptions.

Diagnostics: The U.S. will provisionally provide 16% of the diagnostics, including integration of two upper ports, two equatorial ports, and one divertor port. The design activity focused on examination of more appropriate packaging for the diagnostic work, leading to a decision that the diagnostics would be allocated by ports, with the party responsible for the port providing not only the lead diagnostic for the port but also performing integration of other diagnostics into the integrated port structure.

ICRH Antenna: The provisionally allocated U.S. scope includes an equal sharing with Europe of a state-of-the-art ion cyclotron antenna, and U.S. supply of all of the transmission lines, radio-frequency sources, and power supplies. Research included prototyping of the high-power prototype antenna for the Joint European Torus (JET) tokamak in England as a partnership between Europe and the United States. This work, supported by the Virtual Laboratory for Technology and the international collaborations program, identified issues which are to be addressed prior to the finalization of the antenna.

Electron-cyclotron System: The U.S. allocation includes all of the 120-gigahertz start-up gyrotrons, all the transmission lines, and all of the high-voltage power supplies. Research was conducted on the development of a 120-gigahertz gyrotron, primarily through support by the Virtual Laboratory for Technology.

Pellet Injector: U.S. activity on the pellet injector included protyping of the guide tube and assessment of the survivability of pellets launched at 300 meters per second, the planned ITER injection speed.

Roughing Pumps and Standard Vacuum Components: It was determined that there is no research needed to support U.S. provision of vacuum components.

Tritium Processing System: The provisionally allocated U.S. role in the tritium processing system is the tokamak exhaust processing system, which will take the effluent from the ITER vacuum system and separate out hydrogen isotopes which will then be passed to the European-led isotope separation system, which will lead to the Korean-led gas storage and delivery system. The U.S. activity focused on the integrated design of the tritium processing system, working with Europe and Korea.

Conventional Systems: Balancing the U.S. high technology components were two large conventional systems for steady-state electrical power and cooling water for the divertor and vacuum vessel. The U.S. activity focused only on cost estimation for these systems.

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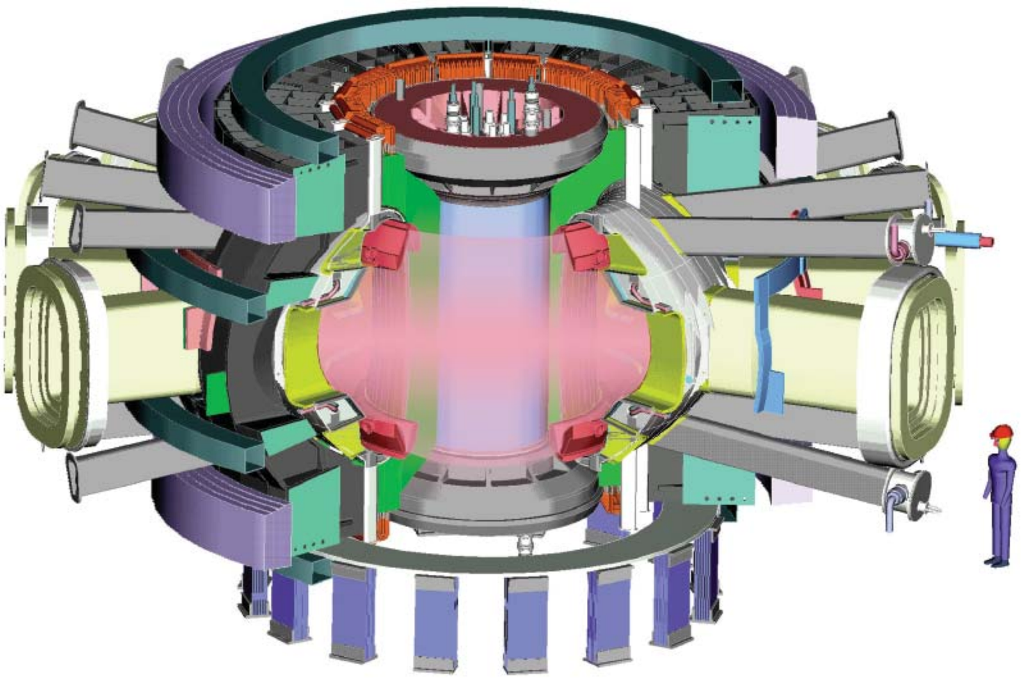
Fusion Ignition Research Experiment



Fusion Ignition Research Experiment

The Fusion Ignition Research Experiment (FIRE) design study has been undertaken to define a low cost burning plasma experiment to attain, explore, understand, and optimize magnetically confined fusion-dominated plasmas. The FIRE Design Study has been undertaken as a national collaboration with participants from more than 15 U.S. institutions and is managed through the Virtual Laboratory for Technology. The technical work on FIRE has been guided by a Next Step Option Program Advisory Committee with members from 12 U.S. fusion institutions, as well as Europe and Japan. The major FIRE and Next Step Options activities for FY04 were the successful completion of the Physics Validation Review for FIRE, continued improvement of the physics basis for FIRE, and the extension of FIRE work to the development and possible implementation of advanced tokamak modes on ITER.

Physics Validation Review

As recommended by the Fusion Energy Sciences Advisory Committee (FESAC)

Burning Plasma Strategy Report, the U.S. Department of Energy conducted a Physics Validation Review (PVR) of the FIRE physics basis on March 30–31, 2004. The Charge to the Physics Validation Review Committee was:

> Using the Technical Assessment at the 2002 Snowmass Summer Study as a starting point, update the assessment of the physics and technical capability of FIRE to address the critical issues in a major Next Step Burning Plasma Experiment. Specifically:
>
> 1. Are the mission and objectives identified by FIRE appropriate to answer the critical burning plasma issues in a major next step experiment?
>
> 2. Is the proposed physical device sufficiently capable and flexible to answer the critical burning plasma issues proposed in #1? What areas are deficient and what remedies are recommended? What areas need supporting R&D from the base program (experimental, theory and modeling)?

The FIRE program received strong endorsement from the Consensus Report of the Physics Validation Review Committee, which found that “The FIRE team is on track for completing the pre-conceptual design within FY04. FIRE would then be ready to launch the conceptual design. The product of the FIRE work, and their contributions to and leadership within the overall burning plasma effort, is stellar.” In regard to the specific charge, question #2, the Physics Validation Review Committee found that “The 2002 Snowmass study also provided a strong affirmative answer to this question. Since the Snowmass meeting, the evolution of the FIRE design has only strengthened ability of FIRE to contribute to burning plasma science.” In addition, the panel noted that since Snowmass, FIRE had doubled the duration of its advanced tokamak modes of operation from 1–3 to 3–5 current redistribution times. They also noted that increased magnet cooling had tripled the full-power shot rate from one per three hours to one per hour.

The nominal operating point for FIRE is stable to instabilities produced by the energetic alpha particles. The panel recommended that FIRE identify conditions under which these instabilities could be studied. A self-consistent analysis of energetic particle stability showed that these instabilities could be produced under controlled conditions in the FIRE advanced tokamak regime. FIRE would operate at reactor level magnetic fields of approximately 6.5 to 10 T, and the generation of radio-frequency power at the electron cyclotron frequency (180 to 280 GHz) to stabilize neoclassical tearing modes is only feasible at the lower end of the magnetic field range. The Physics Validation Review Committee recommended that FIRE model the stabilization of neoclassical tearing modes by lower hybrid current drive (LHCD), which is well suited to FIRE conditions. Additional areas of work that are generic to both FIRE and ITER were identified such as: design of a generic mid-plane port plug, modeling of particle control and helium exhaust, and modeling of toroidal mode numbers $n > 1$ resistive wall modes.

Improved Physics Basis

The International Tokamak Physics Activity (ITPA) has continued its work to extend the understanding of tokamak physics and to provide an improved physics basis for burning plasma experiments such as ITER and FIRE.

Improved Confinement Scaling of H-modes

A new confinement scaling relation developed by the International Tokamak Physics Activity has reduced adverse scaling with beta present in the previous ITER98(y,2) scaling used to predict burning plasma performance. The specific formulation of this new scaling, consistent with recent experiments on the DIII-D tokamak and the Joint European Torus (JET), was published by Cordey, *et al.* in the *Proceedings of the 20th IAEA Fusion Energy Conference* in 2004. The projection of FIRE performance based on the new confinement scaling is shown in the plasma operating contour diagram in Figure 1. In this case, a path to high fusion gain is available for auxiliary heating power of <10 MW. A very interesting operating point at a fusion gain of Q ~ 30 (essentially ignition) producing fusion power of 300 MW for about 20 seconds is within the power handling capability of FIRE. Sustaining normalized beta β_N ~ 2.5 may require some stabilization of neoclassical tearing modes or a flatter safety factor q profile as in the Hybrid Mode.

Hybrid Mode Offers Higher Fusion Gain for FIRE

The so-called hybrid modes developed by ASDEX-Upgrade and DIII-D are well matched to FIRE. The hybrid mode has high confinement [H98(y,2) ≈ 1.6] and moderate beta (β_N ~ 2.5), and moderate densities relative to Greenwald limit. These regimes would result in fusion gains exceeding 20 in FIRE.

Strong Plasma Shaping and Double Null Lead to Improved Confinement and High Beta

The International Tokamak Physics Activity studies have also indicated that high plasma cross-section triangularity in double-null (or near double-null) divertor configurations results in enhanced confinement, higher beta, and less trou-

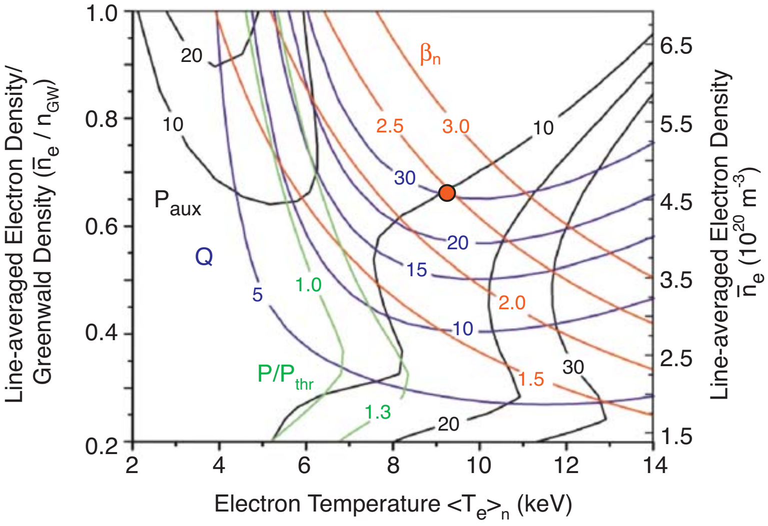


Figure 1. Plasma operating contours for FIRE for the new H-mode confinement scaling developed by the International Tokamak Physics Activity. The red circle identifies a new high-performance operating point. This case had a H-mode enhancement factor H = 1.1 appropriate for high triangularity, 2% beryllium impurity concentration, central-temperature/volume-averaged-temperature = 2.5, and central-density/volume-averaged-density = 1.25.

blesome edge localized modes. During the past year, experiments on Alcator C-Mod tokamak found double-null plasmas to have 15% higher confinement than single-null plasmas. These results are of particular interest to FIRE, since it has the strongest plasma shaping and the only double-null divertor among the proposed burning plasma experiments.

Integrated Modeling of Steady-state ITER and FIRE Advanced Tokamak Modes

A major effort is underway in the U.S. fusion program to develop the computational capability to model burning plasmas. There are two major "state of the art" codes, the Tokamak Simulation Code (TSC) and TRANSP, which are well suited to modeling burning plasmas. High-beta steady-state advanced tokamak modes for ITER and FIRE have been developed using the TSC for integrated scenario analysis. The TRANSP code is used in conjunction with the TSC to incorporate neutral-beam heating for ITER and to provide more detailed information on energetic particle distribution functions for stability analysis of toroidal Alfvén eigenmodes driven by energetic particles using the NOVA-K code.

The "steady-state" high-beta advanced tokamak configurations for FIRE rely on ICRF/Fast Wave on-axis current drive and off-axis LHCD (5 GHz). Off-axis LHCD in FIRE is critical for establishing and controlling the safety factor profile and the LHCD experiments on Alcator C-Mod will be essential for assessing the feasibility of this approach. The TSC simulations of "steady-state" high-beta advanced tokamak discharges on FIRE with 100% noninductive current composed of fast wave, lower hybrid, and bootstrap currents that are sustained for $\approx 4\tau_{CR}$ (where τ_{CR} is the current redistribution time) were reported in the FY03 PPPL Annual Highlights Report. This FIRE scenario has $\beta_N \approx 4$ and about 80% self-driven current with fusion power densities of ≈ 5 MWm^{-3}, which approach the parameters of the ARIES-RS power plant plasma.

Studies of ITER steady-state advanced scenarios are underway using TSC and TRANSP codes. The first scenarios analyzed had approximately 100% noninductive drive with 33 MW of negative-ion neutral-beam injection (NINB) for on-axis current drive and 35 MW of off-axis LHCD (Figure 2). This hybrid-like scenario with beta normalized $\beta_N = 2.5$, bootstrap fraction current $f_{bs} = 44\%$, fusion gain $Q = 5$, and fusion power $P_f = 350$ MW for H98(y,2) = 1.6 is similar to the advanced tokamak scenario developed by the ITER group. Additional optimization of the plasma start-up and the mix of current drive among negative-ion neural-beam injection, fast wave, and LHCD is needed for this scenario to produce a q profile that is flatter or even slightly reversed.

Energetic Particle Effects in ITER and FIRE

Instabilities driven by the gradient of the energetic particle pressure, such as fishbones and toroidal Alfvén eigenmodes (TAEs), are potential threats to alpha-particle confinement in a fusion reactor. A detailed global analysis of different branches of Alfvén eigenmodes using the NOVA-K hybrid code including TAEs showed that they are stable in FIRE $Q = 10$, high-confinement mode plasmas with central plasma temperature $T_0 \approx 12$ keV. A new study of FIRE advanced tokamak plasmas shows weak multiple

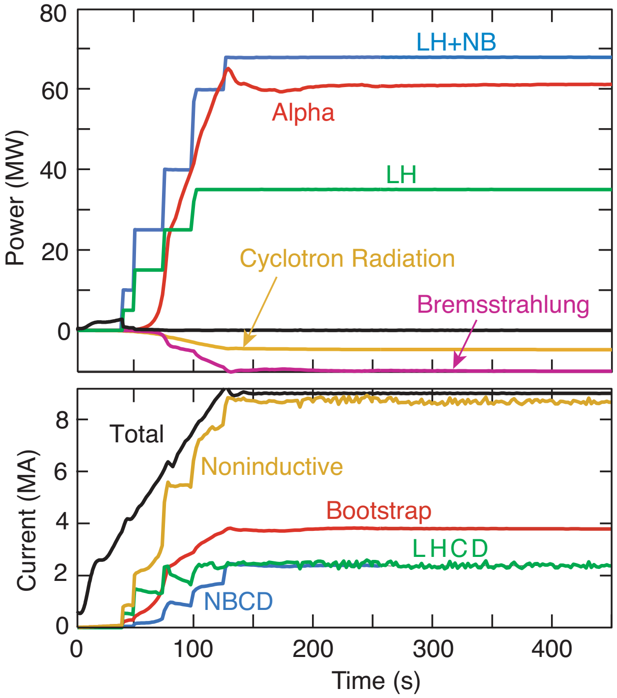


Figure 2. Evolution of steady-state ITER advanced scenario discharge using the TSC. This case has fusion power = 300 MW, fusion gain Q ≈ 5, with 47% of the plasma current driven by the bootstrap effect.

instabilities of TAE modes with toroidal mode numbers n from 6 to 8.

The injection of 1-MeV neutral beams into ITER for plasma heating and current drive introduces sufficient energetic fast ions to destabilize TAE modes. The ratios of the Alfvén velocity to injection velocity of beam ions and to the alpha-particle birth velocity are very similar, about 0.5. The linear universal instability drive of the beam is comparable to the alpha-particle drive, because the phase space density at the particle-wave resonance for a given beta is larger for a beam distribution than for an isotropic distribution. The results of the NOVA-K code stability analysis for the ITER Hybrid-like mode case are shown in Figure 3. Without beam-particle drive the system would be mildly unstable for the plasma temperature ~20 keV. With the inclusion of the beam drive in the NOVA-K analysis, it is found that the system is strongly unstable. As expected, the unstable mode numbers are shifted towards higher toroidal mode numbers in ITER. In both the ITER and FIRE cases, the number of unstable modes is expected to be similar in nominal regimes, so that fast-ion driven transport may be studied in a reactor-relevant case of multiple mode instabilities.

Stabilization of Resistive Wall Modes in ITER and FIRE

Exploitation of the high-beta advanced tokamak operating regime will require the stabilization of resistive wall modes (RWM) when $\beta_N > 3$. Experimental studies of resistive wall mode stabilization using feedback coils mounted inside the vacuum vessel for DIII-D are now underway as part of the PPPL DIII-D collaboration program. Initial results from this program are encouraging. The FIRE

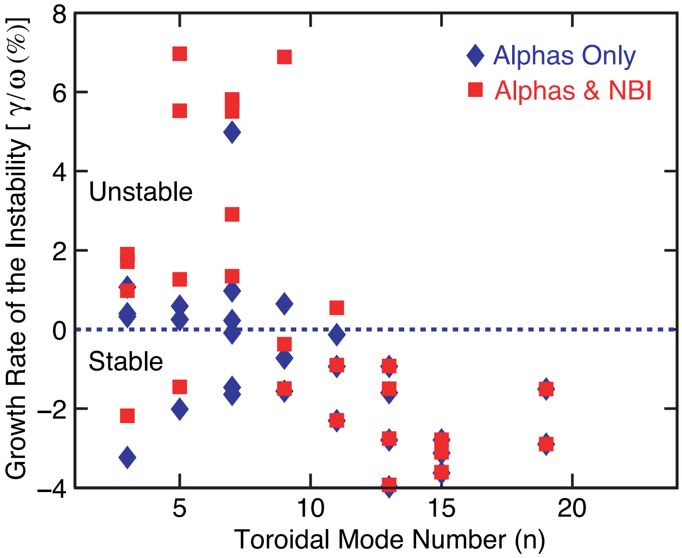


Figure 3. Toroidal mode number dependence of the toroidal Alfvén eigenmode growth rates for cases with the drive from alpha particles only (squares) and with the drive from both the neutral-beam ions and alpha particles (diamonds) in ITER Hybrid-like mode.

design developed the concept of integrating the resistive wall mode coils in the port plug cassettes that fill the mid-plane ports. This approach provides very efficient coupling of the feedback coils, while providing neutron shielding of the coil and the capability to remove the port cassette for maintenance. Stability analysis, using the VALEN code in collaboration with Columbia University, indicates that this approach would provide stability up to $\beta_N \approx 4$ with resistive wall mode coils in every other mid-plane port cassette on either ITER or FIRE.

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Theory and Advanced Simulations

The primary goal of the Theory and Advanced Simulations 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 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 leading to experimental campaigns that improve 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 particle interaction with MHD, and boundary physics. The methods used include analytical theory and numerical codes that are applied to advance the understanding of tokamaks, spherical tori, and stellarators. The goal is to achieve predictive capability relevant to future devices which might be used as energy sources. In addition to the study of magnetic confinement, the Department also engages in research in heavy ion and space plasma physics.

In MHD, recent studies have shown the importance of dissipation in treating resistive wall modes — instabilities which are often responsible for limiting the maximum stored energy. Control of these modes is considered essential for the success of steady-state advanced regime plasma discharges in tokamaks and the spherical torus. Another essential innovation in MHD is the inclusion of a correct kinetic treatment leading to improved understanding based on the hybrid approach in which fluid and kinetic models are synthesized. The hybrid model opens the door to assessing the nonlinear impact of energetic particles in the plasma. This is of importance for estimating alpha-particle confinement in ITER. The Department continues to be in the vanguard of energetic particle physics. The new, nonperturbative NOVA-KN code has been used extensively to analyze the role of $n = 1$ kink type modes on the Joint European Torus (JET).

In the topical area of transport, analytic modeling has advanced the understanding of the Dimits shift, an upshift of the critical ion temperature gradient for the onset of ion-temperature gradient turbulence due to zonal flows. Another study in this area shows the role of nonlinear coupling in turbulence spreading. This represents a new paradigm, as the previous model emphasized linear toroidal coupling. The analytic work of the Department is complementary to the numerical approach, embodied in the gyrokinetic codes GTC and GTC-NEO, which address turbulent and neoclassical transport, respectively. Analysis of the numerical results has played a major role in advancing the understanding of the complex nonlinear phenomena associated with turbulent transport. Modeling of the gas puff imaging experiments on the Alcator C-Mod tokamak (at the Massachusetts Institute of Technology) and the National Spherical Torus Experiment (NSTX) highlights advances in the modeling simulation of neutrals transport as well as detailed simulation of an experimental diagnostic.

The Theory Department has a strong commitment to advancing numerical modeling and has a strong record of achievements in this area. The lead Principal Investigators for two of the U.S. Department of Energy Office of Science "Scientific Discovery through Advance Computing (SciDAC)" Program projects — the Center for Extended MHD Models and the Gyrokinetic Particle Simulation Center — are in the Department. The Department also provides leadership of the Plasma Science Advanced Computing Institute. These activities are seamlessly integrated with the mainline theoretical efforts.

Finally, it is noted that the Department has a strong commitment to supporting theoretical studies of specific relevance to national and international experiments. The National Theory Coordinators for the spherical torus and stellarator are members of the Department. The Department also provides data analysis and interpretation support for the NSTX, the National Compact Stellarator Experiment (NCSX), the DIII-D (at General Atomics), the Alcator C-Mod tokamak, the Current Drive Experiment-Upgrade (CDX-U), the Large Helical Device (LHD) in Japan, the Magnetic Reconnection Experiment (MRX), the Joint European Torus (JET) in England, the JT-60U in Japan, and the W7-AS in Germany.

Significant progress has been made in all the topical areas listed above. All of the major milestones set for FY04 were achieved, including a presidential milestone relating to MHD equilibrium and stability analysis of the W7-AS stellarator in Garching, Germany.

In the following sections, examples of significant progress in the fusion program enabled by scientific results from the PPPL Theory Department are described.

MHD Studies

Sawteeth Simulation and Magnetic Reconnection

Understanding the physics of magnetic reconnection is a longstanding problem in plasma science. In the context of tokamaks this relates to the simulation of sawtooth oscillations, the periodic slow rise and sharp fall of electron temperature in the plasma core within the safety factory $q = 1$ radius. Recent studies using the M3D code to simulate CDX-U plasmas have shown that in the absence of strong perpendicular thermal conductivity, resistive ballooning modes would go unstable in the simulations, swamping the effects of the poloidal mode number $m = 1$ mode, and leading to stochastic magnetic field lines and, presumably, a plasma disruption. However, thermal conductivity values in the experimental range of 200 meters per second stabilize these higher toroidal mode number, n, modes, and then the $m = 1$, $n = 1$ mode dominates. The $n > 1$ modes are driven by the $n = 1$ mode and some stochastic regions still develop during the crash, but these resymmetrize after the crash. Multiple sawtooth cycles have been calculated, but the period is shorter than that experimentally observed.

Halo Currents and Resistive Wall Mode Simulations with M3D

A number of ITER-relevant problems in resistive MHD concern the effects of a resistive wall: vertical displacement events, halo currents caused by plasma disruptions, and resistive wall modes. Simulations of these events have been carried out using the M3D code. Simulations have been done of disruptions caused by large inversion radius internal kink modes, as well as by the nonlinear growth of resistive wall modes. Halo currents flowing during the disruption have asymmetries with a toroidal peaking factor up to about 3. Vertical displacement events have larger growth rates during disruption simulations, which may account for the loss of vertical feedback control during disruptions in experiments. Time-dependent nonlinear three-dimensional simulations have been carried out for the resistive wall modes. The M3D code includes resistive wall boundary conditions, which match the solution inside the resistive wall to the exterior vacuum solution. The exterior problem is solved with a Green's function method, using the GRIN code.

Additional simulations have been made of disruptions caused by resistive wall modes. Simulations were done of several ITER equilibria. The resistive wall simulations necessarily also assumed a plasma resistivity. With nonzero plasma resistivity, the resistive wall mode was found to have a growth rate scaling as $\gamma \sim \eta^{4/9}\eta_w^{1/3}$ where η is the plasma resistivity and η_w is the wall resistivity. Nonlinearly, the modes cause a disruption, with a toroidal peaking factor close to unity. Figure 1 shows the pressure contours during an early and late phase of a resistive wall mode disruption.

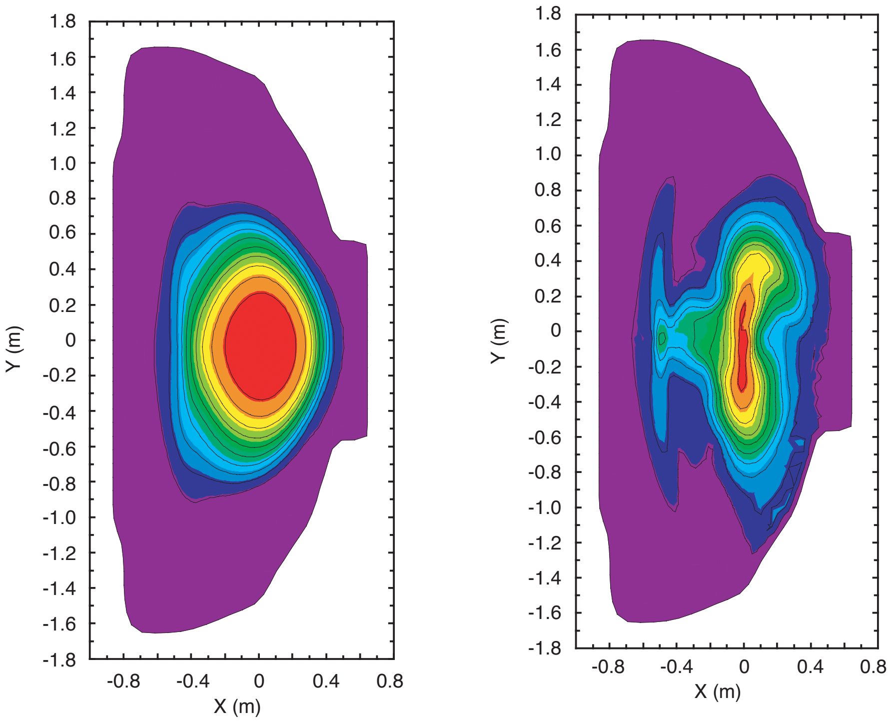

Figure 1. Pressure contours in a poloidal cross section during early and later phases of a plasma disruption.

Hybrid Simulation of Alpha-particle Stabilization of the Internal Kink Mode in ITER

It is well know that energetic particles such as alpha particles produced by the fusion reaction have a significant stabilization effect on internal kink modes due to the fast precession of trapped ions. There have been many studies related to this physics. However, most of the previous theoretical work assumed large aspect ratio and circular flux surfaces. Here, the M3D hybrid code which can treat arbitrary aspect ratio and strongly shaped plasma cross sections such as the ITER configuration has been applied. It is shown that the effects of elongation are important for alpha-particle stabilization of the internal kink.

The alpha-particle stabilization of the internal kink mode is described in the limit of small alpha-particle beta as, $\gamma = \gamma_{MHD} - \beta_\alpha(0)\delta W_\alpha$. Here, γ and γ_{MHD} are the normalized growth rates with and without alpha particles, respectively. The second term on the right represents the stabilization effects of alpha particles with $\beta_\alpha(0)$ being the central alpha-particle beta and δW_α an order of unity numerical factor that depends on the q profile and the alpha pressure profile. Hybrid simulations with the M3D code were carried out to study the stabilizing effects of alpha particles on the internal kink mode for parameters and profiles of ITER. It is shown that plasma shaping has a strong effect on alpha-particle stabilization. Figure 2 shows δW_α as a function of elongation at zero triangularity while all other parameters and profiles are fixed. It is observed that the stabilization effects of alpha particles decreases as elongation increases. At the full ITER shape (elongation = 1.8), alpha-particle stabilization is reduced by a factor of 2.5 as compared to the circular shape case. This result shows that the elongation of plasma boundary is an important factor for alpha-particle stabilization of the internal kink mode, and it must be taken into account for realistic modeling of internal kink stability and sawteeth in ITER.

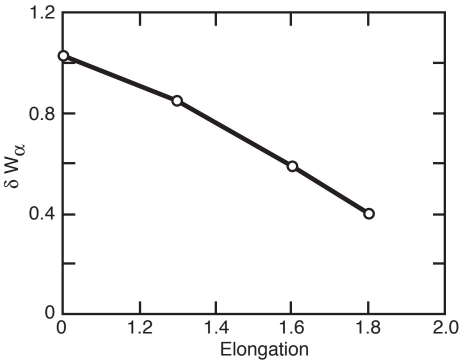

Figure 2. The stabilizing effect of alpha particles on the internal kink mode decreases dramatically with plasma elongation. The δW_α term is an order of unity numerical factor that depends on the safety factor q profile and the alpha pressure profile.

Turbulent Transport Simulations and Analysis

GTC Simulations with Trapped-electron Dynamics Benchmarked against GT3D

The Gyrokinetic Toroidal Code (GTC) has had preliminary nonadiabatic electron effects, including trapped-electron dynamics, implemented into the code since the early part of FY04. The task was accomplished by means of a low-order expansion in the square root of the electron-to-ion mass ratio in the electrostatic circular cross-section limit. This version of the GTC has been applied for benchmarking with the GT3D code of Y. Idomura of the Japanese Atomic Energy Research Institute (JAERI), as part of the PPPL collaboration with JAERI. Initial results for benchmarking of linear growth rates and real frequencies of the ion-temperature gradient modes including trapped electrons and of the trapped-electron modes, showed reasonably good agreement for scans over the toroidal mode number and over the ion-temperature gradient magnitude. The corresponding nonlinear benchmarking of transport coefficients in the nonlinearly saturated regime is in progress.

Velocity Space Nonlinearity

Recent investigations have involved the inclusion of a velocity-space, parallel, nonlinear term in the GTC. Initial results with adiabatic electrons show that this term can enhance the zonal flow and thus reduce the thermal flux, in the nonlinearly saturated state. Enhanced fluctuations of the m/n = 1/0 mode are also observed.

Nonlinear ETG Turbulence

Recent interest in electron-temperature gradient (ETG) turbulence to explain electron thermal transport in tokamak plasmas comes from numerical simulations in flux-tube geometry. In work in collaboration with the University of California at Irvine, the GTC was used to simulate electron-temperature gradient turbulence in an annulus of a DIII-D-sized tokamak, showing that electron-temperature gradient modes saturate by nonlinear toroidal mode coupling. Nonlinearly excited low-n streamers dominate the electron-temperature gradient turbulence, but with a transport level well below that previously found in flux-tube simulations.

Nonadiabatic Electron Response in Turbulent Transport Analysis

The split-weight scheme for particle-in-cell simulations following only the nonadiabatic part of the electron response requires the global solution of Poisson-like equations. The efficiency of the global Poisson solver using finite-element methods has been addressed. Initial results for modes including complete electron response in the electrostatic and electromagnetic regimes were obtained.

General Geometry Capability of the GTC

A general geometry capability with generalized and extended features was developed for the GTC. Application of nonlinear electrostatic simulation to shaped plasmas was begun.

Numerically Calculated Quasilinear Fluxes for Multiple Species

The FULL code can calculate quasilinear particle and energy fluxes for each plasma species as well as linear eigenfrequencies and eigenfunctions. For experimentally realistic NSTX and JET cases with five plasma species, the particle and energy fluxes of each species, normalized by the total energy flux, were calculated as the density and temperature gradients of each species were varied separately. The effects of varying the different gradients were observed, and common trends between the very different JET and NSTX cases were noted.

Zonal Flows in Turbulent Transport

A comprehensive review article of zonal flow phenomena in plasmas including the status of theory, numerical simulation, and experiments, as well as directions for progress in future research was presented for the first time as a theory overview talk at the *20th IAEA Fusion Energy Conference* held in Vilamoura, Portugal, in 2004.

Nonlinear Turbulence Spreading

Analytic understanding of nonlinear turbulence spreading was advanced. Further analytic theory development and comparisons to the GTC simulations, performed in collaboration with the University of California at Irvine and the University of California at San Diego, show that nonlinear coupling rather than toroidal linear coupling plays a dominant role in turbulence spreading and can have a significant impact on edge core coupling.

Zonal Flows

A deeper understanding of the Dimits shift, an upshift of the critical ion temperature gradient for the onset of ion-temperature gradient turbulence due to zonal flows (Figure 3) was achieved by identifying the detailed bifurcation scenario for the transition with the aid of sophisticated techniques from dynamical systems theory.

The understanding of zonal flow dynamics was advanced using analytical methods. A significant advance in the analytic formalism needed to deal with the study of possible interactions between convective cells and the key topic of zonal flow dynamics was achieved. Using a dynamical systems approach, a four-dimensional center manifold is studied and fixed points of its dynamics are identified to predict a "Dimits shift" of the threshold for turbulence due to the excitation of zonal flows.

Further analytic elucidation of transport reduction due to zonal-flow-induced random shearing has been achieved. In the context of both ion-temperature gradient turbulence and interchange turbulence models, a severe reduction in the amplitude of turbulence velocity occurs, while the cross phase is only modestly reduced as in the passive scalar case.

Energetic Particle Physics

The Influence of TAE Modes on Alpha Confinement in ITER-like Plasmas

The study of the toroidal Alfvén eigenmode (TAE) stability and related transport in burning plasma devices continues to be an area of focus, with a new emphasis on ITER. It should be noted that in addition to alpha particles, the planned negative-ion neutral-beam injection in ITER at 1-MeV energy could also drive TAEs strongly unstable. Recent studies of the alpha transport associated with Alfvén modes shows that at an ion temperature above 24 keV strong alpha-particle losses above 5% of confined alphas are expected.

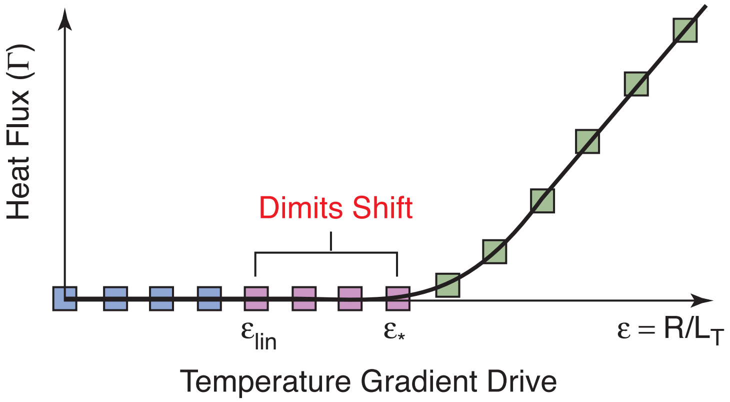

Figure 3. The Dimits shift is an upshift of the critical gradient for onset of ion-temperature gradient turbulence. Previously, this has been identified in numerical simulations; it has now been explained using dynamical systems theory. Here ε_{lin} is the threshold for linear instability and ε_* is the nonlinear threshold for instability. The difference is the Dimits shift.

NOVA-K Code

The NOVA-K code was modified to treat fast particles using a nonperturbative method, overcoming limitations inherent in the delta-f approach. The global NOVA-K code was extended to include fast-particle finite-orbit-width effects in a nonperturbative way. The resulting code, NOVA-KN, correctly treats fast-ion finite-orbit-width coupling with the radial mode structure.

Internal Kink-mode Instabilities in JET

During FY04, the Department initiated a comprehensive study of internal n = 1 instabilities in JET. Studies of n = 1 kink-type modes (fishbones and ideal-kink modes) were conducted by employing the NOVA-KN code to analyze the experimental results in JET and to validate the code against the experiment. Results were used to identify new observations of high precessional frequency fishbones in JET with frequency around 50–80 kHz.

Damping TAE Modes in JET

During the year, a study of the role of continuum damping of TAE modes in JET was initiated. The damping mechanism of the n = 1 toroidal Alfvén eigenmode in JET plasmas was clarified by using a self-consistent kinetic model. It was shown that there is no mode conversion of the MHD toroidal Alfvén eigenmode to kinetic Alfvén waves. The continuum damping near the edge of plasma is found to be a plausible damping mechanism to account for the measured damping rates in JET.

HYM Code

Significant computational advances in the HYM code were made in preparation for numerical applications. The NSTX version of the HYM code and the Grad-Shafranov equilibrium code TKIN were ported to the Seaborg parallel computer at the National Energy Research Scientific Computing Center. Development and debugging of the parallel (message passing interface) version of the HYM code for NSTX studies was performed. The fluid part (MHD) of the parallel HYM code was modified to improve parallel performance and scaling. The new version of the code has nearly ideal parallel scaling for up to 128 processors and achieves a speed of 12 Gflops for modest grid sizes. New diagnostics were implemented in the HYM code, and a new graphically interfaced code was developed to visualize the global Alfvén eigenmode (GAE) mode rotation in the toroidal plane. The resonance between the global Alfvén eigenmode toroidal phase velocity and the Doppler-shifted first ion cyclotron harmonic has been demonstrated.

Alfvén Eigenmodes in NCSX

Alfvén continuum and Alfvén eigenmodes in the National Compact Stellarator Experiment (NCSX) were addressed in collaboration with the Kolesnichenko group. It was shown that modes such as the toroidal Alfvén eigenmode, and others that are noncircularity induced, can be localized for the nominal NCSX plasma.

Fishbone Modes in NSTX

The role of fishbone modes in NSTX was examined. A new kind of instability caused by circulating ions was identified as a “doublet fishbone” mode that has two frequencies. This is a possible model for the observed fishbones on NSTX when the safety factor q at the magnetic axis was greater than unity.

TAE Modes in NSTX

Experimental observations in beam-heated plasma discharges on NSTX, Figure 4(a), show a bursting mode with a wave period that increases as the instability evolves, a phenomenon referred to as frequency "chirping." Nonlinear simulations with the hybrid version of the M3D code have been applied to model this. The frequency chirping is reproduced in the simulations, Figure 4(b), and is caused by the change in the eigenfunction as it moves out radially, Figure 4(c).

Boundary Physics

Validation and Verification of Neutral Gas Simulation using DEGAS 2

The ability to accurately model the flow of neutral gas in the divertor and adjacent pumping ducts of fusion devices like NSTX allows density control mechanisms, such as cryopumps, to be evaluated and optimized prior to use on the machine. To be sufficiently realistic, such models must incorporate three-dimensional details of the geometry of the in-vessel hardware. The DEGAS 2 Monte Carlo neutral transport code is well suited for simulations of this sort, although it had not been previously validated against gas flow experiments. To this end, two sets of three-dimensional validation exercises have been undertaken.

The objective of the first was to benchmark DEGAS 2 against conductances for

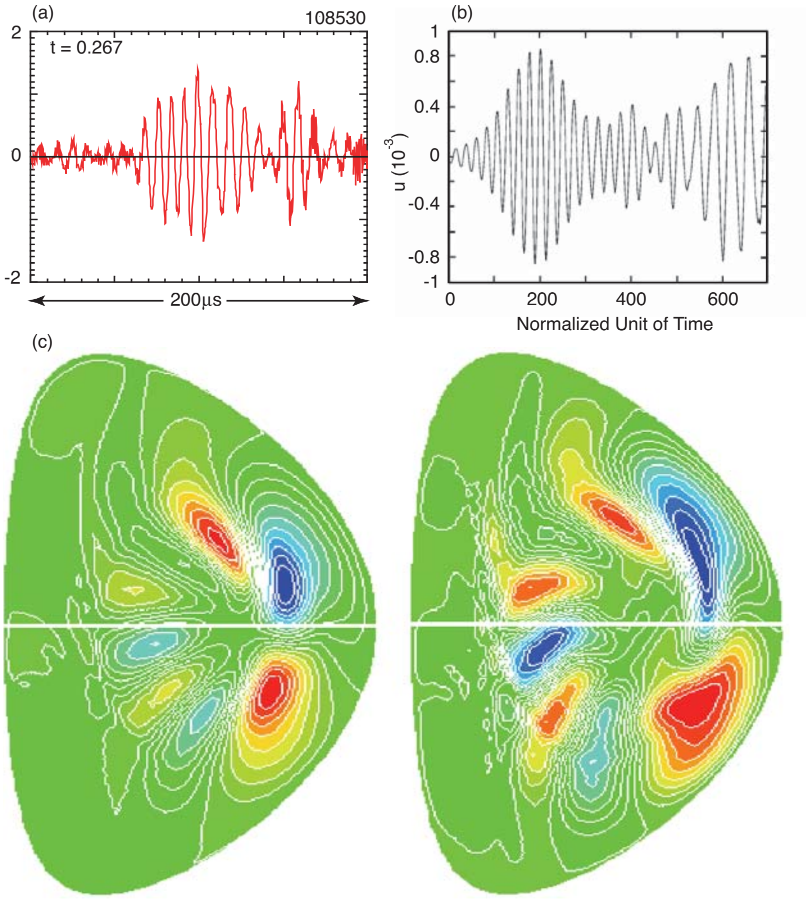

Figure 4. Simulation of bursting toroidal Alfvén eigenmodes modes in NSTX during neutral-beam injection. (a) Experimental signal. Note the change in frequency. (b) The simulation shows a similar frequency downshift. (c) Velocity contours at the linear phase (left) and towards the end of the nonlinear phase (right). The time span in (b) is approximately 330 μs.

gas flow through a pipe obtained from the literature in the limits of low flow rates ("molecular flow regime," molecular mean free path much larger than pipe diameter) and high flow rates ("viscous flow," the opposite limit). The intermediate, transition regime has been less well characterized. Gas flows in fusion experiments are expected to be in either the molecular flow or transition regimes. The DEGAS 2 code simulations in the molecular flow regime gave conductances within 2% of the expected values. Simulations in the transition regime were consistent with a smooth interpolation of the limiting results.

The second benchmark exercise was based on a series of dedicated experiments performed by Brian LaBombard to measure gas conductances through the Alcator C-Mod divertor structure, with and without plasma. The latter were used as the basis for the DEGAS 2 simulations; the physics in this case is the same as in the pipe flow exercise. The geometry was much more complicated, however, as is shown in Figures 5 and 6. In both the experiments and simulations, the pressures in the pumping port containing the gas source and in the main chamber were monitored. The ratio of the gas flow rate to the difference between the two pressures gave the effective gas conductance of the divertor structures. The measured and simulated conductances agreed to within a factor of two; the remaining differences are still being investigated.

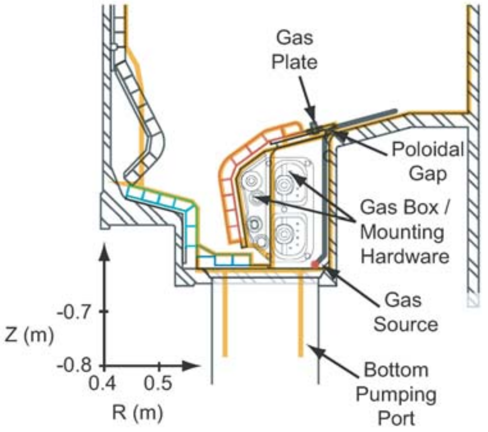

Figure 5. Poloidal cross section of the Alcator C-Mod divertor showing all structures. The tiled surfaces and vacuum vessel are mostly axisymmetric. The ten pumping ports around the device represent the main asymmetry in the divertor. The "gas box" above them is empty and is surrounded on either side by the outer divertor tile "mounting hardware." The "gas source" used for these experiments is provided by a capillary inserted into one of these "gas boxes."

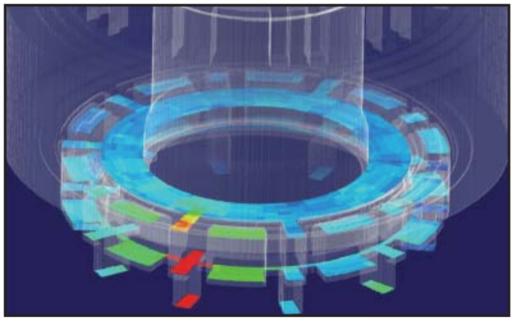

Figure 6. Contours of constant pressure on horizontal slices through a DEGAS 2 simulation. The whitish translucent surface outlines the vacuum vessel and other hardware. The bottom slice is near the top of the bottom pumping port. The middle slice is close to the location of the gas source. The top slice is near the top of the gas box. The highest pressures (red) are in the port containing the source. The lowest pressures (blue) are in the main chamber and in ports far away from the source.

Stellarator Theory

Presidential Milestone Achieved

The exploration of MHD equilibrium and stability in stellarators, including comparison with experimental results, was a milestone in the DOE FY04 fusion budget document. This work has focused on a comparison with results from the W7-AS stellarator in Garching, Germany. The comparison was reported in detail in a talk at the *20th IAEA Fusion Energy Conference* and in an accompanying paper.

Using the PIES code, calculations of the equilibrium flux surfaces corresponding to a series of W7-AS equilibria were performed. The calculations predicted the formation of a stochastic field region at the plasma edge as beta is increased. The experimentally observed beta limit as a function of the current in the divertor control coils was found to correspond to a predicted loss of approximately 35% of the minor radius, or half the plasma volume. The results suggest that the loss of flux surfaces degrade the confinement and limit the achievable beta value. Figure 7 shows the results for two series of PIES calculations scanning beta for a fixed value of the current in the control coils, with the values of beta in the experiment indicated by open circles.

Terpsichore linear MHD stability calculations predict the appearance of m/n = 2/1 instabilities at intermediate values of beta. This is in agreement with W7-AS observations. The instabilities saturate and do not limit access to higher beta values.

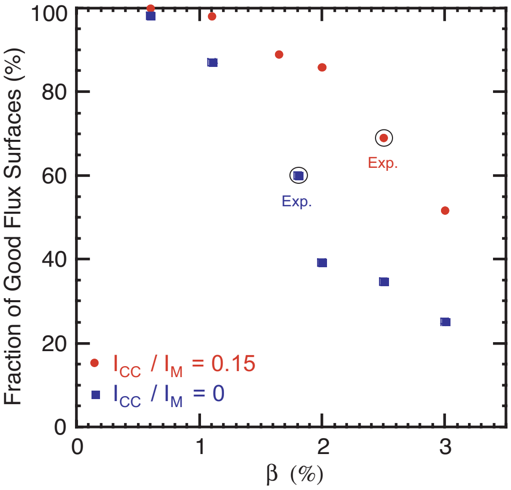

Figure 7. A fraction of good flux surfaces versus β for I_{CC} = 0 and I_{CC}/I_M = 0.15, where I_{CC} is the current in the control coils and I_M is the current in the modular coils.

Modification of the mirror ratio in W7-AS has been found to lead to a bifurcated behavior, with the plasma limited to low beta for some period of time, followed by a period of quiescence and a transition to higher beta. Ballooning stability calculations indicate that the transition corresponds to access to a second stability regime.

Other Progress

An algorithm was developed using singular value decomposition methods to optimize the placement of magnetic diagnostics on NCSX. The algorithm provides an analysis of how much information on plasma equilibria is accessible, in principle, to a "perfect" magnetic diagnostic set, and provides a scheme for determining a realistic magnetic diagnostic set that recovers the maximum amount of available information. Calculations applying the algorithm to the placement of saddle loops on the NCSX vacuum vessel have commenced.

A Monte Carlo transport code was modified to include a spectrum of electrostatic perturbations modeling the effects of turbulence. Calculations show that, while the addition of a fluctuating spectrum to the background fields always enhances transport over neoclassical levels in tokamaks, the fluctuations can sometimes reduce transport losses in stellarators. The conventional assumption has been to treat neoclassical and turbulent losses as additive.

A new computational tool for studying the ballooning stability properties of stellarator equilibria has been further improved and was applied to an analysis of the Large Helical Device in Japan and the W7-AS experimental results in collaboration with those groups.

The theory of the shielding of resonant magnetic perturbations by plasma flow was extended to include the effects of nonambipolar transport in quasi-axisymmetric stellarators. A particularly interesting regime of intermediate ripple amplitude was identified, where the deviation from quasi-axisymmetry is sufficiently small to allow the plasma to flow in the toroidal direction with little viscous damping, yet the deviation is sufficiently large that nonambipolarity significantly affects the physics of the shielding. A reference NCSX equilibrium is predicted to be in this regime. The shielding can be enhanced by this mechanism, with implications for the flexibility of NCSX and for possible start-up scenarios.

In collaboration with the Greifswald group in Germany, the PIES code was used to calculate free-boundary, finite-beta flux surfaces in W7-X (successor to W7-AS), determining the size of the plasma limited by separatrices. The calculations were benchmarked against predictions of the MFBE code.

Spherical Torus Physics

The Theory Department continues its strong support of the NSTX physics program. This is shown by the contributions in analytic theory, physics understanding, modeling, code development support, and comparison of experiment and theory.

Experimental observations have shown that there is an enhanced loss of energetic particles due to MHD modes. This has been successfully explained using the ORBIT code in conjunction with the predicted eigenfunctions from NOVA-K, Figure 8.

Analytic theory development and comparisons to GTC simulations, which were performed in collaboration with the University of California at Irvine and the University of California at San Diego show that nonlinear coupling rather than toroidal linear coupling plays a dominant role in turbulence spreading and can have a significant impact on edge core coupling. This sets the stage for modeling coherent structures near the edge, as observed in the gas puff imaging experiments on NSTX. The FULL code, which calculates quasilinear particle and energy fluxes for each plasma species, as well as linear eigenfrequencies and eigenfunctions, was applied to experimentally realistic NSTX profiles with five plasma species. The effects of varying the density and temperature gradients were studied for each of the species and common trends were noted. The neoclassical particle code with finite-width orbit effects, GTC-NEO, is now being used to obtain results for realistic NSTX cases, which will be compared with standard neoclassical results and with experimental measurements for ion heat fluxes and radial electric fields.

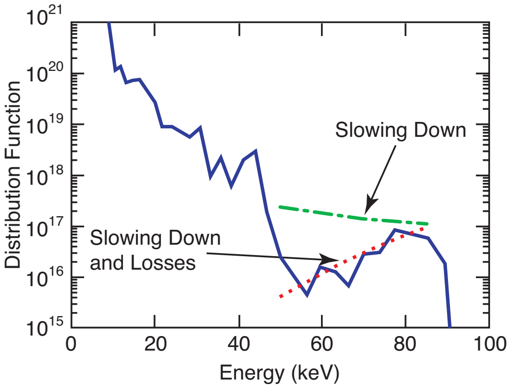

Figure 8. Comparison of the energy spectrum shows the MHD-induced depletion of a part of the spectrum above 55 keV. The theory correctly predicts the difference between the normal slowing down distribution and the observations on NSTX.

Diffusive Transport in Spherical Tori

During FY04, the implication of including full-orbit effects on calculations of diffusive transport in spherical tori was assessed. Calculations of collisional thermal and particle diffusivities in toroidal magnetic plasma confinement devices order the toroidal gyroradius to be small relative to the poloidal gyroradius. This ordering is central to what is usually referred to as neoclassical transport theory. This ordering is incorrect at low aspect ratio where excursions of a particle from its nominal flux surface are much larger than estimated in neoclassical theory, with a consequent increase in radial transport. The correction to the particle and thermal diffusivities at low aspect ratio was calculated by comparing the diffusivities as determined by a full-orbit code, referred to as omniclassical diffusion, with those from a gyro-averaged orbit code. In typical low aspect ratio devices such as the NSTX, the omniclassical diffusion can be up to 2.5 times the calculated neoclassical value. Analytical expressions were obtained which are in good agreement with numerical simulation. It was also verified numerically that the bootstrap current is correctly given by the guiding-center approximation, even when the diffusion is much larger than neoclassical.

Nonlinear Simulations of Bursting TAE Modes in NSTX

During FY04, nonlinear simulations of bursting TAE modes were initiated for comparison with observations on NSTX. The M3D code was used to study neutral-beam-induced MHD. Nonlinear simulations of a bursting TAE show the mode growing and moving out radially. The simulation also shows evidence of frequency chirping, consistent with experimental observations.

Simulation of Experimental Diagnostics

A new code, BST, was developed to aid in the interpretation of X-ray spectroscopy. It uses the experimental profiles with full three-dimensional geometry to reconstruct the observed emissivity (Figure 9).

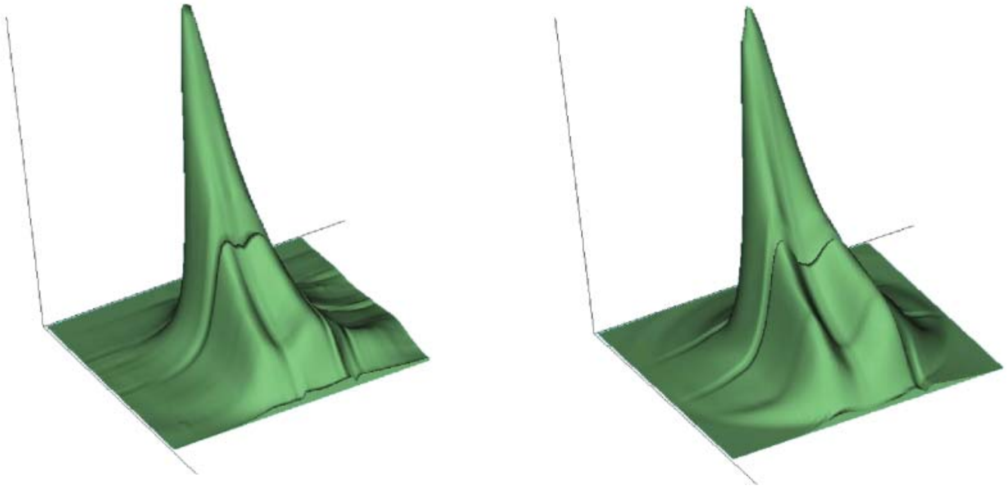

Figure 9. Reconstruction of the soft X-ray emissivity profile of NSTX plasma: left using the fast X-ray camera (64 by 64 pixels and up to 300 frames at the rate 500 frames per millisecond) and right from BST, a new numerical code, created to solve the inverse diagnostic problem in the real three-dimensional geometry of the NSTX plasma.

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Computational Plasma Physics

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

Transport Analysis Service and the FusionGrid

Use of the Transport Analysis Code, TRANSP, increased significantly in FY04. There are now more than 50 FusionGrid TRANSP service users (able to access PPPL TRANSP services remotely over the network), and seven participating tokamak experiments: ASDEX-U (Germany, new in 2004), Alcator C-Mod (MIT Plasma Science and Fusion Center), DIII-D (General Atomics), the Joint European Torus — JET (European Fusion Development Agreement, United Kingdom), the Mega Ampere Spherical Torus — MAST (Culham Laboratory, United Kingdom), the National Spherical Torus Experiment — NSTX (Princeton Plasma Physics Laboratory), and (for predictive studies) the ITER. The PPPL FusionGrid TRANSP service produced nearly 2,700 runs in 2004, up from 1,660 in 2003 (see Figure 1); in addition, a separate production facility at JET, which is coordinated with the PPPL site, produced an additional 2,500 runs. All of the participating experiments used TRANSP code

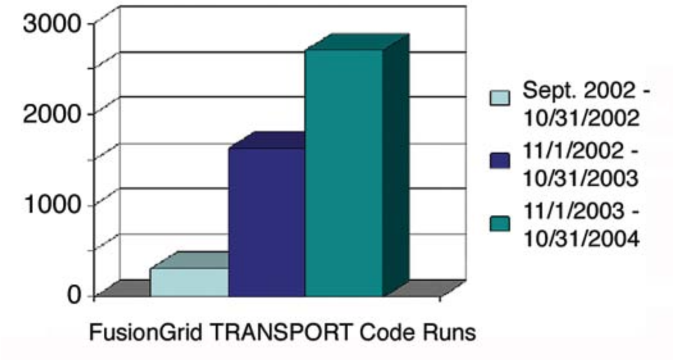


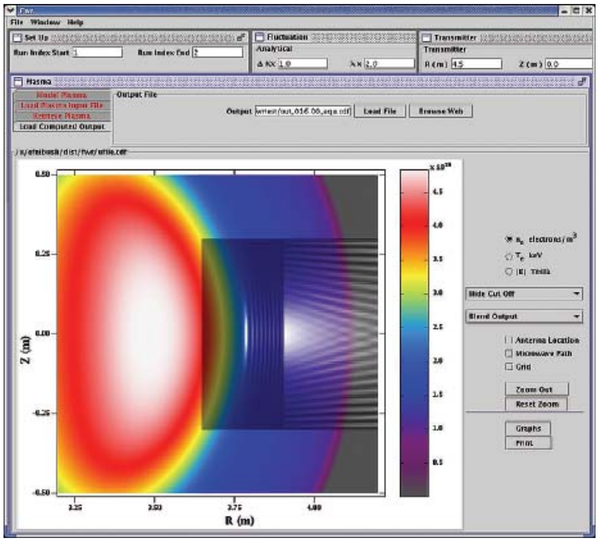
Figure 1. Yearly FusionGrid TRANSP code run production statistics.

results in their presentations at various professional meetings during FY04.

The FusionGrid TRANSP Service replaced disparate deployments of the code at numerous sites. Maintenance and support of distributed versions of this very large software system had proven difficult and expensive. Under the new arrangement, a centralized team of experts supports the code. Production problems are quickly resolved. Problematical runs at the Joint European Torus facility in the United Kingdom can be easily resubmitted to the PPPL system for expert analysis. The FusionGrid TRANSP service is the first operational compute service of the Scientific Discovery through Advanced Computing (SciDAC) National Fusion Collaboratory, (http://www.fusiongrid.org) producer of the FusionGrid. A second code, GATO, is being added to the FusionGrid by General Atomics. The Collaboratory Project is a collaboration among physicists and computer scientists at seven institutions.

Just as the TRANSP run production service is accessible to scientists over the Internet, so are the runs' results. Several tokamak sites maintain MDS+ servers that enable access to experimental data supplemented with TRANSP code simulation results. MDS+ is a network-secure FusionGrid data service developed originally at the Massachusetts Institute of Technology (MIT). The FusionGrid aims to combine secure code services, data services, and collaborative visualization to support effective, geographically dispersed scientific collaboration, as is expected to be needed in future large international fusion projects such as ITER.

A PPPL pilot software project combines all of these elements in the two-dimensional (2-D) Full Wave Reflectometer simulation (see Figure 2). A plasma cross section is input to the simulation. Electron density, temperature, and magnetic field data are retrieved from a TRANSP code run or parametrically modeled by a TRANSP code support tool. The user can graphically set up the antenna geometry and compute areas. Output of the simulation is visualized relative to the input plasma. The system is implemented with a multi-tier architecture: the user interface is a Java applet that runs in a web browser and connects to a servlet that runs jobs on the



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Δ Kx 1.0
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Figure 2. Visualization of two-dimensional full-wave reflectometer simulation.

PPPL cluster. Monitoring is being added to show the progress of long simulations.

The Reflectometry client shares Java-based scientific graphics components with a general-purpose collaborative data display tool, ElVis. This tool, a prototype of which was planned for demonstration at the *2004 American Physical Society (APS) Division of Plasma Physics (DPP) Meeting* in November, enables shared interactive access to graphical displays over a network. It is also used for monitoring of active TRANSP code runs. ElVis details are given in the visualization section of this report.

A new capability of the TRANSP code to analyze the results of predictive simulations, from codes such as the Tokamak Simulation Code (TSC), "as if" these were produced by a live experiment was developed in FY04. This led to the development of integrated ITER simulations for presentation at the 2*004 International Tokamak Physics Activity (ITPA) Meeting* in November, and to a proposal for improvements to the capability, such as making combined TRANSP/TSC capability available as a FusionGrid service.

Fiscal year 2004 was the final year of the National Transport Code Collaboration (http://w3.pppl.gov/NTCC) that created a system for sharing and reuse of code modules developed in the fusion community. In FY04, the PPPL Monte Carlo Fast Ion package NUBEAM, a key TRANSP component, was successfully imported into the ONETWO transport analysis package at General Atomics, and is being used for research.

Adaptive Mesh Refinement Methods for Fusion MHD Applications

Under the auspices of the U.S. Department of Energy Office of Science Scientific Discovery through Advance Computing (SciDAC) Program, the CPPG is collaborating with the Applied Partial Differential Equations Center scientists in the Applied Numerical Algorithms Group at Lawrence Berkeley National Laboratory (LBNL) to develop a structured hierarchical adaptive mesh refinement (AMR) MHD code. AMR is characterized by the efficient placement of meshes to resolve small spatial length scale phenomenon. The AMRMHD code has been used to study pellet injection in tokamaks, magnetic reconnection, and the MHD Richtmyer-Meshkov instability. In the next few paragraphs, the numerical method and the applications are briefly described.

Numerical Method: At present, the AMRMHD code solves the single-fluid resistive MHD equations expressed in conservation form. The hyperbolic fluxes are calculated by a variant of the unsplit method developed by P. Colella of LBNL. The resistive, viscous, and heat conduction terms are treated in an implicit manner. The solenoidal property of the magnetic field is preserved using a projection method. The elliptic equations are solved using a multi-grid technique; a finer mesh is used where there are strong local features. The code is written in C^{++} to manage the higher-level data structures and in FORTRAN for the numerical kernels, and utilizes the Chombo Library developed at LBNL.

Pellet Injection: In pellet injection (a proven method of refueling tokamak plasmas), the process is characterized by the ablation of the pellet (considered well-understood) followed by the large-scale MHD-driven mass distribution. The goal is to understand the latter mechanisms using AMRMHD simulations. Adaptive mesh refinement provides the resolution to resolve the region around the pellet, about three orders of magnitude smaller than the device scale. At present, the differences have been qualitatively reproduced in the high-field-side and the low-field-side launches of the pellet. Current development is to include a flux tube coordinate system to handle shaped plasma (see Figure 3).

Magnetic Reconnection: Single-fluid magnetic reconnection is simulated with a canonical test-bed application whose behavior is relatively well known and useful to test the AMRMHD code. Adaptive mesh refinement is an efficient way to resolve narrow features near the singular current layer (see Figure 4).

Richtmyer-Meshkov Instability: The suppression of the Richtmyer-Meshkov instability (in which a hydrodynamic shock interacts with a density interface) in the presence of a magnetic field has been demonstrated via large-scale AMR simulations. During the early stages of the shock refraction of the density interface, the system of nonlinear partial differential equations has been reduced to algebraic equations that can be solved analytically. A comparison of the numerical solution with the analytical solution is shown in Figure 5. This is an excellent multi-dimensional example of code verification. For further details, visit the website: http://w3.pppl.gov/APDEC-CEMM.

High-order Finite Element for Fusion Applications

Lagrange triangular higher-order finite elements, up to third order, have been

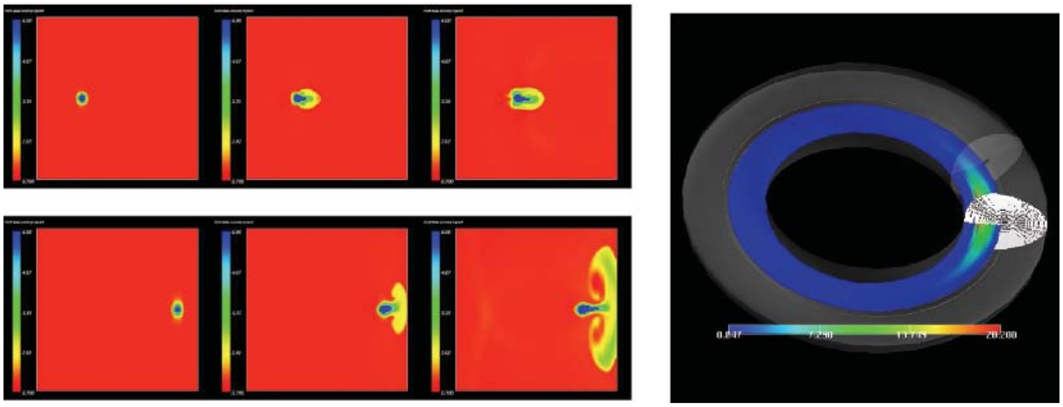

Figure 3. (Left) Poloidal slices taken at the pellet center for high field side (top sequence) and low field side (bottom sequence) launches in pellet injection. (Right) Simulation of the high-field-side pellet injection using a flux-tube coordinate system code. The radial displacement across flux surfaces is apparent in this density image.

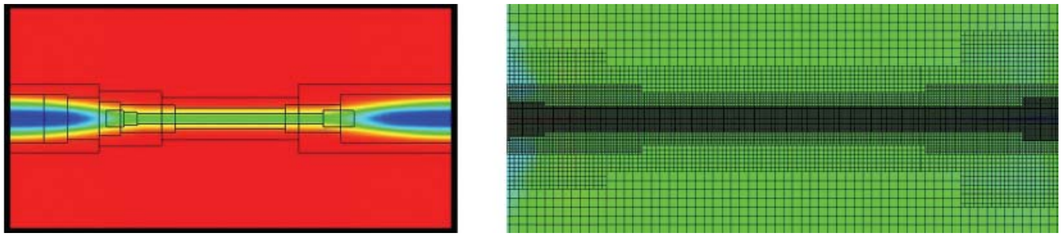

Figure 4. Adaptive mesh refinement (AMR) simulation of magnetic reconnection at S=10^5 (where S is the Lundquist number). The pressure field is shown on the left and the x-direction velocity on the right. The adaptation around the reconnection layer is apparent.

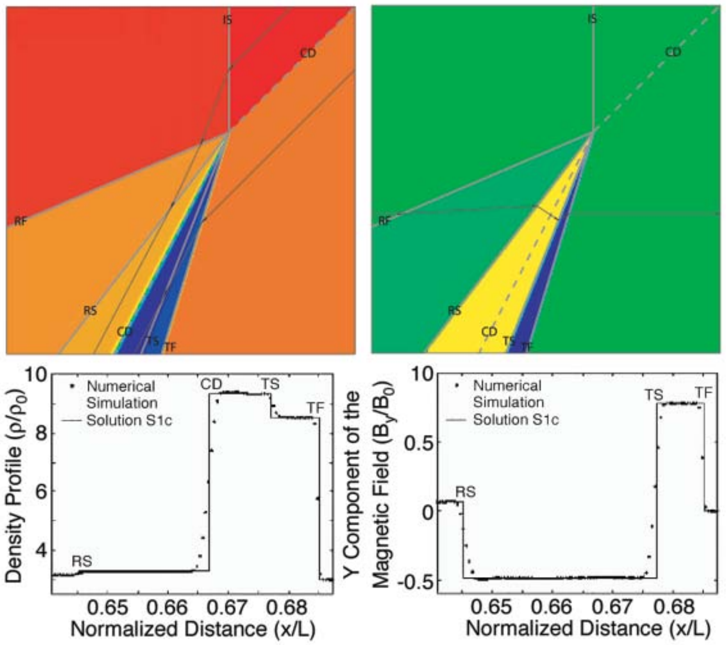

Figure 5. (Top) Analytical solution shown as black lines superimposed upon the adaptive mesh refinement simulation results of the Richtmyer-Meshkov instability during early shock refraction. All the discontinuous waves are in the correct locations. (Bottom) A slice through the refraction region shows good agreement between the analytical and computed results.

implemented as an option in the three-dimensional (3-D) extended MHD code M3D in order to be able to solve highly anisotropic transport problems. It is found that higher-order elements are better than the lower order ones to resolve the thin transition layer characteristic of the anisotropic transport equation, particularly in the limit when the anisotropy ratio becomes very large (Figure 6). It is also observed that in edge plasma modeling, where the solution is likely to have structures highly elongated along the field with steep gradients across it, there is still advantage in aligning the grid with the magnetic field; while in core plasma modeling, where large-scale structures dominate, using higher-order elements clearly yields more accurate results even on misaligned grids.

A second example of the use of high-order finite elements in fusion applications is that of the reduced quintic elements, which are constructed so that the solution is forced to have continuous first derivatives between elements. A test problem, shown in Figure 7, has been constructed where the solution can be obtained analytically, but which is typical of the calculation of heat conduction in a high-temperature plasma with a large anisotropy ratio. The results shown in Figure 7 verify that at least N^{-5} scaling is obtained (where N is the number of elements in each dimension), and that reasonable accuracy can be obtained for anisotropy ratios as large as 10^8 for values of N as low as 60. Note that in the mesh used in these calculations, there was no attempt to align the element boundaries with the magnetic field direction.

Scientific Visualization and Data Management

The CPPG has been working with data from several theory codes, including

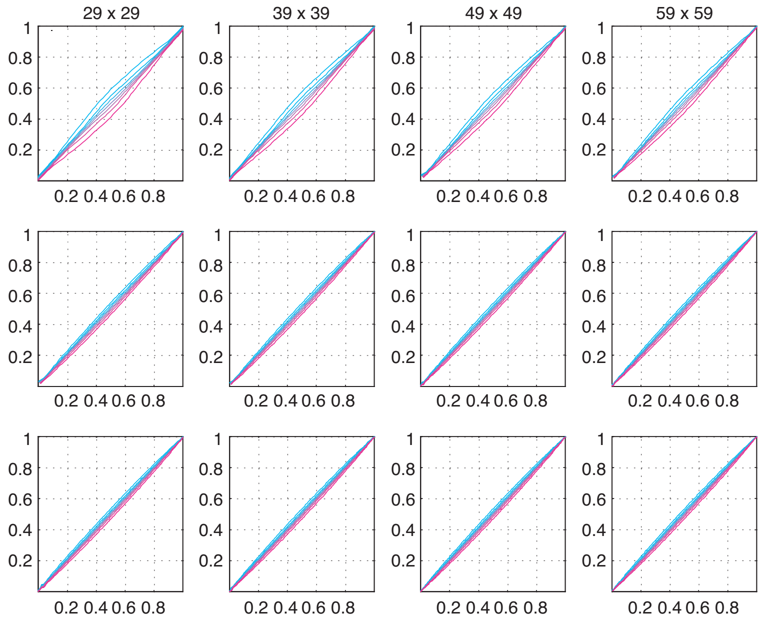

Figure 6: The contour plots of temperature (T) by different grid resolution: 29x29, 39x39, 49x49, and 59x59: (1) Top row: linear elements; (2) Middle row: second-order elements; (3) Bottom row: third-order elements. T=0 at the left and top sides for each square; T=1 at the right and bottom sides for each square. The ratio of parallel to perpendicular thermal conductivity is fixed here at 1,000. The convergence is measured by the profile width, which is the half-width (w) between the contour lines with T=0.25 and T=0.75 along the y direction through the mid-point. The profile width is reduced by finer grids, to some extent (looking from left to right at first row), the higher-order schemes bring in essential improvement (looking from top to bottom for each column) in the convergence.

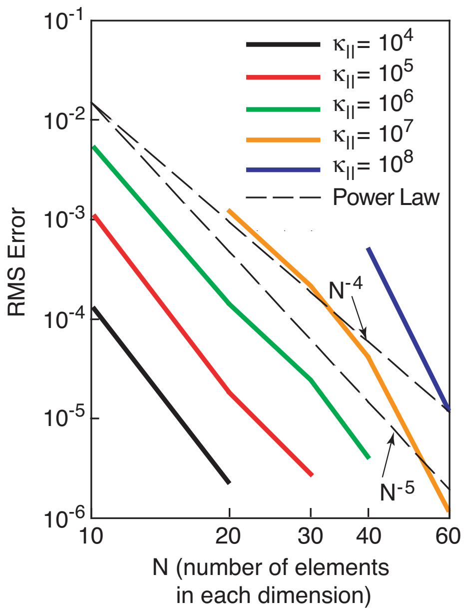

Figure 7. Convergence study shows N^{-5} convergence, where N is the number of elements in each direction, for anisotropic diffusion for the reduced quintic finite elements.

M3D and the Gyrokinetic Toroidal Code (GTC), as well as from experimental analysis codes such as TRANSP and TSC. To accommodate such a wide range of codes, the CPPG has been developing and utilizing several types of visualization software, ranging from ElVis, for code monitoring, to AVS/Express for Integrated Data Analysis and Visualization Environments, to Ensight Gold for parallel visualization running from the display wall software to Kwan Liu Ma's GTC Interactive Volume Rendering Software (courtesy of K.L. Ma). Furthermore, data management strategies are being developed to help assist in the task of handling the large volumes of data which are being moved over to PPPL.

ElVis: The ElVis software, being developed by the CPPG, has now been integrated within the TRANSP code production system. Users can visually monitor the data being computed as a job runs. Their input data is also displayed visually for verification. Data monitoring is fully integrated with the FusionGrid Monitor so users can display their data in a browser and access it on the Internet from anywhere. The National Fusion Collaboratory prepared a demonstration of this visualization capability for data monitoring for the *2004 American Physical Society Division of Plasma Physics Meeting* in November. Recent enhancements allow collaborators to interactively share images and highlight and annotate the graphics, as shown in Figure 8.

CEMM: The SciDAC Center for Extended MHD Modeling (CEMM) is designing an Integrated Data Analysis and Visualize Environment (IDAVE) that will work with all MHD codes (M3D, M3D-C1, NIMROD, AMRMHD), see Figure 9. This work utilizes AVS/Express, and presently has more than ten active users. The major additions to IDAVE were:

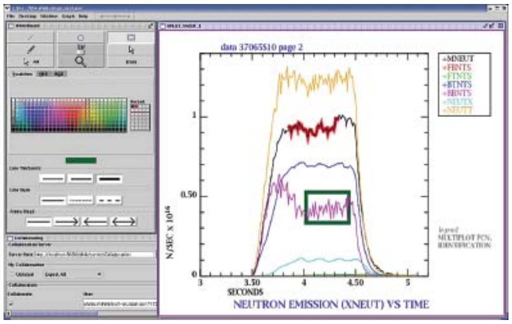

Figure 8. ElVis collaborative visualization — graphics shared over a network.

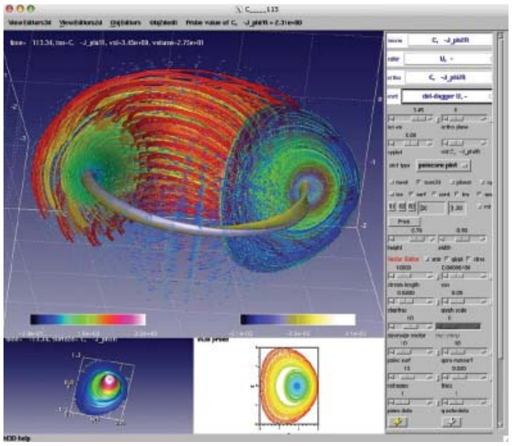

Figure 9. Integrated Data Analysis and Visualization Environment for MHD simulations.

(1) the initial incorporation of the AMR visualization using toroidal geometry; (2) the incorporation of NIMROD visualization into the package; (3) multiple streamlines added inside the 3-D viewer; (4) data management to add the data from complex analysis calculations, such as the puncture plot routine, back into the original data; (5) an increase in the number of supported platforms: now 32-bit linux, 64-bit ADM linux, SGI Altix, Windows, Macintosh OSX; (6) better stability: code can run for days without crashing; and (7) better user interface.

GPS: The SciDAC Gyrokinetic Particle Simulation (GPS) Center has been working with the PPPL visualization team to help define routines that help visualize, analyze, and manage Gyrokinetic Toroidal Code (GTC) data. The work with K. Ma, at the University of California at Davis, has lead to a joint *Institute of Electrical and Electronics Engineers Visualization 2004 Conference* technical paper, "Visualizing Gyrokinetic Simulations." Figure 10 shows the volume visualization that works with commodity-based computers, and illustrates a new visualization approach for the GTC. Traditional isosurface visualization, such as that shown in the shaped plasma in Figure 11, can have a difficult time visualizing the small-scale structures accurately in the GTC.

Initial work has also been done on visually understanding the particle transport in transport turbulence as illustrated in Figures 12 and 13, which show the early and late evolution of the turbulence.

Data Management: In FY04, there were two major accomplishments in data management capabilities. The PPPL Computational Plasma Physics Group worked with scientists at the University of Tennessee, Knoxville, to define netCDF files using logistic networks. This allows researchers to use netCDF application interfaces and write to depots instead of files. This allows research collaborators the ability to access files remotely and efficiently.

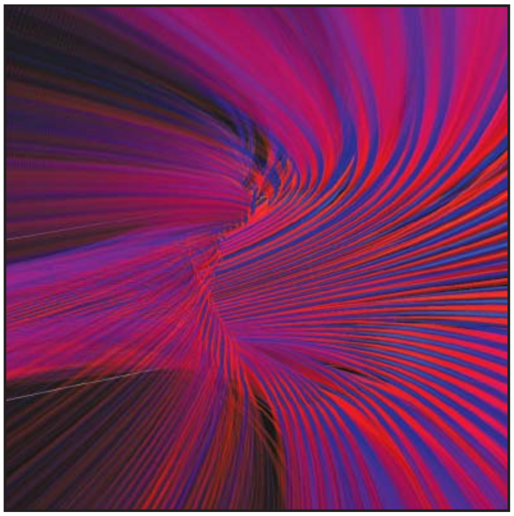

Figure 10. Interactive hardware-based volume visualization for the Gyrokinetic Toroidal Code, GTC.

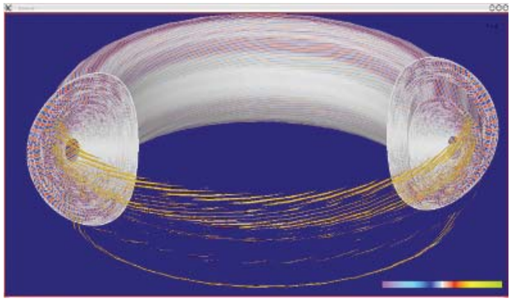

Figure 11. Isosurfaced-based visualization methods for shaped GTC plasmas.

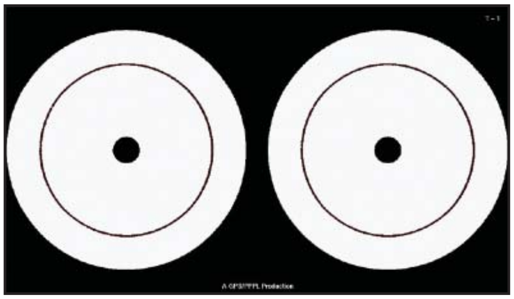

Figure 12. Two Gyrokinetic Toroidal Code simulations showing the scalar potential and the particles that start at a constant radius. As the simulation progresses, the correlation of the movement of the particles by the eddies is shown.

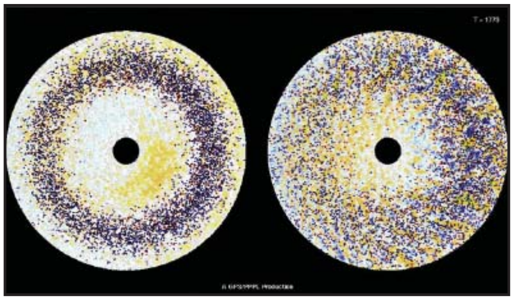

Figure 13. Near the end of the simulations shown in Figure 12, it can clearly be seen that the particles on the right simulation propagate throughout the plasma, compared to the particles on the left.

A threaded parallel data streaming approach was also developed using Logistical Networking to transfer multi-terabyte simulation data from computers at the National Energy Research Scientific Computing Center (NERSC) to PPPL's local analysis/visualization cluster, as the simulation executes, with negligible overhead. Data transfer experiments show that this concurrent data transfer approach is more favorable compared with writing to a local disk and later transferring this data to be post-processed. The algorithms are network aware, and can stream data at up to 97 Megabytes per second on a 100-Megabytes link from California to New Jersey during a live simulation, using less than 5% of the CPU overhead at NERSC. This method is the first step in setting up a pipeline for simulation workflow and data management.

NSTX Collaborative Display Wall: The CPPG has designed and deployed a new collaborative display wall for the National Spherical Torus Experiment (NSTX) control room. Presently there are two high-resolution projectors providing almost three million pixels of data on a 21-foot by 6-foot screen. Researchers can display information on this shared screen by running Virtual Network Computer software. The CPPG is presently working with researchers in the Princeton University Computer Science Department to use some of their research software in PPPL's production environment. Scientists running experiments on the NSTX now use this system on a daily basis, as shown in Figure 14.

Parallel-vector Processor Optimization

In FY04, most of the computational work involving the GTC focused on parallel-vector architectures. The impressive performance achieved by scientific codes on the Japanese Earth Simulator computer in 2002 (26.58 Teraflops, 64.9% of peak) revived interest in vector processors in the U.S. In 2003, the Oak Ridge National Laboratory (ORNL) acquired a system of similar architecture, a Cray X1, which is now fully operational, although much smaller than the Earth Simulator (512 processors versus 5,120), Figure 15.

The CPPG participated actively in a performance study of modern parallel-vector architectures in collaboration with a LBNL/NERSC team lead by their

Figure 14. The National Spherical Torus Experiment display wall.

Figure 15. Modern parallel-vector computers: (left) The Cray X1 at the Oak Ridge National Laboratory (ORNL) and (right) the Earth Simulator in Yokohama, Japan. [Photos courtesy of the National Leadership Computing Facility at ORNL and the Earth Simulator Center/JAMSTEC (Copyrighted), respectively.]

Future Technologies Group. As part of this work, the GTC was ported to both the Earth Simulator and the Cray X1, and extensive optimizations were carried out. Although similar in their low-level inner-workings, the Cray X1 includes an extra level of parallelism, called multi-streaming, which makes the programming more flexible but requires additional optimizations that are not compatible with the more classic vector programming of the NEC SX6-based Earth Simulator computer.

The optimizations implemented in the code resulted in an impressive increase in performance when compared to the current superscalar computers on which GTC usually runs. Although limited to 64 processors at the time of the first visit to the Earth Simulator Center (ESC) in Japan, the results of the test runs showed that both the Cray X1 and the Earth Simulator were running more than 20% faster on 64 processors than on the 1,024 processors of the IBM SP3 at NERSC, when using the same test case.

A systematic comparison with modern superscalar platforms was carried out using the same number of processors in all cases and exercising only the coarse-grain Message Passing Interface (MPI)-based domain decomposition in GTC. The results are shown in Figure 16, where the inverse wall clock time as a function of processor count is plotted for two vector computers, the Cray X1 (ORNL) and the Earth Simulator (ESC), and three superscalar computers, SGI Altix (ORNL), IBM SP Power4 (ORNL), and IBM SP Power3 (NERSC). The vector computers, which

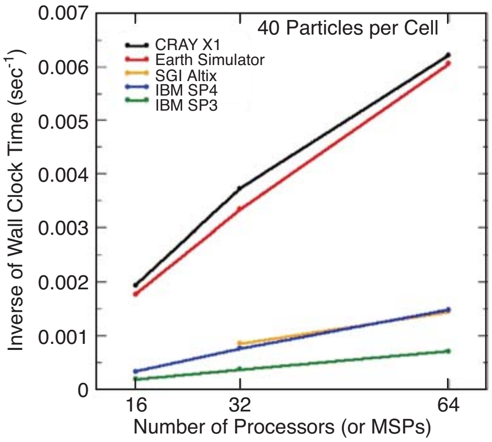

Figure 16. Performance results for a GTC test run on two vector computers and three superscalar computers.

run GTC at almost the same speed, are clearly faster than their superscalar counterparts. Plotting the inverse wall-clock time allows one to observe the scaling while making sure that all the communication latencies and overheads are included. This work was presented at the *Supercomputing Conference SC2004* as part of the LBNL/NERSC team collaboration (http://www.sc-conference.org/sc2004/schedule/pdfs/pap247.pdf).

Although the results were good, the vectorized version of GTC was capable of using only a small fraction of the Earth Simulator's total processor count, which stands at 5,120. The modifications necessary to fully vectorize the code prevented the use of the loop-level shared memory parallelism that allows GTC to make use of more processors than what is possible with its main coarse-grain domain decomposition.

In order to resolve this issue, a new MPI-based level of parallelism was added to the code. Particles inside each geometrical domain are now split between several MPI processors. This allows GTC to reach extremely high statistical resolution by using a very large number of particles.

This new version of the code was ported to the Earth Simulator during the second visit to the Earth Simulator Center in the fall of 2004 as part of the same LBNL/NERSC collaboration. This improved version of GTC achieved an unprecedented 3.7 Teraflops on 2,048 processors of the Earth Simulator supercomputer using 5 billion particles.

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Off-site Research

The Princeton Plasma Physics Laboratory's (PPPL's) Off-site Research Department seeks to answer key scientific questions in magnetic fusion research by working as members of multi-institutional teams and by bringing PPPL's tools and understandings to leading fusion programs worldwide. The resultant teams exploit the synergies of the integrated institutions, using the best facilities and tools for answering the questions. PPPL researchers are partners on integrated teams both at the remote facility and via remote access to the experimental equipment and data. They compare and contrast phenomena at different scales and in different configurations and extend innovations and discoveries to other facilities. They bring PPPL's strengths in experiment design, diagnostics, data analysis, experiment and theory comparison, engineering design, and operations support to the remote collaborations.

D-III-D Collaborations

The DIII-D tokamak collaboration with General Atomics in San Diego, California in FY04 continued to make major contributions toward the development of the advanced tokamak reactor concept through active control of resistive wall modes, fast wave hardware enhancements for plasma current profile control, diagnostic upgrades, and scientific advances for understanding magnetohydrodynamics (MHD), microturbulence, and energetic particle phenomena. PPPL has also been a major contributor to the machine operation, providing mechanical, radio-frequency, and diagnostic engineering support to the DIII-D facility.

MHD Stability

Resistive Wall Modes. In practice, the finite resistivity of the plasma boundary limits the attainable pressure when compared to calculations assuming a perfectly conducting wall. Image currents in a perfectly conducting wall will have the effect of stabilizing certain edge localized modes. Finite resistivity dissipates these image currents, lowering the stabilizing effect of the wall, and giving rise to instabilities that evolve on the current dissipation time scale for the wall — called resistive wall modes (RWMs). To stabilize these modes, a resonant field perturbation needs to be induced using external coils to simulate the image currents in a perfect conductor.

Twelve internal coils (I-coils) are used for the control of resistive wall modes in DIII-D. These coils were initially driven by slow (<500 Hz) high-power switching amplifiers. In a new development, PPPL has supplied fast low-power audio amplifiers to drive the needed current to control the resistive wall modes at high frequency. At present, 400–800 Amperes has been delivered to the I-coils using the audio amplifiers and there is already data indicating the control of resistive wall modes as shown in Figure 1. Future system upgrades include increasing the number of amplifiers for increased current capability, installation of low impedance strip line for higher frequency response, and 12 transformers (one per coil) for optimum impedance matching and power transfer. Operation near a normalized beta of 4.0 has been achieved with the I-coils driven by the audio amplifiers and the external coils driven by the switching power amplifiers.

Shaping and Profile Studies. The maximum pressure that a plasma can sustain is typically set by MHD stability limits. PPPL researchers worked to understand these limits in DIII-D and to predict the optimum operational parameters for achieving the highest possible plasma pressures.

A systematic study of double-null high-beta equilibria in DIII-D revealed that sustained operation above a normalized beta of 4.0 would be highly challenging with the peaked pressure profiles in existing experiments. The conclusion of this study is that achieving high pressure would require careful regulation of the minimum magnetic safety factor, however much higher pressure could be achieved if the plasma pressure profile were significantly broadened. Figure 2 shows the calculated pressure limits in DIII-D advanced tokamak plasmas as a function of the minimum in the magnetic safety factor. The boundary lines indicate the threshold for toroidal mode number n = 1 and n = 3 MHD stability. The analysis indicates that the maximum pressure in the absence of a stabilizing wall decays rapidly with increasing minimum in the magnetic safety factor. However, with the inclusion of a perfectly conducting wall (or a smart wall as with the I-coils) the maximum pressure is set by n = 3 modes. The analysis indicates that the minimum in the magnetic safety factor q_{min} must be maintained in the range $q_{min} = 1.5–1.9$ for a normalized beta $\beta_N > 4.0$.

As part of the Advanced Tokamak Program in DIII-D, efforts were made to identify and produce very high normalized beta plasmas. Even though they

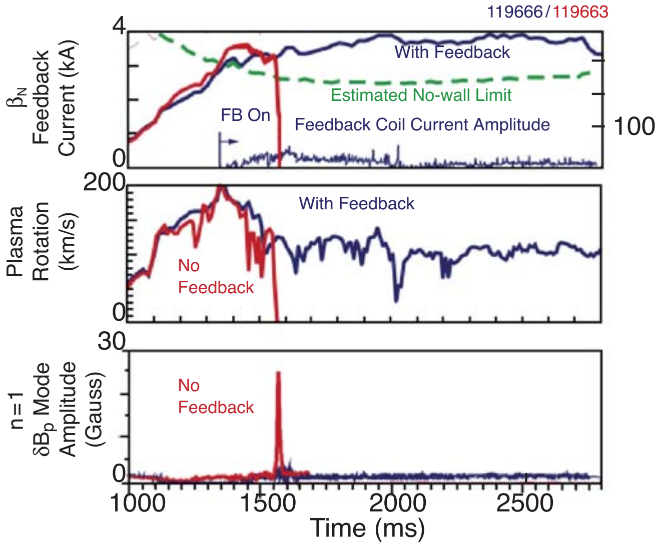

Figure 1. Comparison of DIII-D discharge with audio amplifier feedback (blue) and without (red).

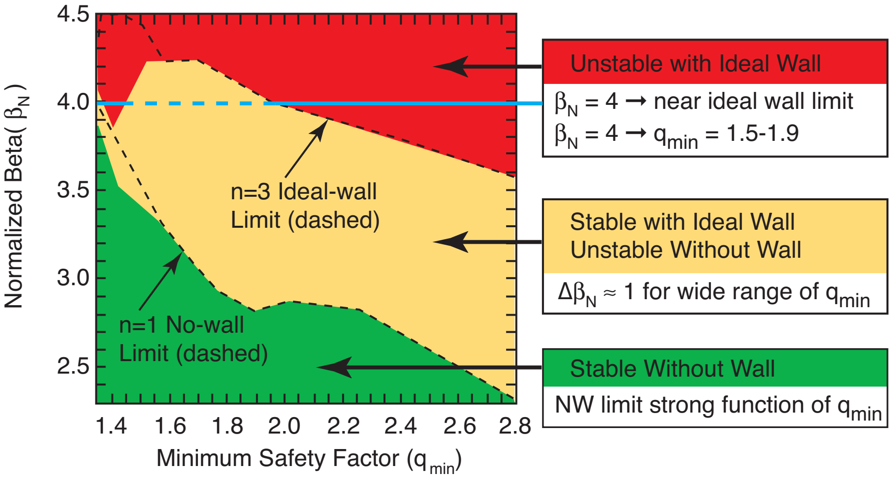

Figure 2. Normalized beta β_N as a function of minimum magnetic safety factor q_{min} in DIII-D advanced tokamak plasmas. The ideal wall limit is set by the upper (n = 3) stability boundary, while the no wall limit is set by the lower (n = 1) stability boundary.

may be transient on the long current diffusion time scale, they would demonstrate that plasma shape and current and pressure profile combinations exist where these pressure limits can be reached. Ideal-MHD stability analysis was performed to examine plasmas at $\beta_N = 5$. The location of the minimum safety factor, the pressure profile, the plasma current, and toroidal field were varied. It was found that flat q-profile plasmas similar to those achieved in present experiments can be made stable to n = 1, 2, and 3 modes for an ideal conducting wall. Ideal-MHD stability results indicate that larger radius of the minimum magnetic safety factor, more peaked pressure, and higher current have the best stability behavior for $\beta_N = 5$.

Edge-localized Modes. Edge-localized modes (ELMs) are an unwanted phenomenon at the boundary of a fusion plasma that lead to high concentrations of power deposited on material surfaces. These surfaces can be severely eroded, and so the control of the edge-localized modes or their influence on the material surfaces is a subject of great importance to fusion research. Much effort has been devoted by the fusion community toward understanding the physical mechanisms that lead to edge-localized modes and devising methods for preventing them. PPPL's Off-Site researchers are studying the role of scrape-off-layer current (SOLC) in the edge-localized mode phenomenon. Scrape-off-layer currents are currents that are detected in the material wall. These are usually nonaxisymmetric, and a key question being addressed is whether the magnetic field from these currents in the wall significantly affects the onset and evolution of the edge-localized mode.

Fast Wave Heating and Current Drive

A key element of PPPL's mission on DIII-D is to effectively couple fast waves into advanced tokamak plasmas for heating and current drive. Advanced tokamak research seeks to replace inductive (finite duration) currents with steady-state non-inductively driven current. Rapid progress has been made in restarting the fast-wave systems on DIII-D. Presently, 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. Duration and power are expected to increase next year, along with efforts to couple power into advanced tokamak plasmas. Figure 3 shows the application of fast-wave power into a DIII-D plasma together with analysis indicating significant coupling of the fast waves to the beam ions.

Confinement and Transport

The maximum attainable plasma pressure within a particular magnetic geometry (before the onset of MHD instabilities) depends critically on the form of the pressure, current, and rotation profile. These are not predefined; instead they are determined by internal processes in the plasma in response to sources of heat, particles, and momentum. How the plasma responds to these stimuli is typically attributed to binary collision processes (neoclassical diffusion) and microinstabilities (so called anomalous transport). Understanding and predicting transport processes in plasmas is one of the major challenges in fusion science.

Rotation plays a critical role in high-performance fusion plasmas, including the suppression of turbulence, the formation of internal transport barriers through **E**×**B** shear, and the stabilization of both resistive wall modes and neoclassical tearing modes. However, momentum confinement remains a poorly understood topic in fusion plasmas. Neoclassical theory provides predictions for the poloidal rotation, and hence experimental verification of these predictions is highly desirable. Nonetheless, progress in this particular area has been hampered by complications in the interpretation of charge-exchange measurements, specifically, distinguishing the apparent velocity caused by atomic physics phenomena from true plasma rotation.

A set of new diagnostic charge-exchange views was designed and installed on DIII-D to try to address some of the uncertainties caused by the atomic physics issues. Using this upgraded system, poloidal rotation profiles were measured in

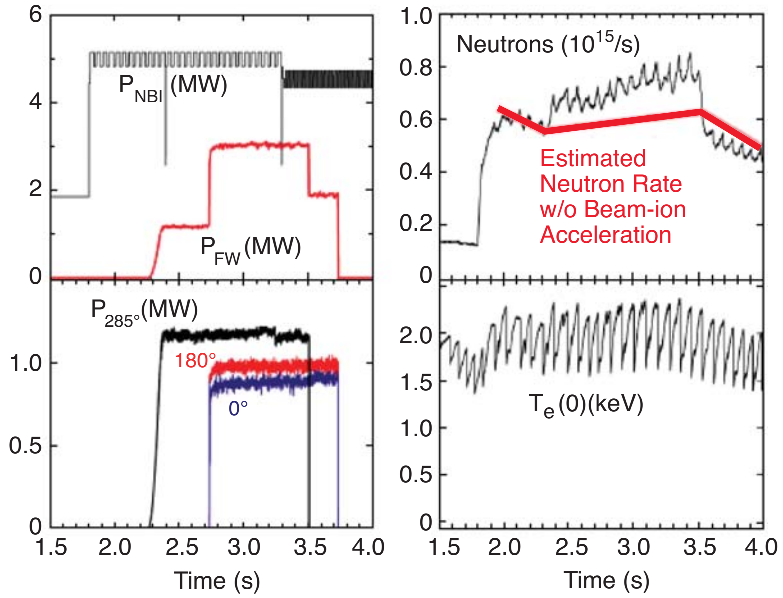

Figure 3. Application of 3 MW of fast-wave power (top left) for one second in a DIII-D plasma. The predicted neutron emission underestimates the measured value (top right). The phase of the three fast-wave antennas is given (bottom left) and the central electron temperature is shown (bottom right).

quiescent high-confinement mode (QH-mode) plasmas, and the experimental results were compared with theoretical predictions from the code NCLASS, which calculates the neoclassical transport properties of a multi-species plasma. Significant disagreement was found between the theoretical and experimental profiles. In fact, the experimental poloidal rotation was determined to be an order of magnitude larger than the NCLASS prediction, and the rotation was in the opposite direction. This large discrepancy in the poloidal rotation leads to significantly different inferred radial electric fields (the radial electric field is determined from force balance), depending on whether the measured or predicted poloidal rotation profile is used. The motional Stark effect (MSE) measurements give radial electric fields that agree better with the result obtained using the measured poloidal rotation profile than the NCLASS prediction. Interestingly, the turbulence (as measured by beam emission spectroscopy) appears to propagate poloidally at the same **E×B** velocity when the experimental poloidal rotation data is used in the force balance equation (Figure 4). Additional diagnostic charge-exchange views are planned for installation in FY05 for improved cross-section measurements.

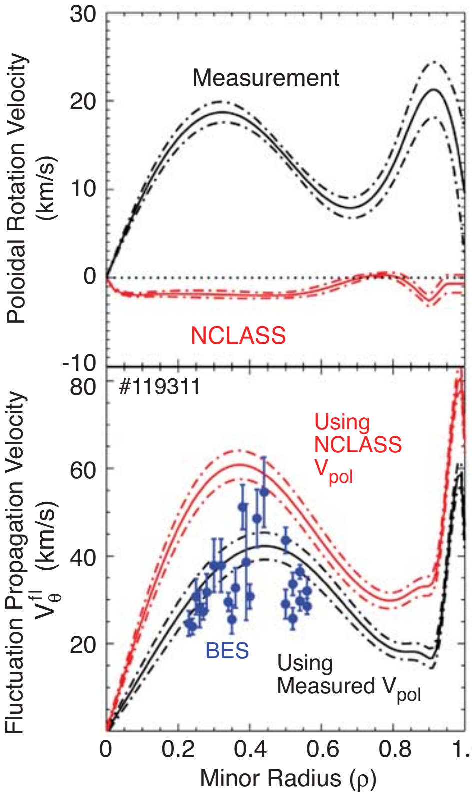

Figure 4. Inferred poloidal rotation and E×B velocity (black) versus NCLASS code prediction (red) plotted against minor radius (ρ). The E×B velocity is also inferred from beam emission spectroscopy (blue).

Energetic Particle Physics

A key issue to address in fusion science is whether large numbers of shear Alfvén waves can be excited in a burning plasma experiment such as ITER and whether the excitation of these oscillations can significantly affect the alpha-particle distribution. This year saw a revolution in the understanding of such instabilities with the observation of a "sea" of Alfvén eigenmodes in the DIII-D tokamak plasma. These modes are observed in the core of weak and reverse magnetic shear plasmas and are not observed on external magnetic probes. They are only observed using core density fluctuation diagnostics. They are readily excited by suprathermal ions traveling well below the Alfvén speed, and they appear with toroidal mode numbers (n) in the range relevant to fusion reactors: n = 5–40.

Figure 5 shows a spectrum of such modes excited in a DIII-D tokamak plasma, obtained from far-infrared (FIR) scattering measurements. The range of excited modes is similar to that expected in a fusion reactor driven by 3.5-MeV alpha particles. The observation of so many modes allows fusion researchers to assess the physics of such a sea of Alfvén eigenmodes which are predicted to occur

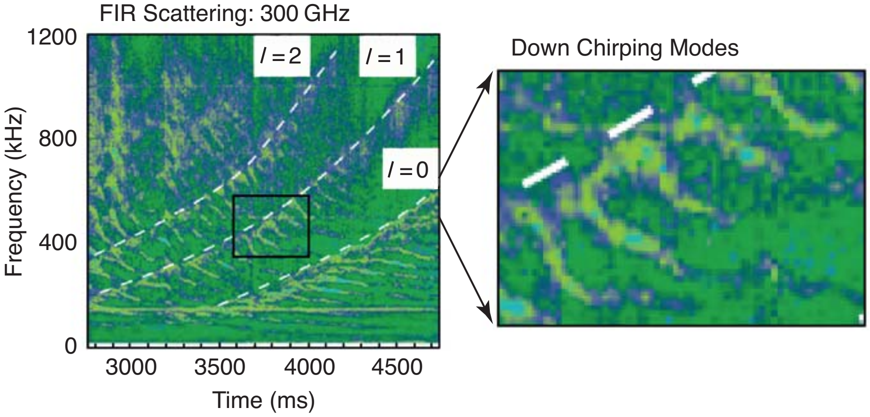

Figure 5. Far-infrared (FIR) spectrum of core fluctuations shows high-frequency bands (*l* = 0, 1, 2) of Alfvén modes extending up to 1,200 kHz. Each band is made up of individual frequency chirping modes (right).

in a future burning plasma experiment such as ITER.

Alpha Channeling. The presence of abundant energetic alpha particles from deuterium-tritium (D-T) fusion reactions is a special feature of a burning plasma. Normally, these alpha particles are expected to heat the electrons, which then transfer their energy to the ions through collisions. However, electron transport is poorer — generally speaking — than ion transport, and so it would be beneficial if a method was found to deposit more of the alpha-particle energy directly to the ions. This is called alpha channeling.

Alpha particles can excite various waves that travel at the Alfvén speed. These waves can affect the properties of the alpha-particle distribution in the plasma; they can eject the alpha particles before they have a chance to heat the electrons, or they can actually have a beneficial effect such as alpha channeling. PPPL researchers have demonstrated in DIII-D that the redistribution of energetic ions (neutral beam ions in this case) by the Alfvén instabilities they excite can produce a quasi-steady-state broad current profile essential for the advanced tokamak concept. If this can be accomplished in a burning plasma, then it could relax the need for additional auxiliary power in order to maintain the plasma current profile.

Operations Support

PPPL continues to provide valuable on-site support of tokamak operations on DIII-D. In addition, PPPL has undertaken the role of supporting the operation of the fast wave systems on DIII-D in collaboration with General Atomics and Oak Ridge National Laboratory researchers.

Alcator C-Mod Collaborations

In FY04, PPPL research collaboration on the Alcator C-Mod tokamak at the Massachusetts Institute of Technology (MIT) continued to advance understanding of the behavior of plasmas in areas key to ITER and to improve the attractiveness of the tokamak as a possible fusion reactor. PPPL scientists participate in experiments as integrated members of the research and operations team. Core teams at the PPPL provide theoretical support, data analysis and modeling, and coordination with other PPPL research endeavors through the Laboratory's Science Focus Groups. In addition, PPPL provides a team of engineers and technicians for the design and construction of upgrades and for technical support at Alcator C-Mod.

Research accomplishments in the areas described below were particularly significant in FY04.

Advanced Tokamak Studies

These studies are aimed at the achievement of enhanced plasma confinement predicted by modeling of advanced tokamak parameters. This will provide information for the extension of the already successful tokamak concept toward an attractive reactor. It is planned to achieve these parameters through modification of the plasma current profile with the application of off-axis lower hybrid current drive and the application of on-axis ion cyclotron range of frequencies (ICRF) fast-wave current drive; the plasma pressure profile will be modified through the application of high-power ICRF on- or off-axis heating.

The proposed lower hybrid power system utilizes the 4-MW 4.6-GHz system originally used on Alcator C-Mod, and subsequently used on the Princeton Beta Experiment-Modification (PBX-M) tokamak at PPPL. The Laboratory has designed and fabricated a lower hybrid launcher (Figure 6), procured new high-power phase shifters/splitters, and will participate in performing integrated commissioning and testing of the entire system. The Massachusetts Institute of Technology has provided a suitable location for the equipment, the high-voltage power system and controls, water and energy supply, and the installation labor. At the end of FY04, repairs of the microwave coupler's ceramic window assembly, damaged in FY03 during commercial removal of improperly electroplated copper, were nearing completion at MIT.

Modification of the current profile, whether by fast wave current drive, mode conversion current drive, or lower hybrid current drive, requires a measurement of the resulting current profile for analysis. This will be achieved through the motional Stark effect diagnostic. The motional Stark effect optical system, electronics, and software have been supplied

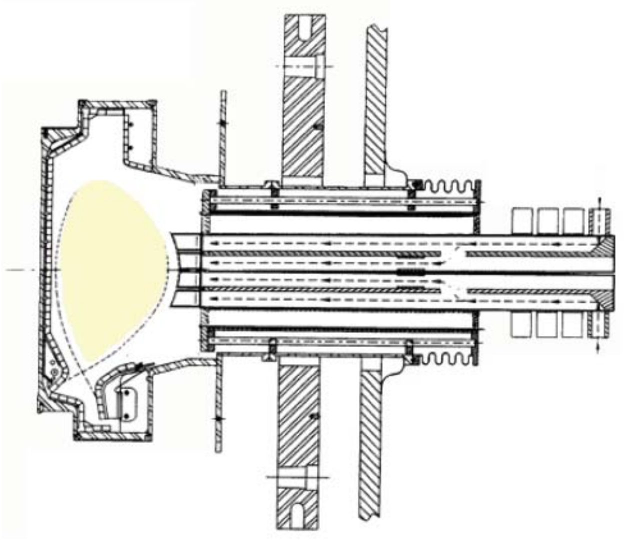

Figure 6. Cross-sectional diagram of the lower hybrid launcher on the Alcator C-Mod tokamak.

by PPPL; the diagnostic neutral beam generating the signal is supplied by MIT. Initial measurements of magnetic pitch angle have been made, and extensive in-vessel calibrations (Figure 7) and analysis have been performed to derive accurate current distributions from them.

Burning Plasma Studies

The Alcator C-Mod experiment is unique in the tokamak community because it relies solely on radio-frequency wave heating as a source of auxiliary heating and current drive power.

In the area of high-power ICRF plasma heating and current drive, the goal is to use the increased heating power and current-drive capability to expand the Alcator C-Mod physics operating regime and enable understanding of a wider range of plasmas, especially relevant to the high-field approach to burning plasmas. More generally, it is desired to increase the understanding of the physics of ICRF heating and current drive at high power.

Alcator C-Mod's high multi-frequency auxiliary heating power allows heating of the core of internal transport barrier confinement modes produced by simultaneous off-axis heating. Following systematic antenna improvements in FY04, the ICRF heating power was brought up to 6 MW for 0.35 s (Figure 8) and 5 MW for 1.0 s.

Since Alcator C-Mod is a diverted tokamak with plasma shape control, a comparison of plasma performance for single-null versus double-null discharges (Figure 9) as input to the ITER physics base was done. The double-null discharges were found to have a systematic 10–15% increase in H-mode confinement (Figure 10).

Wave-particle Studies

The interaction of radio-frequency waves with the plasma components can result both in localized plasma heating and the generation of a locally driven current. Understanding the basic physics processes will allow extrapolation of these results into the reactor-grade plasma regime. The ICRF heating studies investigate various aspects of heating mechanisms including comparisons of the heating efficiency of strong single-pass absorption heating [hydrogen minority ion species in a deuterium majority D(H)] with weak single-pass absorption heating [helium-3 minority in a deuterium majority D(^{3}He)]. Also there is a rich

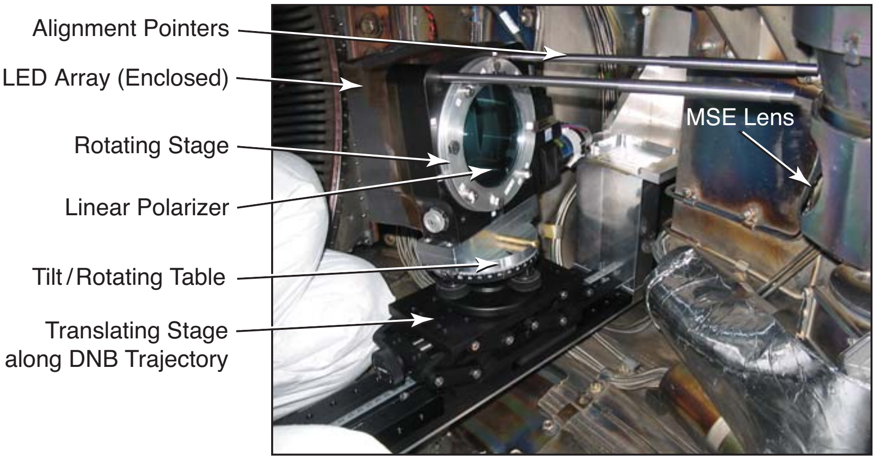

Figure 7. Photograph of the optical equipment used during the in-vessel calibration of the motional Stark effect diagnostic.

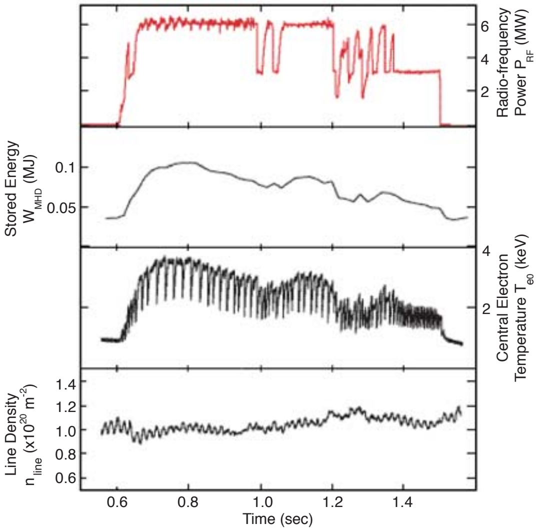

Figure 8. The achievement of 6 MW of ICRF radio-frequency heating power into the Alcator C-Mod plasma.

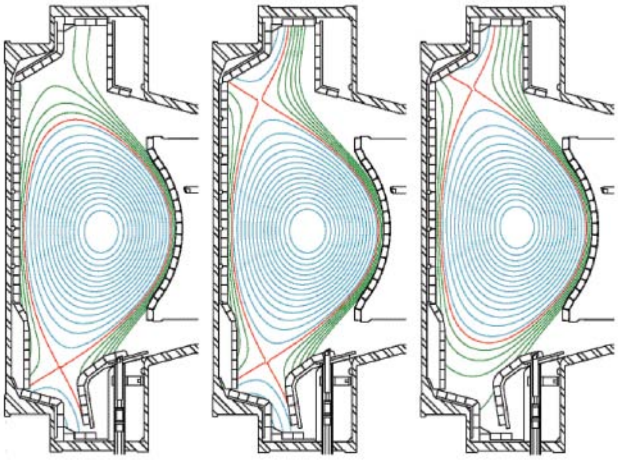

Figure 9. Reconstruction of the plasma magnetic flux surfaces for (left to right) lower single-null, double-null, and upper single-null diverted discharges in Alcator C-Mod. (From B. LaBombard, MIT.)

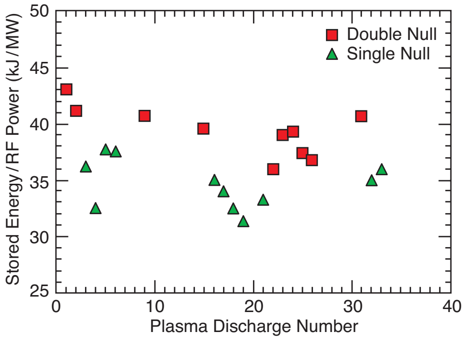

Figure 10. Ratio of the plasma stored energy to radio-frequency heating power for a series of interspersed single-null and double-null diverted discharges in Alcator C-Mod. (From E. Marmar, MIT.)

spectrum of phenomena associated with fast wave mode conversion.

Launching an ICRF-directed wave allows plasma current to be driven by fast wave current drive (core) and mode conversion current drive (off-axis). This allows the further exploration of plasma rotation with directed waves without external momentum input and the study of flow shear suppression of turbulence through off-axis mode conversion current drive. It will also be used in an attempt to form an internal transport barrier through flow shear generation and to develop the capabilities to control the radial electric field through toroidal rotation.

Existing Alcator C-Mod ICRF diagnostics assist in these studies. These include phase contrast imaging to measure density fluctuations, radio-frequency probes, microwave reflectometry to measure edge and pedestal density profiles, and optical and X-ray spectroscopy to measure H/(H+D) ratios, impurity behavior, and plasma rotation.

Although the electrical performance of the ICRF antennas has, in general, been satisfactory with the achievement of 6-MW power with the boron nitride protection tiles, these tiles have demonstrated mechanical fragility and are being replaced with molybdenum tiles (Figure 11).

PPPL scientists have participated in the experiments and modeling of the physical processes involved in the mode conversion of a launched fast wave into both an ion cyclotron wave and an ion Bernstein wave. PPPL researchers have also participated in experiments that have observed changes in the sawtooth period with changes in antenna phasing for on-axis H-minority heating conditions. Core localized Alfvén modes have been observed and studied in high-power ICRF experiments (Figure 12). Their analysis is based on the use of the PPPL NOVA-K code.

Transport Studies

Studies of plasma transport compare the results of careful measurements with a variety of models to gain insight into the effect of plasma turbulence on transport. The relationship between marginal stability and turbulence involves the comparison of data from all the Alcator C-Mod fluctuation diagnostics with nonlinear gyrokinetic simulations using the codes GS2 and GYRO. Insight into electron transport is gained by measuring electron gradient scale length to high precision and comparing experimental and theoretical dependencies of the electron temperature gradient on variation of important parameters, such as the safety factor (q) profile. Transport processes in-

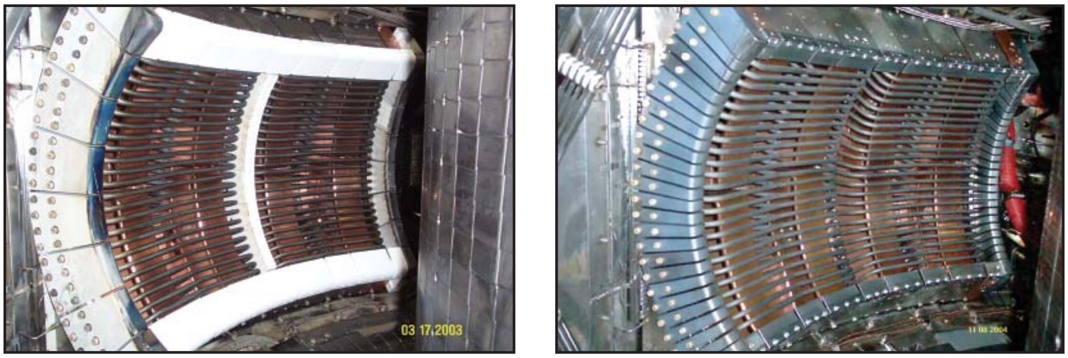

Figure 11. The four-strap ICRF antenna with its former insulating tiles (left) and its new all-metal protection tiles (right).

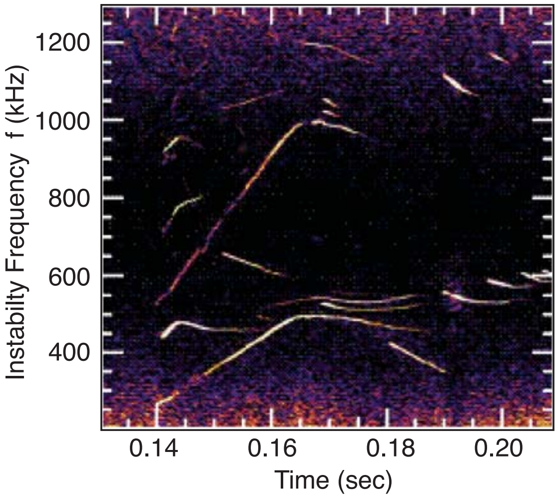

Figure 12. High-frequency plasma instabilities (core localized Alfvén modes) observed during plasma ramp-up with high-power radio-frequency heating. (From S.J. Wukitch, MIT.)

volved in the formation of internal transport barriers are modeled with the GS2 (Figure 13) and possibly GYRO stability codes.

Extensive discussions with the Alcator C-Mod team have produced two ideas for experiments designed to elucidate the role of microturbulence. Tools for preparing input for the GYRO turbulence simulation code have recently been extended to extract the needed input from TRANSP simulations of Alcator C-Mod plasmas. Gyrokinetic simulations of plasma turbulence with the GS2 code were continued to examine H-mode radio-frequency-heated plasmas that exhibit internal transport barriers. Nonlinear calculations have also been started.

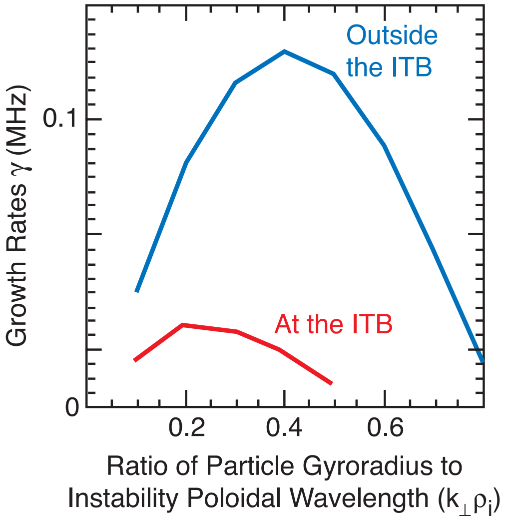

Figure 13. Modeling of internal transport barrier processes with linear GS2 code calculations shows that at the internal transport barrier onset time, long-wavelength drift modes are not strongly growing at or to the inside of the barrier location.

A new X-ray crystal spectrometer built in conjunction with the Korea Basic Science Institute has been installed on Alcator C-Mod to measure the Doppler shift of helium-like neon and determine poloidal and toroidal rotation of the plasma edge.

Plasma Boundary Studies

During FY04 an additional fast camera with as short as 4-μs exposure time and 300-frame capability was added to Alcator C-Mod allowing improved edge turbulence (blobs) visualization to increase the measurement of edge turbulence growth and motion. Evaluation of the velocity field of turbulent motion in the edge was performed, showing dominantly outward radial motion outside the separatrix and dominant poloidal motion inside the separatrix (Figure 14). Comparison of edge turbulence behavior with modeling by the Risø group is in progress.

Hardware Upgrades

Alcator C-Mod hardware upgrades during FY04 included both plasma control and diagnostic components. There were ongoing improvements to the 4-strap ICRF antenna for plasma heating and current drive. A lower hybrid current drive launcher and coupling hardware were added for control of the plasma current profile through current drive. Current profile diagnostics were improved to increase understanding of current drive and plasma behavior (in conjunction with a diagnostic neutral beam provided by MIT). Further improvements to edge diagnostics were made to increase understanding of turbulence and transport in the scrape-off region and the pedestal. This included edge fluctuation measurements at the plasma periphery with reflectometry and two-dimensional imaging of edge turbulence.

PPPL Engineering Support

PPPL engineers, physicists, and technical staff participated in discussions of technical issues involved in the lower hybrid launcher repair activities. They worked on the installation and initial checkout of the lower hybrid launcher and continued to assist MIT with the ICRF transmitter operation, retuning, and repairs.

Publications

PPPL scientists published five first-author papers on Alcator C-Mod work in FY04 and were included as co-authors on 13 papers by the Alcator C-Mod group.

International Collaborations

The U.S. Department of Energy has invested significant effort in developing international collaborations with facilities that present a unique opportunity for U.S. scientists to advance fundamental understanding in strategically important areas for the development of fusion energy. Key among these is the pursuit of burning plasma science in facilities, such as the Joint European Torus (JET)

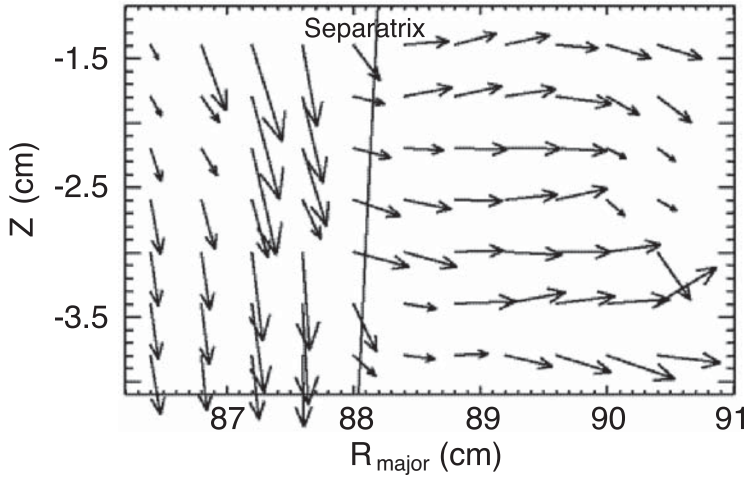

Figure 14. An example of the turbulent motion velocity and direction for a low-confinement mode (L-mode) discharge in Alcator C-Mod. Turbulence motion is mostly poloidal (vertical) inside the magnetic separatrix and radially (horizontal) outside the separatrix. (From J. Terry, MIT.)

in the United Kingdom and the JT-60U tokamak in Japan, that approach the dimensionless parameters relevant to ITER. Superconducting tokamaks now under construction, including the Korea Superconducting Tokamak Advanced Research (KSTAR) device and the East Asian Superconducting Tokamak (EAST) present new opportunities for advancing steady-state research. Stellarators such as the Japanese Large Helical Device (LHD), the German Wendelstein-AS, and the Spanish TJ-II also present a major opportunity for the U.S. to advance steady-state research.

JET Collaborations

The primary goal of the JET collaboration is to address burning plasma physics issues on a scale and in a parameter regime not accessible to domestic fusion facilities. In addition to its large size, JET is the only facility in the world capable of carrying out deuterium-tritium experiments in the near term (5–10 years), with the potential to advance fundamental understanding of alpha-particle-driven instabilities.

Fast-particle Research. PPPL is collaborating with JET to provide two diagnostics to measure the loss of 3.5-MeV D-T fusion alpha particles from JET plasmas. The diagnostics are also capable of measuring the loss of MeV fast ions from deuterium-deuterium fusion reactions and from ion cyclotron heating. One diagnostic consists of an array of thin-foil Faraday cups extending from near the outer mid-plane downward to just above the divertor region (Figure 15). Each detector consists of a stack of micron-thickness nickel foils and separating mica insulators, arranged so that only energetic ions can reach the stack. The profile of ion current versus foil depth in the stack gives an energy spectrum of the lost fast ions. This diagnostic is developed under a collaboration agreement between PPPL and the Colorado School of Mines. The second diagnostic is a scintillator-based magnetic spectrometer that resolves the gyroradius and pitch angle of the escaping energetic ions. This instrument is being developed under a collaboration between the Max Planck Institute for Plasma Physics in Germany and PPPL.

In FY04, both of these diagnostic projects moved forward from design to fabrication. For the Faraday cup array, draw-

Figure 15. Joint European Torus alpha particle detector built at PPPL.

ings were reviewed and approved by JET, then sent for fabrication. For the scintillator detector, a scientific grade CCD camera was purchased, and specifications for an image-carrying fiber optic bundle were finalized and issued for quotation. Both diagnostics will be installed in the JET vacuum vessel in spring 2005, in preparation for subsequent experimental campaigns. PPPL will operate and maintain these diagnostics at JET for this and future experimental campaigns.

Radio-frequency Technology Development. As part of the JET Enhancements Program (JET-EP), a new ITER-relevant ICRF antenna is to be added to JET during the 2006 opening. To support the antenna development, a multi-institutional collaboration between PPPL, Oak Ridge National Laboratory (ORNL), and the European Union was initiated to build a prototype. PPPL had taken responsibility for the design and construction of the prototype antenna enclosure box, Faraday shield, and protective tiles. Testing has been performed at ORNL and significant design issues were identified. The work on the high-power prototype antenna has been particularly successful in identifying technical issues for the full-size antenna and thus the prototyping will continue for another year.

Divertor Physics and Impurity Screening. Impurities, elements other than deuterium and tritium, involve three processes in a fusion reactor. Impurities, which are due to the erosion of some part of the plasma-facing surface, can contaminate the plasma core and reduce the fusion reactivity by displacing deuterium and tritium ions. In addition the impurities can migrate to a final resting place outside of the plasma, forming a co-deposited layer which can retain trapped tritium and lead to an unwanted build up of tritium in the vacuum vessel. The three processes (erosion, contamination, and migration) occur in present experiments. PPPL researchers are attempting to understand these processes by comparison of scrape-off layer fluid code calculations with experimental observations. These codes are then used to extrapolate to ITER parameters.

The EDGE2D/NIMBUS code is being used, by PPPL researchers, to interpret the results of experiments where methane is injected into JET plasmas. Methane is used to simulate a burst of impurity in the periphery of the plasma. A key finding is that carbon contamination (for the case where the ITER first wall is all carbon) would be much lower than on JET. The basis for such a prediction is that the carbon impurity sources in ITER will be ionized much further from the ITER separatrix (a key plasma boundary line) than for JET. This is expected to occur because the ITER scrape-off layer is calculated to be much hotter than the JET scrape-off layer due to the higher power entering the scrape-off layer and the longer parallel length to the divertor. However, calculations indicate that the improved ITER screening will be offset by larger ITER sputtering rates, making the calculated ITER contamination similar to JET.

JT-60U Collaboration

PPPL has for many years maintained a collaboration with the JT-60U tokamak and the LHD stellarator in Japan to understand the physical processes which limited the performance of the first generation of high-power negative-ion neutral-beam systems. This knowledge is used to improve the performance of these systems, while enhancing the performance and reliability of future generations of neutral-beam systems for such devices as ITER.

During the past year, the JT-60U negative-ion neutral-beam system injected into the machine many shots of about 1.5 MW at about 350 keV with a duration of 10–20 seconds, and one pulse of variable power lasting 25 seconds. This marked a major extension of the pulse length capability, which in the early years was only a fraction of a second. This was the result of many improvements, including recent changes to the cathode operation and grid extraction area suggested by PPPL. At LHD, a three-way collaboration between PPPL, the Japanese National Institute of Fusion Science, and the Japanese Atomic Energy Research Institute produced high quality measurements of the beam energy distribution, showing that excessive stripping of the beam prematurely to neutrals was not occurring even during very long beam pulses.

Stellarator Collaboration

With the rise of the compact stellarator program in the U.S., there is renewed interest in international collaboration on existing large-scale stellarator facilities in Japan and Europe to validate theoretical models and develop the necessary tools for initiating the National Compact Stellarator Experiment (NCSX) program in the U.S. The central elements of the stellarator program are in transport and MHD equilibrium studies.

Equilibrium and Stability. In FY04, PPPL collaborations centered on the Wendelstein 7-AS stellarator in Garching, Germany. A key element of the collaboration was focused on understanding the high plasma pressure achieved in joint experiments with U.S. scientists. This effort involves use of the PIES code, which calculates self-consistent plasma equilibria, including magnetic islands.

The critical question addressed by this collaboration was whether magnetic islands and stochastic magnetic fields set an equilibrium limit on the high-beta performance of the W7-AS device. The work presented at the *20th IAEA Fusion Energy Conference* in Portugal in 2004 showed that the pressure limit observed in W7-AS was consistent with the onset of magnetic stochasticity at a toroidal beta of 3.5%. These studies will continue in 2005 in order to develop an understanding of the dependence of high-beta performance on key plasma parameters.

Transport. In preparation for NCSX, researchers from PPPL, ORNL, and the Institute for Plasma Physics in Greifswald, Germany are developing a transport analysis code for stellarators. Each party prioritized the needed simulation modules, and the status of existing modules was reviewed.

The configurational flexibility of the NCSX places a high priority on development of a method for rapidly calculating neoclassical transport in nonaxisymmetric configurations. Existing stellarators operate in very few configurations, so the fundamental diffusivities are typically interpolated from tables. The highly variable internal currents and boundary shape of NCSX plasmas make the traditional approach intractable. Development of more efficient computational methods are proceeding jointly with researchers at the Technical University of Graz, Austria.

A U.S.-Spanish collaboration was started this year between PPPL and the CIEMAT fusion lab in Madrid. The topic of the collaboration was edge turbulence imaging in the TJ-II stellarator. The goal was to make movies of the edge turbulence on TJ-II and to use these movies to help understand the physics of the edge transport processes.

An ultra-fast PSI-5 CCD camera was purchased (in collaboration with MIT) from Princeton Scientific Instruments. This camera was sent to TJ-II for three months in FY04, and initial images of the edge turbulence were obtained. These images showed intermittent "blobs" moving rapidly through the edge similar to those seen in the National Spherical Torus Experiment and the Alcator C-Mod tokamak at MIT. The initial results will be presented at the *32nd European Physical Society Conference on Plasma Physics* in 2005. The camera will be sent back to TJ-II in 2005 with an improved fiber-optic bundle for further detailed studies.

KSTAR Collaboration

The Korea Superconducting Tokamak Advanced Research (KSTAR) will be one of the world's first tokamaks to be fully superconducting. The device will begin operation in late 2007. In 2004, PPPL completed the designs for the electron cyclotron microwave launcher needed for initial plasma breakdown and current-drive studies. In 2005, the launcher fabrication has started, with delivery planned in 2006.

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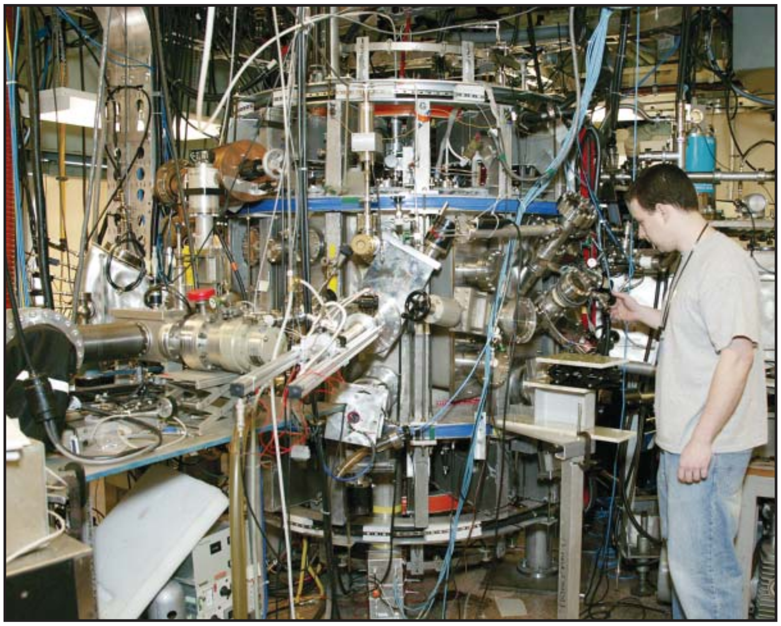
Lithium Tokamak Experiment



Lithium Tokamk Experiment

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

Reactor designs for inertial fusion reactors have relied for some time on the concept of a flowing liquid wall in order to guarantee survivability under conditions of repetitive micropellet ignition and burn. However, flowing liquid metal walls have only recently been proposed for magnetic fusion. In a tokamak, a flowing metal wall of liquid lithium may provide not only heat removal, but stabilization of plasma instabilities to unprecedented high values of the plasma beta, which is a measure of the plasma pressure relative to the confining magnetic field.

Liquid lithium walls would also greatly reduce the uncontrolled recycling of cold gas back into the plasma edge, thus promising high-plasma performance under reactor conditions. Production of high-performance plasmas with lithium-coated walls was first tested on the Tokamak Fusion Test Reactor (TFTR), and resulted in the highest fusion power and gain obtained on that device. All these factors combine to make the concept of a tokamak reactor with flowing liquid lithium walls very attractive for fusion energy production.

Facility Description

The Current Drive Experiment-Upgrade (CDX-U) was the world's first fusion experiment to operate with large area liquid lithium plasma-facing components. At the start of FY04, the CDX-U was renamed the Lithium Tokamak Experiment (LTX) to better reflect its mission. The LTX is a small spherical torus (ST), with a major radius of 34 cm, a minor radius of 22 cm, and a plasma elongation of 1.6. The toroidal field is 2.2 kG, and the maximum plasma current is 100 kA. The plasma pulse length is limited to 20 msec by the ohmic power supply, which is used to drive the plasma current inductively. Although the ohmic power supply is based on a capacitor bank, the toroidal-field coils and the poloidal-field coil set are powered by six large 12-phase computer-controlled power supplies which can provide up to 18 MW for several hundred milliseconds. Radio-frequency of power 300 kW at 8 MHz is also available for auxiliary heating. Diagnostics for the device include a 12-point Thomson scattering system, a 140-GHz interferometer, a number of Langmuir probes, and many edge and core plasma spectroscopic diagnostics covering the visible to soft x-ray regions of the spectrum.

Experiments with Lithium Limiters

The first experiments involving the use of solid and liquid lithium as a plasma limiter in CDX-U took place in FY00, utilizing a lithium-covered rail 5 cm in diameter and 20-cm long, which was developed at the University of California, San Diego (UCSD). The lithium limiter was inserted or removed via a double gate valve airlock system to prevent exposure of the lithium to air. When the limiter was fully inserted, it formed the upper limiting surface for the plasma discharge and was intended to define the last closed flux surface for the discharge. When the limiter was retracted, ceramic boron carbide rods formed the upper limiting surface for the discharge. The limiter had an internal heater and was operated in contact with the plasma over the temperature range of 20–300 °C.

The rail limiter experiments demonstrated that an ST plasma could successfully operate with a liquid lithium plasma-facing component (PFC), and were instrumental in identifying numerous problems and safety concerns with lithium operations. However, the surface area of the rail limiter was small (approximately 300 square centimeters, less than half of which is in contact with the plasma), and so the effects of the lithium-coated limiter on the discharge itself were minimal. In FY01, the lithium PFC experiments on CDX-U entered a second phase, when the toroidal liquid lithium belt limiter was placed in operation.

The toroidal belt limiter is shown in Figure 1. It consists of a shallow, heated toroidal tray, with a radius of 34 cm and a width of 10 cm, which is filled with lithium to a depth of a few millimeters. If completely filled with lithium, the belt limiter presents an exposed area of 2,000 square centimeters to the plasma. First operation of CDX-U with the lithium belt limiter yielded clear indications of the ability of a liquid lithium limiter to reduce impurities, despite difficulties in

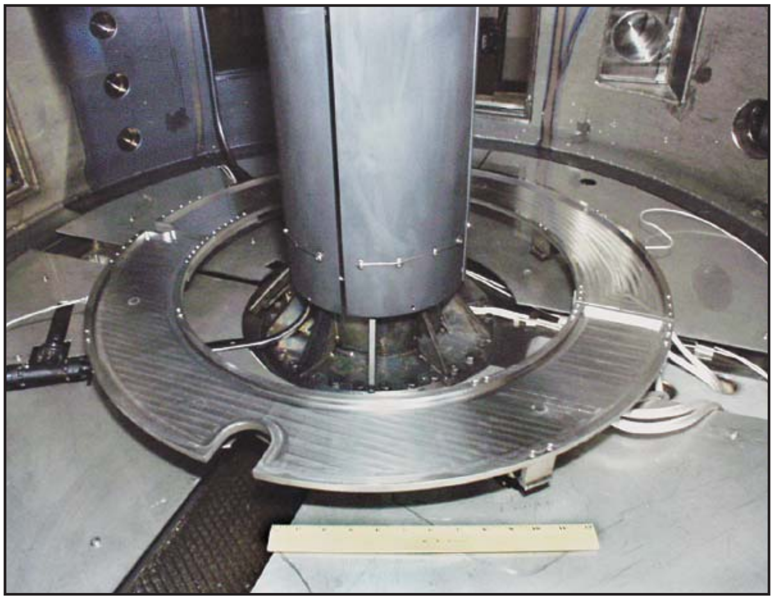


Figure 1. The interior of CDX-U, showing the (empty) toroidal liquid lithium belt limiter.

obtaining a uniform fill of the tray with lithium and the rapid development of oxide and hydroxide layers on the surface of the lithium.

During the first lithium tray campaign (2002–2003) the tray was loaded with solid lithium at room temperature, after which it was heated to 300 °C in order to melt the lithium (which melts at 180 °C). This method of filling the tray proved difficult, and resulted in incomplete coverage of the tray with lithium as well as oxidized surface conditions. It is estimated that at most 50% of the tray was covered. Despite these difficulties, the primary predictions for the utility of lithium as a plasma-facing component were verified. Plasma recycling was reduced to very low levels at the surface of the lithium. The impurity content of lithium-limited discharges dropped significantly. These results provided motivation for further efforts to improve the quality and quantity of the liquid lithium PFC in CDX-U.

In 2003 CDX-U was vented, the limiter tray and vessel interior were cleaned, and the tray was reinstalled in the vacuum vessel. A new lithium filling technique was tested at UCSD, and implemented on CDX-U. This new approach involved injecting liquid lithium onto a very hot (500 °C) tray in order to obtain immediate wetting and spreading of the liquid lithium in the tray.

This approach proved very successful. The lithium immediately covered 80% of the tray with visibly clean, metallic lithium. Subsequent cycles of heating and discharge cleaning led to 100% tray coverage with the highly reflective liquid metal. A photograph of the tray during discharge cleaning is shown in Figure 2.

The liquid lithium fill had an immediate effect on CDX-U plasma operations. For the several weeks of plasma operations prior to the lithium fill, plasma current was limited to less than 60 kA. Within a half-hour of resuming plasma operations after the lithium fill, the maximum plasma current had increased to nearly 80 kA. In addition, the amount of deuterium gas required to fuel the plasma increased by a factor of four, indicating

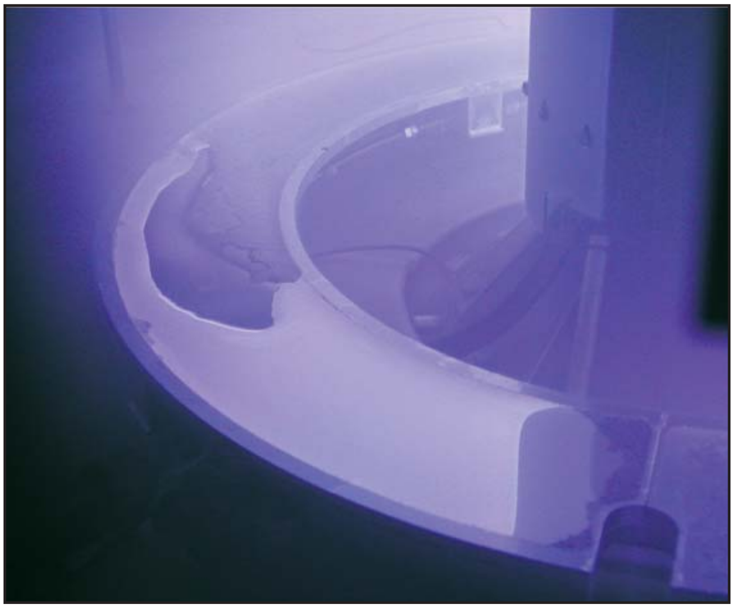


Figure 2. The liquid-lithium-filled tray limiter during clean-up with an argon glow discharge. The dark area at 9 o'clock is a surface coating which was eventually removed by the glow discharge.

that recycling on the liquid lithium was significantly reduced, in comparison to the bare tray. A summary plot of the large differences in fueling with, and without, lithium is shown in Figure 3.

The effect of a large liquid lithium PFC on the loop voltage required to maintain the plasma current and on the gas required to fuel the plasma is indicated in Figure 4. Without lithium in the tray, a loop voltage of approximately 3 V is required to maintain the plasma current. With lithium in the tray, only 1 V is required to ramp the plasma current upward at 2 MA per second, and only 0.5 V is required to maintain a constant plasma current.

The last cycle of operations with the lithium-filled tray on LTX were completed in FY04. Subsequent experiments on LTX in FY04 explored the use of thin lithium films to achieve low recycling. The lithium film system is prototypical of the lithium coating system for the LTX, components of which are now being fabricated, and of a divertor target system under consideration for the National Spherical Torus Experiment (NSTX). Whereas the tray system in CDX-U exposed 2000 square centimeters of lithium to the confined plasma, LTX will have a fully lithium coated wall with an area of five square meters.

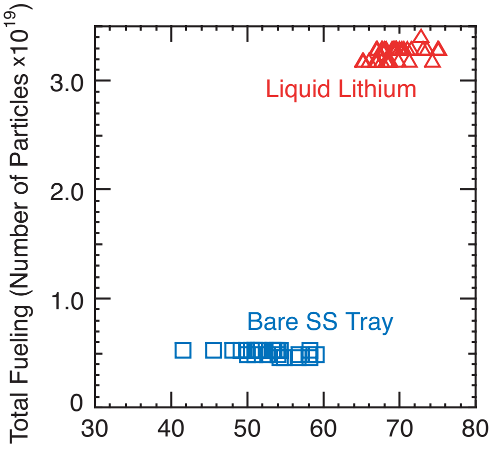


Figure 3. Summary plot of the total discharge fueling for plasma discharges with and without lithium in the tray. A discharge requiring high fueling implies low recycling.

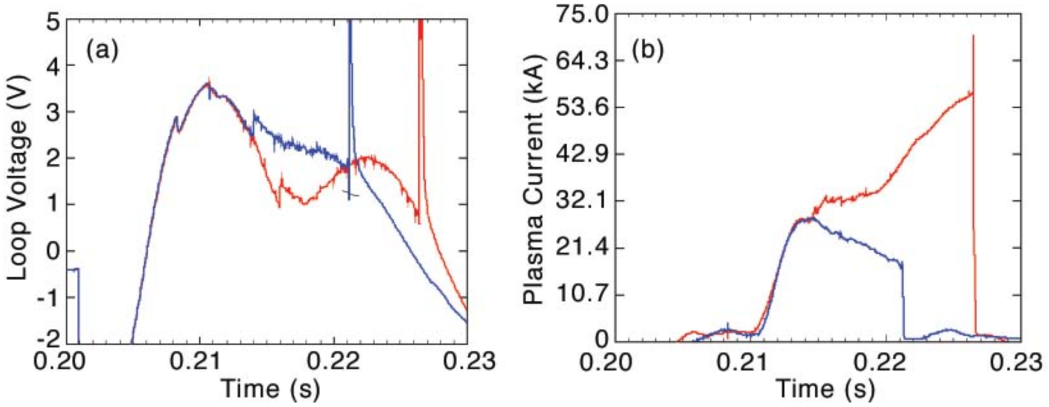


Figure 4. Applied loop voltage (a) and resultant plasma current (b) for discharges without (blue) and with (red) liquid lithium in the tray. For the non-lithium discharge, the plasma current decays when the loop voltage drops below 3 V. For the lithium discharge, the current continues to increase until the loop voltage drops below 1 V and the discharge is terminated.

Future Work

The LTX is designed to explore the impact of a full liquid lithium wall on a confined plasma. In LTX, the lithium will not be renewed through flows, as in an eventual reactor. Instead, the lithium will form a thin, molten coating on the wall, which is renewed between every discharge by a system of evaporators. The film of lithium will be deposited on a heated shell, which will be constructed from a laminated stainless steel-copper sandwich (copper for heat conduction, stainless steel for resistance to chemical erosion from the liquid lithium).

Components of the LTX are currently under construction. The fabrication of LTX will involve a near-complete rebuilding of its predecessor, CDX-U. The design for the internal shell in LTX is shown in Figure 5. The reconfigured LTX is scheduled to be operational in 2007.

Figure 5. The Lithium Tokamak Experiment (LTX) shell is formed from an explosively bonded stainless steel-copper sandwich.

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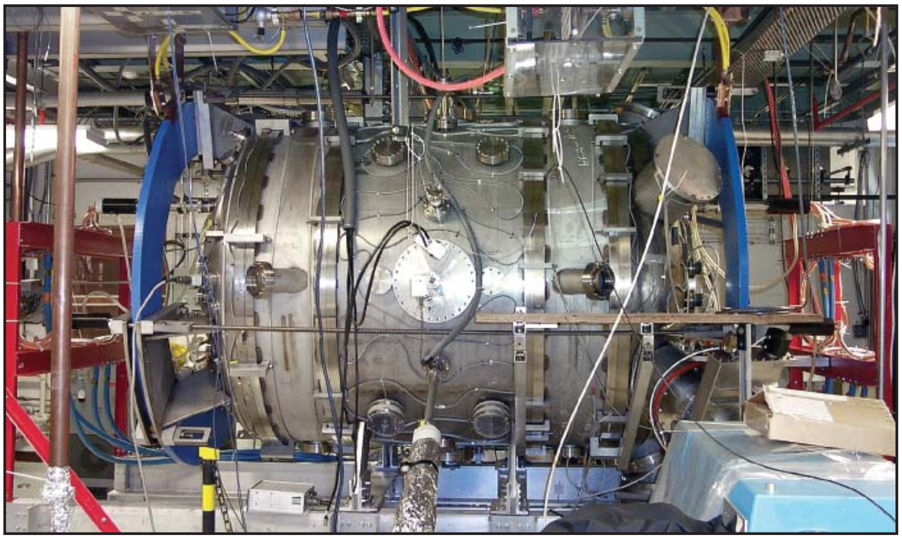
Magnetic Reconnection Experiment



Magnetic Reconnection Experiment

The Magnetic Reconnection Experiment (MRX), shown above, was built to study magnetic reconnection as a fundamental plasma process in a controlled laboratory environment. Magnetic Reconnection — the topological breaking, annihilation, and reconnection of magnetic field lines — can occur in virtually all magnetized plasmas, both in the laboratory and in nature (Figure 1).

Despite its omnipresence, reconnection is not a well-understood phenomenon. In laboratory fusion plasmas, such as tokamaks, reconnection manifests itself as "sawtooth" oscillations in electron temperature and often affects plasma confinement. In nature, reconnection plays an important role in the evolution of solar flares, coronal heating, and in the dynamics of the Earth's magnetosphere. Reconnection at the dayside magnetopause is often considered as the onset and trigger of such events as auroral substorms and geomagnetic storms. However, the rate of energy release is not resolved by the current 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. Cross-disciplinary

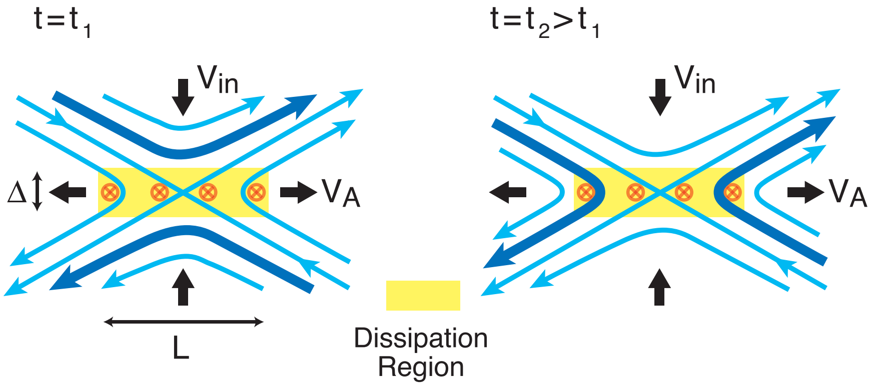


Figure 1. The process of magnetic reconnection. The dark field lines in the left-side frame move toward the dissipation region and magnetic reconnection occurs. After reconnection, the field lines move into the outflow region, as illustrated in the right-side frame.

interactions have led to fertile discussions and useful reassessments of the present understanding.

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

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. The analysis focuses on the coupling between local microscale features of the reconnection layer and global properties such as external driving force, magnetohydrodynamic (MHD) flows, and the evolution of plasma equilibrium. In particular, MRX has the following research goals:

- Experimentally test two-dimensional and three-dimensional theoretical models of reconnection layers.
- Investigate the role of effects beyond resistive MHD (turbulence and Hall-MHD) in the reconnection layer.
- Identify the mechanisms by which magnetic energy is efficiently converted 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.

During FY04, a substantial upgrade in the MRX facility was carried out, enabling studies of the global and local physics of reconnection over an extended range of parameters and configurations. The study of global effects on magnetic reconnection was commenced with flux-core separation experiments. The quadrapole out-of-plane magnetic field predicted by Hall-MHD was observed. Preparations were made for spheromak merging experiments. These different activities will be discussed below in the "2004 Highlights" section.

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.

In the geometry which has been utilized most frequently to date, 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 causes 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 second type of configuration, two independent toroidal plasmas (spheromaks) are formed adjacent to the flux cores, and then allowed to merge via their mutual attractive force. Magnetic reconnection occurs during this merging, and a fusion-relevant field-reversed configuration is formed.

A set of carefully chosen diagnostics provides insight into the physics of magnetic reconnection and real-time monitoring of MRX plasmas. These include Langmuir probes (electron density and temperature, and plasma flows), spectroscopic probes (ion temperature and 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 that of resistive diffusion, but still much slower than those observed in solar flares. For nearly fifty years, the merits and shortcomings of this model have been debated.

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 measured 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.

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. Those measurements are carried out using a Hodogram probe capable of measuring the fluctuation polarization based on all three spatial components of the fluctuating magnetic field acquired at the same location, with a frequency response up to 40 MHz. The fluctuation amplitude is similar for the three 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 the 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 regimes.

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 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

2004 Highlights

MRX activities in FY04 were composed of substantial facilities upgrades in the first part of the year and fundamental advances in reconnection science in the second part. These activities, as discussed below, amount to a significant advance in the capabilities of the device and the scientific understanding of magnetic reconnection.

Facilities Upgrades at MRX

The first half of FY04 was devoted to a major upgrade of the MRX facility. The MRX vacuum vessel was made larger, the flux cores received a new coating, and the power supplies were relocated and/or upgraded.

Two extensions to the vacuum vessel were fabricated and installed on the device (see photo at the beginning of this section). This vacuum vessel enlargement adds to the capability of the device in a number of ways. The larger volume allows for a wide range of flux core spacing (between 0.30 m and 1.2 m). By varying the separation between the flux cores, it is possible to study how boundary conditions and the length of the current sheet affect the reconnection rate, as described in "Impact of Boundary Conditions on Magnetic Reconnection" below. This extra volume of the extensions will further allow for better optimization of the spheromak merging sequence, especially with the help of soon to be installed shaping-field coils. These coils, which will be installed in early 2005, will enhance the experimental control of the merging spheromaks and further extend the operation space of the MRX device.

As the second major phase of the upgrade, all of the magnet power supplies for MRX were upgraded. The MRX capacitor banks were moved to a new room directly underneath the test-cell, and are shown in their new location in Figure 2. The reconstructed capacitor banks contain substantially more stored energy than the previous banks (~240 kJ at full capacity and voltage, compared to ~60 kJ previously), and are connected to MRX

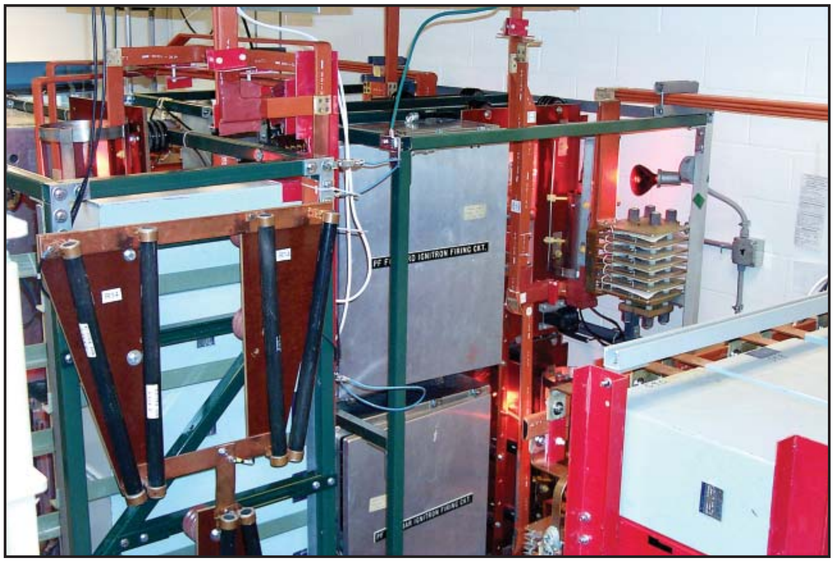


Figure 2. The newly upgraded MRX capacitor banks. This view mainly shows the upgraded poloidal-field power supply.

through bus work with lower parasitic inductance than the previous systems. Hence, it is possible to put more energy into the plasma, and have more fine control of the current waveforms which drive the magnets. As an added benefit, the relocation of the power supplies from the MRX control room to the new space allows for a larger control room, so that more members of the MRX team can actively participate in experiments. Finally, the dc power supplies for the equilibrium field coils were refurbished with a doubling of the possible current to 5,000 A, allowing larger equilibrium fields for the confinement of higher-performance MRX plasmas.

Impact of Boundary Conditions on Magnetic Reconnection

A major focus of FY04 operations was the study of the impact of boundary conditions on the physics of magnetic reconnection in MRX. The classical Sweet-Parker model indicates that the reconnection rate would decrease as the length of the current sheet is increased. More recent simulations using Hall-MHD have indicated that in the low-collisionality regime, the reconnection rate would be independent of current sheet length. With the facilities upgrades described above, it is possible to modify the separation between the surfaces of the flux-cores from 35 cm to 80 cm, while still making high-quality reconnecting plasmas. By scanning this distance (known as Z_0), we have been able to study the effects of current sheet length on magnetic reconnection.

It has been found that in the collisional regime ($\lambda_{mfp} < \delta$), the reconnection rate is largely independent of the flux-core separation, as show in Figure 3. These detailed experiments have revealed that as the flux core spacing is increased, the current sheet length is also increased, tending to slow down reconnection. On the other hand, there is a decrease in the pressure in the outflow region at larger flux-core spacing. This decreased pressure leads to an increase in the outflow speed, accelerating the reconnection. The combination of increasing current sheet length and increasing outflow speed tend to cancel, yielding a constant reconnection rate as a function of flux core spac-

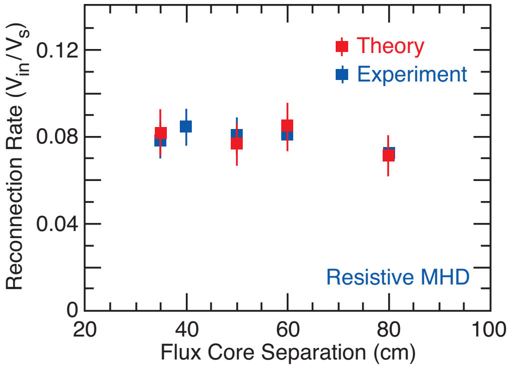


Figure 3. The reconnection rate as a function of flux-core separation in MRX. The rate is largely independent of the flux-core separation, consistent with the generalized Sweet-Parker model.

ing. These observations are included in the generalized Sweet-Parker analysis of the data shown in Figure 3, indicating good agreement. A more restricted data set in the low-collisionality regime indicates a similar trend.

These observations verified that the local plasma resistivity is determined independently of the flux-core spacing. This is presented in Figure 4, where the resistivity is plotted as a function of the collisionality. For the three flux core spacing values presented in the figure, the resistivity is seen to be a function of collisionality only. In the collisional regime, the resistivity is equal to the Spitzer resistivity, and is thus found to be classical. In the low-collisionality regime, the resistivity is much larger than the classical value, for all flux core separations. Hence, it is concluded that the resistivity is determined by local physics in MRX, an important conclusion which is consistent with the fluctuation studies presented above.

Detailed studies of the resistivity as a function of the pressure (collisionality) have been performed, in plasmas both with a guide-field (co-helicity) and without (null-helicity). In collisional plasmas, the Spitzer theory predicts that the resistivity in the case with a guide-field should be twice the value of the case without the guide-field. This is indeed observed in Figure 5, where the resistivity is shown for both null- and co-helicity cases as a function of fill pressure. The resistivity in the co-helicity case is a factor of 1.5–2 larger, confirming the Spitzer theory.

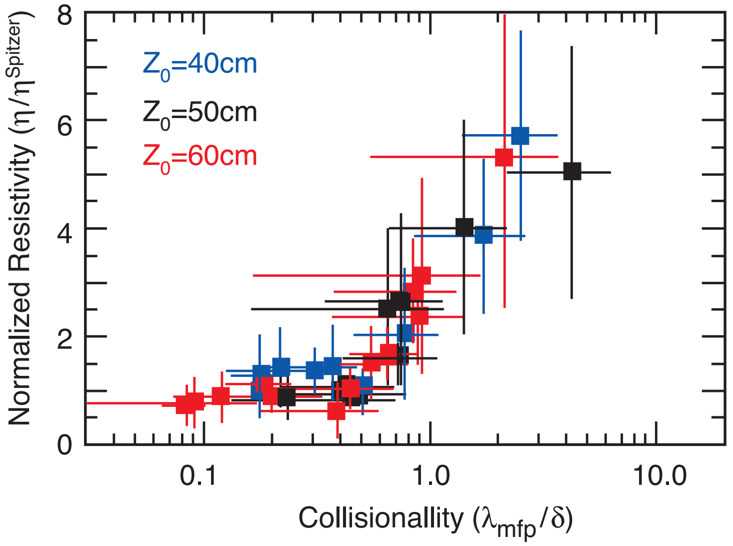


Figure 4. The resistivity (normalized to the Spitzer value) as a function of collisionality, for different flux-core spacings (Z_0). The resistivity in MRX is determined by local physics, not the global boundary conditions.

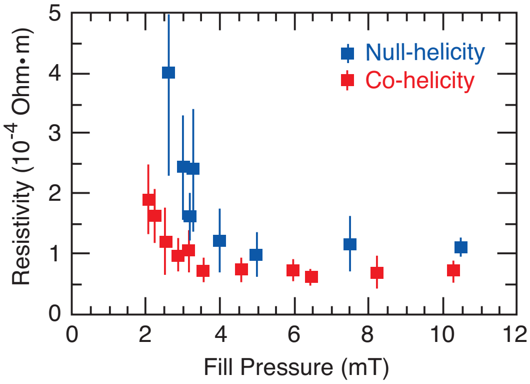


Figure 5. The resistivity in the null- and co-helicity cases, as a function of fill pressure. The ratio of ~2 between the two cases is consistent with Spitzer theory.

Observation of the Hall Quadrapole Toroidal Field 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. The enhancement of resistivity due to fluctuations is one possible mechanism for fast reconnection, and has been positively observed in MRX. A second proposed mechanism for enhancing the reconnection rate involves the Hall effect, a mechanism which is not present in simple resistive MHD. 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 separation of the electron and ion flows causes currents in the plane of the reconnection, resulting in a quadrapole out-of-plane magnetic field.

This quadrapole out-of-plane field has been observed in MRX, as illustrated in Figure 6. The profile of the out-of-plane field is shown for measurements on either side of the current sheet. At Z = -7 cm, the toroidal field is positive at for R < 37.5 cm and negative for R

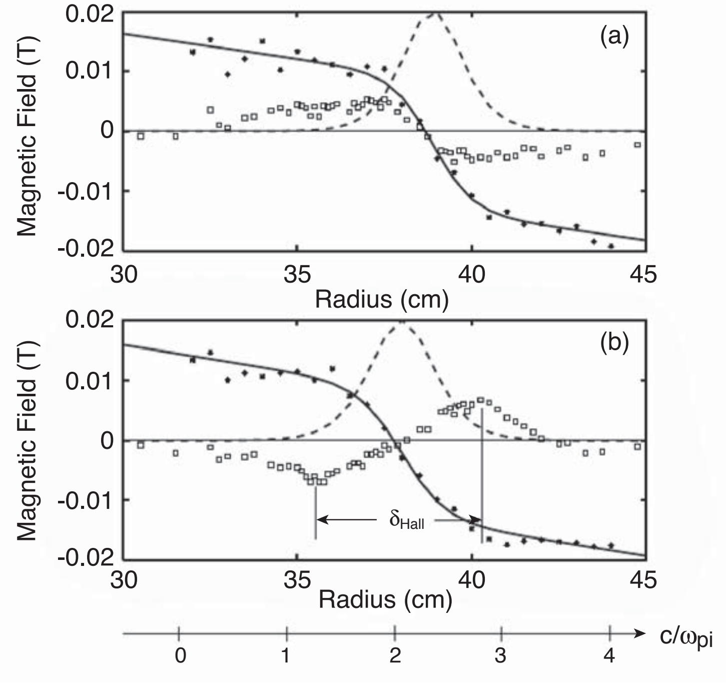


Figure 6. Experimental verification of the Hall effect in MRX. The solid points represent the reconnecting magnetic field, the dashed line is the profile of the current sheet, and the open points are measurements of the out-of-plane (toroidal) field. The data is shown for measurements of the out-of-plane field at (a) Z = -7 cm and (b) Z = +7 cm.

> 37.5 cm. This trend is reversed at Z = +7, illustrating quadrapole nature of the toroidal field. Also shown are the reconnecting B_Z-field components, indicating that the width of the Hall quadrapole field (δ_{Hall}) is comparable to the current sheet width (which is comparable to the ion skin depth c/ω_{pi}). This represents the first laboratory verification of the Hall effect during magnetic reconnection.

Electromagnetic Fluctuations in the Lower-hybrid Frequency Range

Theoretical work for MRX this year has concentrated on the understanding of electromagnetic fluctuations and their contribution to resistivity. By using a local two-fluid theory, this research has investigated an electromagnetic instability in the lower-hybrid frequency range driven by cross-field current or relative drifts between electrons and ions. The theory self-consistently takes into account local cross-field current and accompanying pressure gradients. It is found that the instability is caused by reactive coupling between the backward propagating whistler (fast) waves in the moving electron frame and the forward propagating sound (slow) waves in the ion frame when the relative drifts are large. The unstable waves propagate obliquely to the unperturbed magnetic field and have mixed polarization with significant electromagnetic components. The resultant waves are qualitatively consistent with the measured electromagnetic fluctuations in reconnecting current sheets in MRX. The resulting resistivity and plasma heating have been calculated from quasiliner theory, and within the experimental uncertainties they are quite important for the reconnection process.

Future Work

The hardware upgrades and the scientific progress described above open up many new avenues for physics studies in MRX. The fundamental question remains: Why does magnetic reconnection in nature proceed faster than predicted by resistive MHD? MRX has now experimentally identified two mechanisms which can accelerate the reconnection process: electromagnetic fluctuations and the Hall effect. Studies in the next year will focus on the relationship between the two mechanisms, with the goal of understanding which effects enhance the reconnection rate under different circumstances. Simultaneously, spheromak merging studies will begin in earnest, investigating reconnection physics in a new geometry, and focusing on topics such as field-reversed configuration formation, equilibrium, and stability studies, as well as local reconnection physics.

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Space Plasma Physics

The Space Physics Group at the Princeton Plasma Physics Laboratory (PPPL) is interested in understanding the dynamical evolution of the solar-terrestrial system and how energy and momentum are coupled between the sun, magnetosphere, and ionosphere. In this report, progress in understanding (a) the relationship between thin ionization layers in the ionosphere and the enhanced aurora and (b) formation and expulsion of large-scale flux ropes in major solar eruptions by reconnection among smaller-scale flux tubes is described.

Enhanced Aurora and Thin Ionization Layers

Nearly half of the time, auroral displays exhibit thin, bright layers known as "enhanced aurora," an example of which is shown in Figure 1. The layers appear at a stable altitude within auroral curtains and are often observed to be at least five times as luminous as the surrounding auroral emissions. The layers appear to be quite stable and may remain at the same altitude for one or two hours. Strong evidence that the layers are related to relatively stable atmospheric structures comes from auroras with high variability. Such active aurorae may have variations in the downcoming electron flux, which causes the aurora to suddenly penetrate to lower altitude. When this phenomenon occurs, the location of the enhanced aurora remains the same, but the relative location within the arc changes.

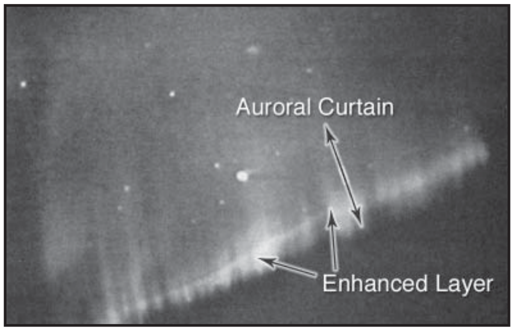

Figure 1. An image of an enhanced auroral layer. From T.J. Hallinan, H.C. Stenbaek-Nielsen, and C.S. Deehr, "Enhanced Aurora," J. Geophys. Res. (Space Physics) 90:A9 (1 September 1985) 8461-8475. Copyright 1985 American Geophysical Union. Reproduced by permission of the American Geophysical Union.

Thin ionization layers in the ionosphere have been observed for decades. The layers arise when heavy metal ions that have a long recombination time (e.g., iron and magnesium) are driven into layers by convective electric fields in the ionosphere. An example of such a layer detected by incoherent scatter radar is shown in Figure 2. These layers occur at roughly the same altitude that the enhanced auroral emissions are observed, and the thickness of the layers is similar.

Based on the spectral characteristics of the enhanced layers, it is believed that they result when wave-particle interac-

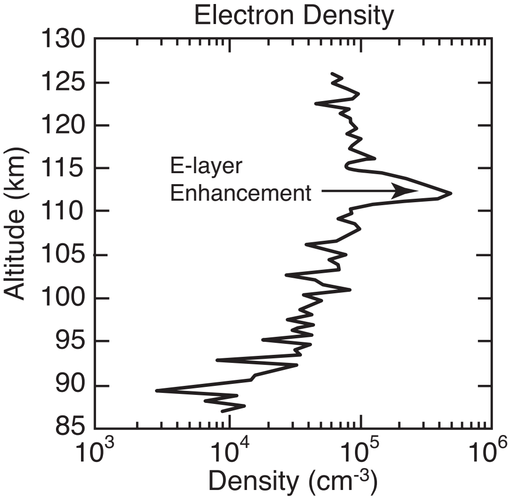

Figure 2. The density profile of electrons in the E-region measured by incoherent-scatter radar during the period 2105-2120 Universal Time on July 27, 1991. A thin ionization layer can be seen around 110 km. The thin layer remained at this altitude for around two hours. From W.A. Bristow and B.J. Watkins, "Incoherent-scatter Observations of Thin Ionization Layers at Sondrestrom," J. Atmosph. Terr. Phys. 55:6 (May 1993) 873-894. Copyright 1993 by Elsevier Science Ltd. Reproduced by permission of Elsevier Science Ltd.

tions heat ambient electrons to energies at or just above the 17 eV ionization energy of molecular nitrogen (N_2). While there are several possible instabilities that could produce suprathermal electrons in thin layers, there has been no clear theoretical investigation that examines in detail how wave instabilities in the thin ionization layers could develop and produce the suprathermal electrons.

Instabilities that would occur in thin, dense, heavy ion layers were examined using extensive analytical analysis combined with particle simulations. When the aurora is visible, the Hall and Pederson currents that flow in the ionosphere across the magnetic field are enhanced. An analytical stability analysis of a nonuniform, multispecies plasma was also performed that demonstrated that a cross-field current instability is strongly unstable and localized in the heavy ion layers.

An eigenmode analysis was done of the modified two-stream instability in an inhomogeneous plasma containing a thin dense layer of heavy metal ions (iron and/or magnesium) embedded in an ambient (O_2^+-NO^+) plasma. The presence of the dense ion layer introduced new modes with larger growth rate that were localized in the dense ion layer. When thermal effects are also included, it is found that heavier ions have smaller thermal velocity relative to the **E×B** drift of the electrons and therefore the growth rate for the instability is enhanced while the threshold for the instability is lowered.

The Space Physics Group performed 2.5-dimensional electrostatic simulations with full ion dynamics and guiding-center electron dynamics. The simulations included a dense layer of heavy ions (such as iron and/or magnesium) embedded in the ambient plasma. Initially, electrons were streaming across the ambient magnetic field with the **E×B** drift velocity (estimated from typical ionospheric electric fields). The ions were initially considered to be stationary due to their limited mobility in the collisional ionosphere. The simulations were run using the real mass ratio (m_i/m_e = 102,827 for iron) until $\omega_{pe}t$ = 24,000. It was found that an instability developed that was localized in the heavy ion layer. As shown in Figure 3, the electron distribution in the layer was heated by a factor of 25–100 with respect to the initial electron energy of 0.4 eV. Electrons with this energy would be able to excite the atoms responsible for the auroral emissions.

Erupting Flux Ropes Generated by Magnetic Reconnection

Observations of solar eruptions often show a sudden appearance and ex-

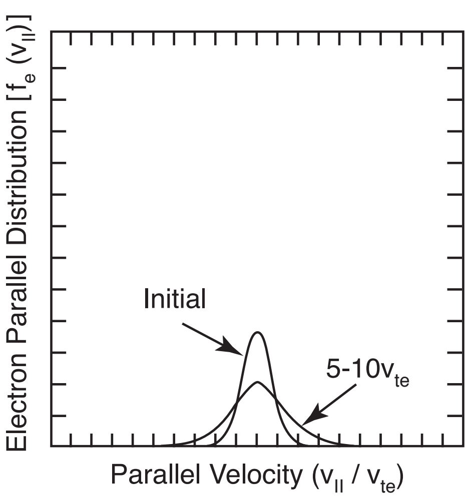

Figure 3. Electron parallel distribution after $\omega_{pe}t = 24{,}000$ which shows that electrons are heated substantially by an electrostatic instability in the thin ionization layer. The energization is sufficient to heat ambient ionospheric ions from 0.4 eV to above the ionization energy of molecular nitrogen.

pulsion of a large-scale loop structure following a brightening of smaller-scale loops. Also, the distance between the legs of a CME (coronal mass ejection) loop is generally much larger than the separation between Hα flare ribbons or between hard X-ray emission features. To explain this with the standard solar eruption model (conventionally called Kopp-Pneuman model), an antiparallel footpoint motion is required along the polarity inversion line over a huge distance, which, however, is not observationally confirmed.

To address this problem, a three-dimensional MHD simulation was performed for the evolution of an idealized solar active region composed of several magnetic flux tubes. This modeling was motivated by the observation that magnetic fields in the solar photosphere are discrete. Although the corona is everywhere permeated with magnetic fields and magnetic reconnection may take place wherever a current sheet exists, the partitional structure of each flux tube is still regarded to be preserved in most parts until a major solar eruption occurs.

Initially the magnetic field is assumed to be potential (current-free) and field lines cross the polarity inversion line perpendicularly. Next a footpoint twisting motion was applied within each flux tube so that the longitudinal magnetogram does not change at all, whereas magnetic shear near the polarity inversion line rapidly increases as is usually seen in a vector magnetogram. The increase of current in the current sheet between different flux tubes leads to magnetic reconnection. The reconnected field has a new field line connectivity.

In Figure 4(a), the colors differentiate the footpoint positions of the original untwisted flux tubes. By magnetic reconnection, field lines starting in the red region do not necessarily end in red regions, but also in green regions and even in blue regions. Thus, the distance between the new conjugate footpoints is larger than the original one. Also, the reconnected flux, whose footpoint separation becomes larger, gains magnetic helicity compared to the state before magnetic reconnection. This is attributed to the helicity redistribution action of magnetic reconnection. Here, not only the self-helicity is redistributed, but also the mutual helicity between flux tubes is converted into a self-helicity of the reconnected flux. In this way, the reconnected flux forms a helical flux rope, whose scale is larger than the original flux tubes. The flux rope expands and ascends like an expanding coronal mass ejection loop [see Figure 4(b)]. While the flux rope in the earlier 2.5-dimesional model was topologically totally separated from the solar surface boundary, the new flux rope in three dimensions is still tied to the solar surface. However, the latter can escape from the sun more easily than the former because fanning out of field lines in the third direction makes way for the flux rope to escape.

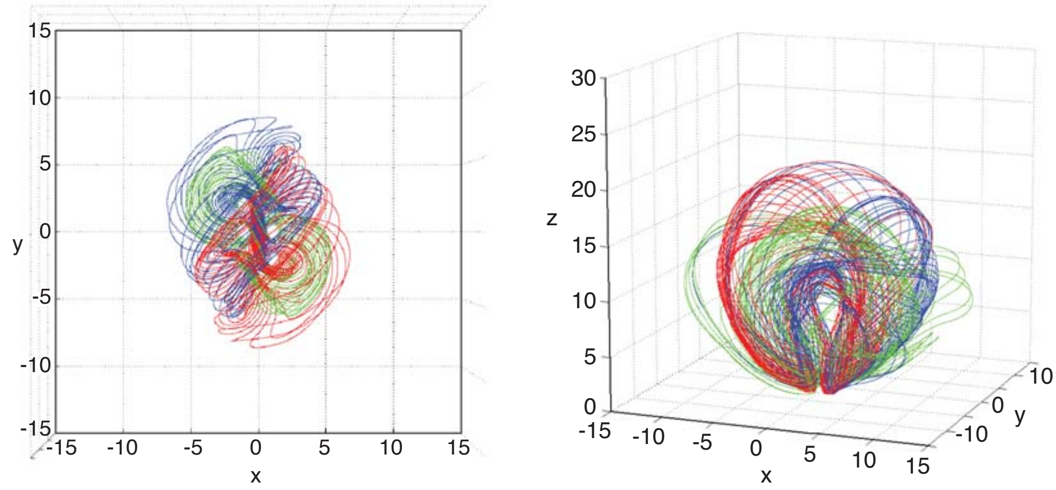

Figure 2. (Left) Head-on view of flux tubes undergoing magnetic reconnection. Here each flux tube end is twisted by 1.3 π. (Right) Formation of a large helical flux rope by magnetic reconnection among smaller-scale flux tubes. Here each flux tube end is twisted by 2.5 π. With further twist, this flux rope totally erupts leaving open field lines.

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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 document, 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

The amount of fuel that a satellite must carry depends on the speed with which the thruster can eject it. Presently, the vast majority of satellites worldwide rely on chemical thrusters, but chemical thrusters have very limited fuel exhaust speed. A Hall thruster is a plasma-based propulsion system for space vehicles. Plasmas can be ejected at much higher speeds, therefore less fuel need be carried onboard. Until recently, the Hall thruster approach had been pursued most vigorously in Russia; during the past quarter century, the Russians have placed about 100 Hall thrusters in orbit.

In FY99, a Hall Thruster Experiment was established at the Princeton Plasma Physics Laboratory. 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, 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 the U.S. Air Force Office of Scientific Research, 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 facility is pictured 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. Thrust is exerted on the anode-cathode system in a direction opposite to that of the flow. Unfortunately, positive charge builds up in the space between the grids, limiting the ion flow and, therefore, the thrust that can be attained.

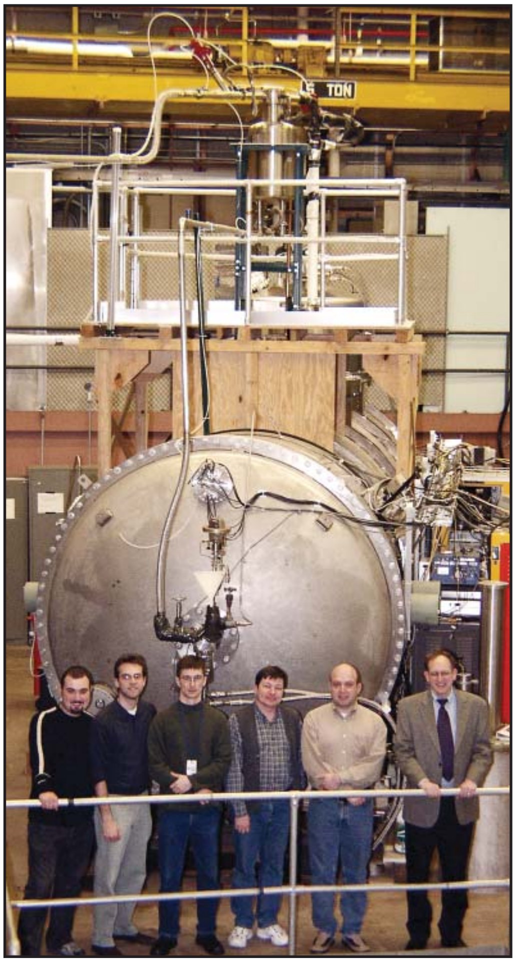
Figure 1. The PPPL Hall Thruster Experiment and research team.

In a Hall thruster (see Figure 2), electrons injected into a radial magnetic field neutralize the space charge. The magnitude of the field is approximately 200 gauss, strong enough to impede the electrons axial motion. The electrons then spiral azimuthally around the thruster axis. 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.

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

Hall 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, about one or two watts of on-board pow-

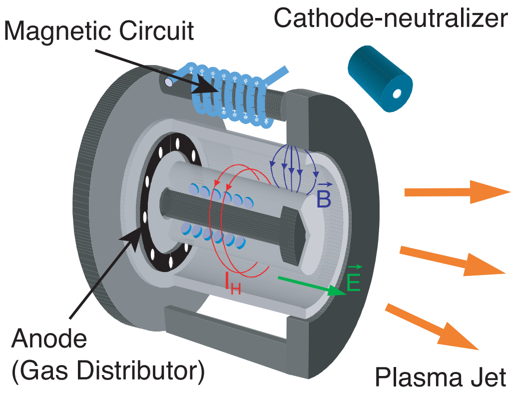

Figure 2. The Hall thruster concept.

er are available. At PPPL, Hall thrusters ranging from below a hundred watts to more than 2 kilowatts have been built. Successful PPPL results will be useful both for thrusters operating at many thousands of watts (for planetary missions), as well as for thrusters in the small power limit (for very small satellites with masses of 50 to 100 kilograms).

Hall Thruster Results

PPPL's Hall Thruster Experiment was designed with a modular configuration to allow multiple thruster geometries that could be easily examined in detail. This includes the ability to measure precisely the plasma plume in three dimensions. This information can be used to arrive at techniques to narrow the plume and obtain more control over the outflow from the thruster, possibly improving its efficiency. A small plume divergence is a very important design feature for facilitating integration of the thruster in a spacecraft.

The Hall Thruster Experiment operated initially at 900 watts with efficiency equivalent to state-of-the-art thrusters. The thruster was then modified to a segmented configuration. Each segment was held at a specific electric potential, enabling researchers to control exactly where the voltage drop occurred along the length of the thruster. In a low mass-flow-rate situation, segmented thruster operation lead to narrowing of the plume by as much as 20 degrees. Since then, detailed and unique measurements of the electrical potential were made in the physically challenging interior of the Hall thruster. The potential distribution was shown to be correlated to the plume divergence. Moreover, in FY04, it was shown that the emission properties of the segmented electrodes could affect the electron current, suggesting important regimes for high-efficiency operation. The diagnostics used in these experiments can be seen inside the thruster vacuum chamber (Figure 3).

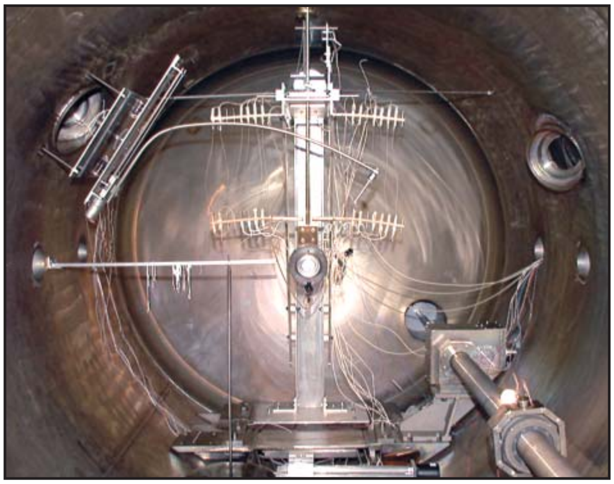

Figure 3. Interior view of the Hall thruster vacuum chamber.

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 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 PPPL Hall Microthruster has now operated below the 100-watt range, useful for very small satellites with masses of 50 to 100 kilograms. Efficiencies in the range of 30% for 100-watt operation were attained, surpassing present-day microthruster technology. Recently, using unique plasma diagnostics inside the channel of the PPPL Hall Microthruster, several interesting phenomena were discovered, including a density peak near the thruster axis. In FY04, by optimizing the magnetic field configuration, a high-efficiency regime was identified at about 150 W.

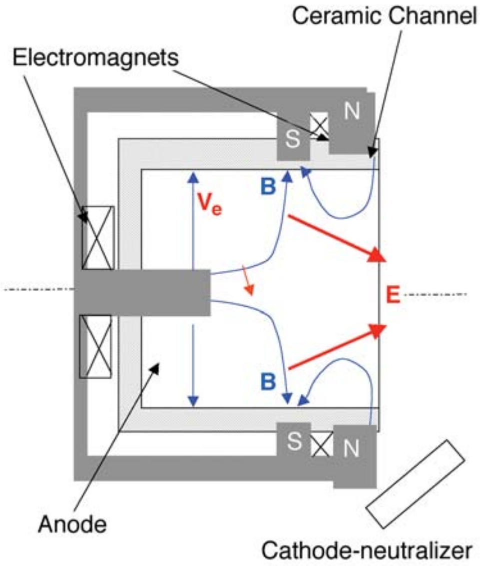

Figure 4. Schematic of the PPPL Hall Microthruster with cylindrical geometry.

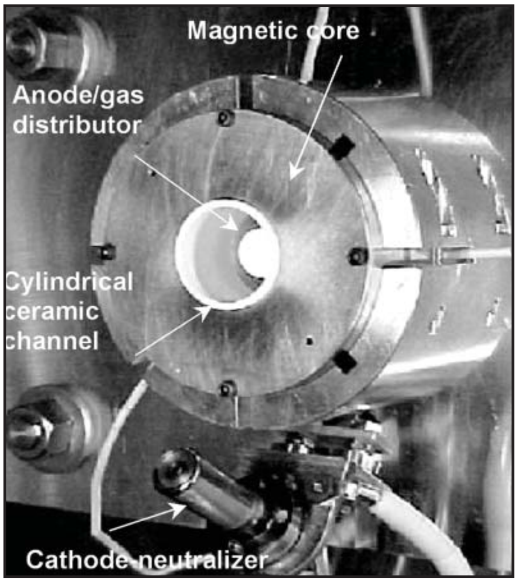

Figure 5. Cylindrical design the PPPL Hall Microthruster.

Magnetic Nozzle Experiment

The Magnetic Nozzle Experiment (MNX) is used to study the physics of mirror-geometry helicon-heated plasmas expanding through magnetic field gradients. One of the important applications of this research is to spacecraft-propulsion.

In FY04, the MNX was extensively operated at kilowatt power levels for eight-hour periods at 100% duty factor. Typically, argon and/or helium plasmas were formed. The highest specific impulse achieved with argon was 1,700 seconds. Operations with these characteristics were continued for months without need for repair or maintenance, an important element for the application of helicon techniques to propelling spacecraft on missions to remote planets. In FY04, three graduate students, X. Sun, M. Miah, and N. Ferraro, performed research on MNX.

Scientific investigations during FY04 were in four areas: (1) measuring radial profiles of directed ion energy and electron density and temperature in different modes of operation; (2) exploring means to increase ion energy above the 30-eV level achieved in FY03; (3) understanding asymmetric Zeeman peaks observed in the expansion region (ER) downstream of the magnetic nozzle; (4) and testing spectroscopic techniques for noninvasive measurement of electron temperature and density in the higher-density operational mode termed the "blue-core" mode, see Figure 6.

Radial profiles of plasma parameters were measured with two techniques: (1) Langmuir probes for electron temperature and density and (2) laser-induced fluorescence (LIF) for directed ion energy. The LIF system was loaned to PPPL by West Virginia University. Scanning Langmuir probes, 30 cm from the helicon source, showed peaked density profiles to $n_e(0) = 5 \times 10^{13}$ cm^{-3} and flat temperature profiles. (Electron temperature was in the range 3–10 eV, depending on gas species, neutral pressure, and helicon power.) The LIF measurements in the expansion region showed values of directed ion energy independent of radial position. This result, uniform specific impulse across the exhaust plume, is a desirable attribute of the helicon method for generat-

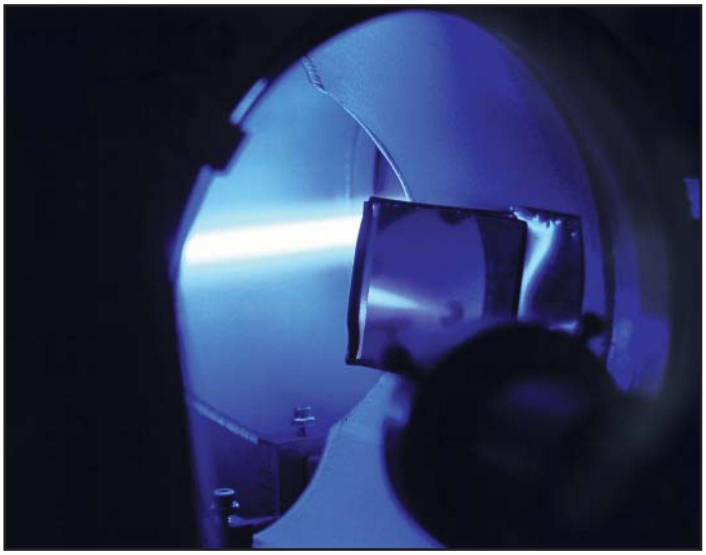

Figure 6. Photograph of an argon plasma column in the Magnetic Nozzle Experiment (MNX) main chamber, viewed through a quartz window. The bright white region shows intense emission in the blue, due to argon ion lines. This "blue core" is about one centimeter in diameter, a size that can be changed by varying the magnetic field, radio-frequency power, or neutral gas pressure. The tilted rectangular object near the picture's center is a mirror which allows viewing of the plasma as it exits the MNX main chamber through an aperture located near the nozzle coil. Laser-induced fluorescence measurements, with 1-mm spatial resolution, can be made on both sides of the aperture.

ing propulsion and illuminated the double-layer mechanism responsible for ion acceleration to supersonic energies.

The effects of plasma and neutral density, helicon power, nozzle field strength, and nozzle aperture location on directed ion energy were investigated. Within the high-density, peaked blue-core mode of operation, plasma and neutral density and helicon power had little effect on the directed ion energy. Increase in nozzle field strength decreased the specific impulse by up to a factor of two. In contrast, a large increase in the specific impulse — corresponding to a directed ion energy reaching above 70 eV — was achieved by moving the location of an aperture plate closer to the helicon antenna. The location and thickness of the double layer was deduced from LIF-measured ion velocity distributions in front of and behind the aperture and the nozzle.

Using laser-induced fluorescence in FY03, asymmetric Zeeman peaks for argon metastable ions were observed under certain operating conditions, see Figure 7. Whether this unusual phenomenon was due to plasma effects (such as μ conservation) or to atomic physics (such as level crossing, possibly the Hanle Effect) or to other effects was explored in FY04. From a practical point-of-view, the question was simply which Zeeman peak should be used to measure the ion density in the exhaust plume. In collaboration with colleagues from Professor E. Scime's West Virginia University plasma research group and with Professor F. Skiff of the University of Iowa, an extensive set of experiments were performed on MNX. These experiments, described in a paper accepted by *Physical Review Letters*, showed that the asymmetry is caused by the combined effects of a changing Zeeman splitting in the field gradient and ion acceleration in the double layer. These results are relevant to the broader plasma physics community, particularly those in solar plasma science, in that they offer a new way for remote measurement of plasma density and turbulence, without need for a calibrated light source.

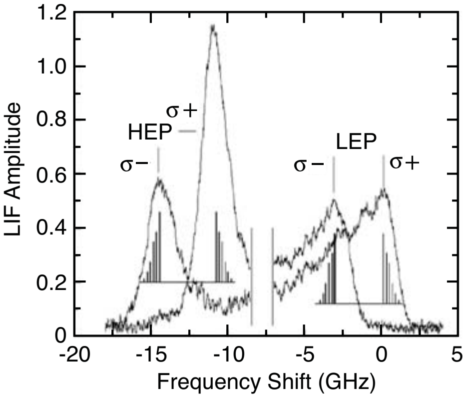

Figure 7. Laser-induced fluorescence signal for right (σ-) and left (σ+) circularly polarized laser light versus difference between laser frequency and natural frequency of the absorption line. Data were obtained 2.9 cm in front of the plasma limiting aperture for B_H = 465 G, B_N = 1,995 G, source radio-frequency power P = 550 W, and neutral pressures of 0.6 mTorr and 0.23 mTorr in the source and expansion region, respectively. A clear asymmetry is seen in the high energy peaks, HEP, (HEP, large Doppler shift) but not in the low energy peaks, LEP, (LEP, small Doppler shift).

Diagnosis of radio-frequency-heated plasmas, such as produced with helicon waves, becomes progressively more difficult at higher power flows. The use of passive (emission) spectroscopic data, interpreted with collisional-radiative models, to measure the electron temperature in the range 1–200 eV was explored. The results show better agreement between the spectroscopic information and Langmuir probes at higher densities. This is an important activity in the ongoing research program. Results are to be presented at the November *2004 American*

Physics Society's Division of Plasma Physic Meeting.

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 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 resonant frequency. More speculative benefits, such as stabilization against the internal tilt mode, have also been suggested. 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. In FY04 two graduate students, S. Landsman and N. Ferraro, and one undergraduate, E. Coleman, performed PFRC research. The research strongly benefited from collaborations with theoreticians at the Los Alamos National Laboratory (A. Glasser) and Courant Institute of Mathematical Sciences, New York University (G. Zaslavsky and M. Edelman).

Scientific investigations during FY04 were in three areas: (1) forming field-reversed configurations by odd-parity rotating magnetic fields, both with and without a seed target plasma; (2) measuring impurity concentrations in the odd-parity rotating-magnetic-fields-formed plasmas; and (3) investigating the odd-parity rotating-magnetic-fields plasma-heating mechanism. Progress on these efforts depended on several technical advances, especially the development of the odd-parity rotating magnetic fields system and the implementation of noninvasive diagnostics. Two microwave interferometers and an iCCD spectrometer system were installed. A photograph of an odd-parity rotating magnetic fields plasma discharge in the PFRC is shown in Figure 8.

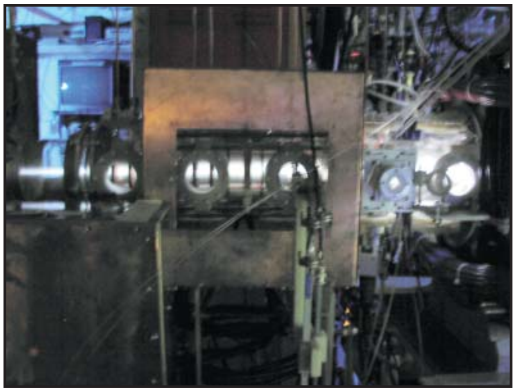

Figure 8. Photograph of a helium plasma in the Princeton Field-reversed Configuration Experiment Pyrex chamber. The rotating magnetic field heating section is surrounded by a copper box with rectangular cut-out windows. The plasma duration is 0.5 ms. The radius of the plasma to the left of the copper box decreases as it enters the bore of an axial field magnet. The bright region to the right is due to plasma streaming into the rotating magnetic field section from the seed-plasma source, a steady-state helicon-wave-heated region.

Beam Dynamics and Nonneutral Plasmas

Nonneutral Plasmas

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 atomic cross sections and multielectron loss events, and optimization of negative ion beams for heavy ion fusion 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. The simulation is possible because the transverse dynamics of the particles is equivalent in the compact PTSX configuration and periodic-focusing magnetic alternating-gradient transport systems.

Planned experimental studies include investigations of beam mismatch and envelope instabilities, collective wave excitations, chaotic particle dynamics and production of halo particles, and mechanisms for emittance growth. 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. Applied static voltages on the 40-cm-long end cylinders provide axial confinement of the trapped one-component pure ion plasma. The temporal frequency of the oscillating voltage in the PTSX corresponds to the spatial frequency of the magnets in the actual alternating-gradient transport system.

Plasmas are trapped for hundreds of milliseconds in the PTSX device, which corresponds to equivalent propagation distances of tens of kilometers. Recent experiments have explored the effects of "spoiling" the applied oscillatory voltage by suddenly changing the amplitude of the voltage for several oscillation periods, or by applying gradual changes to various transition voltage amplitudes. For the 'sudden-change' experiments, the effect on the one-component cesium plasma [as measured by the charge along the machine axis, Q(r=0)], is not monotonic with the number of cycles modified (see Figure 9). There is a periodic nature to the effect. Note also from Figure 9 that even turning off the applied voltage completely for several cycles does cause the plasma to entirely 'lose confinement.'

High-intensity Accelerators

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 transverse electromagnetic Weibel-type instability. Previous numerical and theoretical studies of intense charged particle beams with large temperature anisotropy demonstrated that a fast, electrostatic, Harris-type instability develops, and saturates, for sufficiently large temperature anisotropy. The total distribution function after saturation, however, is still far from equi-partitioned, and free energy is available to drive a transverse electromagnetic Weibel-type instability. The finite transverse geometry of the confined beam makes a detailed theoretical investigation difficult. The Beam Eigenmode and Spectra (bEASt) code which solves the linearized Vlasov-Maxwell equations has been developed and used to investigate the detailed properties of the Weibel instability for a long charge bunch propagating through a perfectly conducting cylindrical pipe.

The stability analysis has been carried out for azimuthally symmetric perturbations about a two-temperature thermal equilibrium distribution in the smooth-focusing approximation. To study the nonlinear stage of the instability, the Darwin model, which neglects radiation effects, is being developed and incorporated into the Beam Equilibrium Stability and Transport (BEST) code.

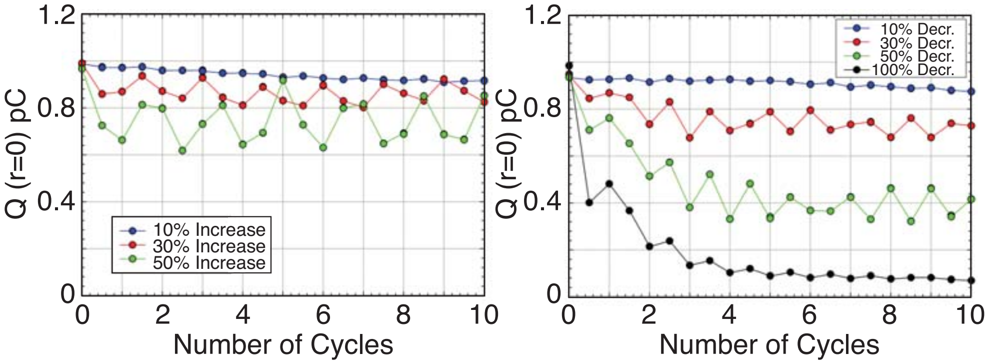

Figure 9. It is expected that an abrupt change in the amplitude of the applied oscillatory voltage for a few oscillation cycles of the wall voltage, followed by an abrupt change back to the original amplitude, would have a deleterious effect on the plasma. Surprisingly, there is a periodic nature to the effect.

Neutralized Transport and Compression of Charged Particle Beams

Heavy ion fusion research has developed reactor design concepts requiring multiple heavy ion beams to be focused to small spot size (millimeter-scale) in the target chamber. Tightly focused heavy ion beams are also an attractive research tool for performing detailed high energy density physics studies of the fundamental properties of warm dense matter. The Neutralized Transport Experiment and the Neutralized Drift Compression Experiment at the Lawrence Berkeley National Laboratory (LBNL) are investigating the most promising charge neutralization methods to achieve this level of focusing of intense heavy ion beams.

One neutralization approach utilizes a large-volume plasma to charge neutralize the heavy ion beam. The charge neutralization process has been modeled theoretically as a heavy ion beam pulse propagating through a highly ionized cylindrical plasma column. The background plasma ion motion is neglected, and electrons from the background plasma move into the ion beam channel, reducing the net positive beam space charge over the larger volume of the plasma channel.

An analytical electron fluid model has been developed to describe the plasma response to a propagating ion beam. The theoretical model predicts very good charge neutralization during quasi-steady-state propagation, provided the beam pulse duration is much longer than the electron plasma period. In the opposite limit, the beam pulse excites large-amplitude plasma waves.

The influence of a solenoidal magnetic field on charge and current neutralization has also been investigated. Analytical studies show that the solenoidal magnetic field begins to influence the radial electron motion when $\omega_{ce} > \beta\omega_{pe}$. Here, ω_{ce} is the electron gyrofrequency, ω_{pe} is the electron plasma frequency, and $\beta = V_b/c$ is the ion beam velocity. If a solenoidal magnetic is not applied, plasma waves do not propagate. In contrast, in the presence of a solenoidal magnetic field, whistler waves propagate ahead of the beam and can perturb the plasma ahead of the beam pulse. In the limit $\omega_{ce} >> \beta\omega_{pe}$, the electron current completely neutralizes the ion beam current and the beam self magnetic field greatly diminishes. For expected ion beam densities in the range of 10^{10}–10^{11} cm^{-3}, present calculations require the plasma to exceed one meter in length with an electron density in the range of 1 to 100 times the ion beam density.

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) at LBNL will investigate the key scientific issues that determine the effective limits of drift compression. The Mission Research LSP 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. Measuring the beam compression and current density with high resolution is critical for the NDCX and an understanding of the accessible parameter space is possible with numerical simulations using the LSP code. Knowledge of the current density of the compressed heavy ion beam is important for determining the amount of power that can be delivered to the target. Using the LSP simulation code, a 25-mA singly charged potassium ion beam was injected with an energy of 250 keV and accelerated with a 50% head-to-tail velocity tilt into a plasma of density 10^{10} cm^{-3}, which is a model for the one-meter-long ferroelectric plasma source being constructed by PPPL for use on NDCX. The numerical simulations show that the ion beam's initial pulse length of 500 ns is compressed to less than 5 ns at the focal point, near the end of the plasma source. The peak current at the focal point is expected to be about 5 A, which corresponds to a compression factor of 200 in current and 1,000 in beam density.

In heavy ion fusion scenarios utilizing background plasma to neutralize the beam space charge during drift compression and/or final focus of the ion beam, it is important to minimize the effects of collective instabilities associated with beam-plasma interactions. The properties of the multispecies Weibel and electrostatic two-stream instabilities for an intense ion beam propagating through background plasma have been investigated. Assuming that the background plasma electrons provide complete charge and current neutralization, detailed linear stability properties have been calculated within the framework of a macroscopic cold-fluid model. Stability properties have been determined for a wide range of beam current and plasma density, including the important effects of transverse beam geometry.

Charge Neutralization Experiments

PPPL researchers have developed advanced plasma sources to support the charge neutralization studies conducted on the Neutralized Transport Experiment (NTX) at LBNL. 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 of electrons for charge neutralization on NTX 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. Ceramic rings with relative dielectric coefficients of several thousand are stacked together to form a one-meter long, three-inch-diameter, thin-walled cylinder. 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 (Figure 10). Measurements show that plasmas with densities of 10^{11} cm^{-3} and temperatures less than 10 eV are created.

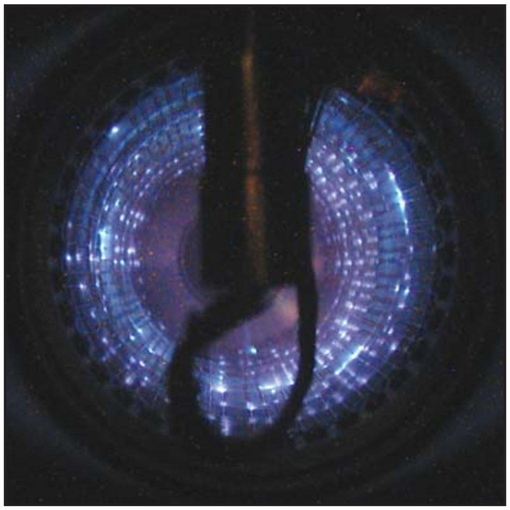

Figure 10. A time exposure of 24 plasma discharges of the PPPL ferroelectric plasma source shows the numerous small plasma discharges (bright spots) that expand and fill the cylinder with a plasma that has a temperature of less than 10 eV and a density exceeding 10^{11} cm^{-3}.

Negative Ion Beams for Heavy Ion Fusion

Negative halogen ion beams, proposed by PPPL some years ago for the role of heavy ion fusion drivers, have advantages relative to conventional positive ion beams. They will not accumulate electron clouds, which have the potential to adversely affect beam focusing, and they can easily be converted to neutrals by photo detachment which, even with subsequent reionization in the target chamber, results in lower average space-charge expansion of the spot size hitting the target. Initial tests of a chlorine source in collaboration with the Lawrence Berkeley National Laboratory have produced negative-ion current densities almost as high as the corresponding positive ions, which together with the low co-extracted electron component, suggest that ion-ion plasmas were achieved in the extractor plane, a topic of interest in its own right.

During the past year an expanded set of experiments began on a test stand at the Lawrence Livermore National Laboratory (LLNL) in collaboration with LBNL as part of the Heavy Ion Fusion Virtual National Laboratory. Initial operations measured the emittance and current density scaling of an Ar^+ beam extracted from a new radio-frequency ion source. Since argon forms essentially no negative ions, the parameters of the Ar^+ beam will be used as a benchmark for the properties of a beam extracted from a conventional ion-electron plasma to compare to beams of Cl^-, Cl^+, and electrons extracted from an ion-ion chlorine plasma in the next phase of experiments. By using the same source, ion optics, and double slit emittance measuring device, all in the same configuration, and beams with approximately the same mass (argon and chlorine), the comparison should show whether beams extracted from ion-ion plasmas have any advantages (such as lower effective temperature) over beams from ion-electron plasmas. The experiments also provide the basis for determining the optimum parameters of a negative heavy ion fusion driver beam.

An invited talk on this work, "Experimental Evaluation of a Negative Ion Source for a Heavy Ion Fusion Negative Ion Driver," by L.R. Grisham, S.K. Hahto, S.T. Hahto, J.W. Kwan, K.N. Leung was given at the *15th International Symposium on Heavy Ion Inertial Fusion* held at Princeton University in June 2004 and will be published in the refereed proceedings of a Special Issue of *Nuclear Instruments and Methods in Physics Research, Section A*.

A paper, "Moderate Energy Ions for High Energy Density Physics Experiments," by L.R. Grisham was published in the December 2004 issue of *Physics of Plasmas*. In this paper, the author describes research which found that choosing the target thickness and beam energy such that the ion beam enters at an energy just above the top of the energy loss peak in dE/dX (sometimes erroneously called the Bragg peak) and leaves the target at an energy which is still near the top of the peak, results in achieving the maximum intensity of energy deposition while simultaneously obtaining the most uniform deposition through the target. This approach, which is contrary to the traditional strategy of operating at energies far above the dE/dX peak, makes a virtue of the relatively low energies available to the heavy ion fusion program over the next 10–15 years, allowing meaningful warm-dense-matter experiments to be performed with moderate cost facilities.

Magnetorotational Instability Experiment

Background

Astrophysicists have long inferred 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 (Keplerian) equilibrium profile of a fluid disk bound by the gravity of a central object produces a circumferential velocity that decays as angular velocity proportional to the radius to the power of -3/2 so that this arrangement is linearly stable to the centrifugal instability. Although there is some possibility of a nonlinear (or subcritical) hydrodynamic transition to turbulence in these systems, it is now commonly held that the transition to turbulence in astrophysical accretion disks is via the magnetorotational instability (MRI). Although the MRI was discovered some half-century ago, it came to the attention of the astrophysical community relatively recently, around 1990. The instability mechanism is essentially the coupling of the Keplerian shear flow, which represents a gradient in kinetic energy, by a magnetic field component aligned with the axis of rotation.

The strength of the magnetic field is important for the MRI: it must be high enough to be effective in communicating energy before differential motion separates radially adjacent fluid parcels, and also adequately strong so that perturbations in the magnetic field do not rapidly diffuse away. But the magnetic field strength must not be so strong as to restrict relative motion (as would happen within a perfectly conducting fluid). Thus a maximum magnetic field strength exists, depending upon the shear rate, above which MRI is quenched.

The physical requirements described above may be considered more quantitatively with a consideration of nondimensional parameters derived from the dynamical equations of motion. For the Magnetorotational Instability Experiment to overcome the dissipative effects of hydrodynamic viscosity and magnetic diffusivity, it should be expected that the Reynolds numbers $Re \equiv UL/\nu$ and $Re_m \equiv UL/\eta$, along with the Lundquist number $S \equiv V_A L/\eta$, significantly exceed unity. (Here U is the characteristic velocity, L is the characteristic scale, ν is viscosity, η is resistivity, and V_A is the Alfvén velocity.) These requirements set lower limits for size, speed, and magnetic field strength for a fluid of given viscosity and resistivity.

Implementation

Achieving a dynamical regime pertinent to any large-scale astrophysical scenario may seem like an unfruitful avenue for laboratory science. And although the reaching of a full dynamical similarity appears impossible, it does seem possible to achieve a regime ($Re >> 1$, $Re_m \geq 1$, $S \geq 1$) where MRI is possible. The means devised to accomplish this is a relatively large mass of liquid metal spinning rapidly and differentially within a magnetic field. The apparatus for this experiment is shown in Figure 11.

The apparatus is essentially a Taylor-Couette flow device, that is, a cylinder within a larger cylinder, which generates a sheared profile within the fluid annulus in-between cylinders. Based on results from a prototype experiment in water and corresponding hydrodynamic simulations, the traditional design has been modified to accommodate two intermediary disks at both axial boundaries. These intermediate disks should allow for the reduction of unwanted secondary flows produced by the frictional effects of the top and bottom boundaries. (Such secondary/Ekman flows, though interesting in their own right, are irrelevant to the astrophysical disks it is hoped to emulate, which possess a stress-free periph-

Figure 11. The Magnetorotational Instability Experiment (MRI).

ery. Moreover, these flows redistribute angular momentum in a manner that is detrimental to the establishment of a relevant velocity profile.) Motors drive each of the six rotating components, at speeds up to 4,000 revolutions per minute, via a belt and gear attached to a shaft that is directly connected to a component. Between shafts are housings for Teflon seals, which prevent leaking of fluid from the high-pressure environment within the rotating apparatus below. The shafts are supported and aligned by thrust-bearing roller collars. The machining, sealing, and overall alignment of the inter-nested shafts has proved to be challenging. The total rotating apparatus is housed in a robust frame, which itself can be rotated to expedite maintenance. Temperature and vibration sensors are monitored during operations to ensure an environmental consistency for experiments.

For the MRI to be possible, an electrically conducting fluid needs to be used; an alloy of gallium (67% gallium, 20.5% indium, 12.5% tin) has been chosen. Figure 12 shows the results of a stability calculation delineating three regimes that the experiment will be able to achieve with liquid gallium in the rotating and magnetized environment. Region I is centrifugally unstable, and will be avoided, while Region III is always stable regardless of the magnetic field. It is Region II that is of interest, which is stable hydrodynamically, but unstable magnetohydrodynamically via the MRI. Figure 12 demonstrates that the MRI is possible in the laboratory. With several (axisymmetric) modes being unstable (1–5), nonlinear activity is expected; perhaps even turbulence. The nonlinear saturation of the instability should prove useful in benchmarking astrophysical codes, and provide

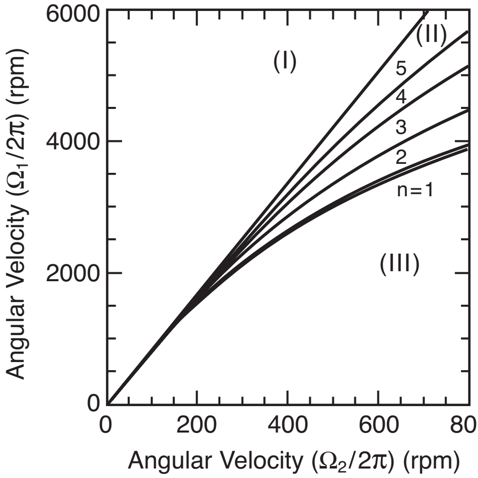

Figure 12. Results of a stability calculation delineating three regimes with liquid gallium in the rotating and magnetized environment.

insight into physical mechanisms that are important to accretion disks.

Status and Experiments Planned

Initial data on the flow field within the apparatus with water, using light reflected from small neutrally buoyant particles in the flow (also known as streak velocimetry), has indicated that the intermediary disks are successful in reducing the secondary flow circulation. Consequently, circumferential velocity profiles can be created in the fluid that are favorable for the MRI study. Experiments in gallium will begin after assessing effects from possible nonlinear hydrodynamical instabilities in large Reynolds numbers. Use of liquid gallium presents certain diagnostic challenges however. In particular, its opacity means that the plethora of optical-based diagnostic techniques is of no use. Instead, various noninvasive methods for diagnosing an opaque flow field, such as acoustics (sonar) and ultrasound, are being actively pursued. 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 — the angular momentum transport — will be measurable simply via torques upon the driving motors. These diagnostic methods are all being actively developed so that when the MRI is produced it can be well characterized. If successful, the MRI experiment will be a significant advancement in astronomical knowledge generally, and for the budding field of 'laboratory plasma astrophysics' in particular.

Diagnostic Development

Electron-Bernstein Wave Emission Diagnostic

In "overdense" plasmas, such as those in the National Spherical Torus Experiment (NSTX), the electron plasma frequency far exceeds low harmonics of the electron cyclotron frequency, precluding the use of conventional electron cyclotron emission (ECE) as an electron temperature profile diagnostic. Electron-Bernstein wave emission (EBE) has the potential to provide an electron temperature profile measurement in such an overdense plasma. Unlike electron cyclotron emission, EBE must be detected via mode conversion to electromagnetic radiation. Two EBE mode-conversion processes are being investigated on NSTX: conversion to the extraordinary mode (X-mode) at normal incidence to the magnetic field and conversion to the elliptically polarized ordinary mode (O-mode) at an oblique angle to the magnetic field.

In FY04, an 8 to 18-GHz EBE X-mode antenna with a local adjustable limiter to enhance the EBE mode conversion was tested. Unlike similar X-mode coupling experiments on Current Drive Experiment-Upgrade (CDX-U) that yielded close to 100% mode conversion two years ago, coupling of EBE via the X-mode was found to be insensitive to the plasma conditions on NSTX. The EBE coupling efficiency was determined by comparing the radiation temperature of the thermal X-mode emission to the local electron temperature measured by Thomson scattering. A nearby microwave density reflectometer provided valuable data on the density profile in the vicinity of the EBE mode-conversion layer. A number of different plasma conditions were investigated, but they all yielded low mode-conversions efficiencies (<10%). For all of the plasma conditions investigated there was insufficient density to reach the critical density for fundamental EBE mode conversion ($n_e < 2 \times 10^{18}$ m^{-3}) at the local limiter. Consequently, the local limiter was ineffective.

To correct this, a gas valve is being installed near the moveable limiter assembly that will allow the local electron density to be raised above the critical density for EBE conversion.

Although X-mode antenna measurements showed low-conversion efficiency, efficient EBE conversion via the O-mode was measured on NSTX. Microwave emission at 16 to 18 GHz was measured by a quad-ridged horn antenna with its axis aligned oblique to the confining magnetic field at the outer edge of the plasma. Emission at 16.5 GHz, corresponding to the frequency of fundamental EBE emitted from r/a ~ 0.4 on the high field side of the magnetic axis, was measured to mode convert from EBE to electromagnetic radiation with an efficiency of 80±20%. Orthogonally polarized signals detected by the antenna were similar in magnitude, a result that is consistent with theoretical calculations that predict near-circularly polarized mode-converted EBE. These results and modeling predictions suggest that a temperature diagnostic can be developed using circularly polarized emission. These results are important because they show that the O-mode conversion efficiency is sufficient for a wide range of local density gradients and that circularly polarized EBE has real potential for being developed into a robust temperature diagnostic for overdense plasmas.

3-D Microwave Imaging System on TEXTOR

Diagnostic systems for fluctuation measurements in plasmas are, of necessity, evolving from simple one-dimensional to multi-dimensional systems due to the complexity of the fluctuation physics, as illustrated by advanced numerical simulations. Utilizing the recent significant advancements in millimeter wave imaging technology, Electron Cyclotron Emission Imaging (ECEI) and Microwave Imaging Reflectometry (MIR), which simultaneously measure density and temperature fluctuations, have been developed for the TEXTOR tokamak. This is a result of a strong collaboration between three institutions (PPPL, the University of California at Davis, and the FOM Instituut voor Plasmafysica "Rijnhuizen" in the Netherlands).

Both ECEI and MIR systems operate in a similar microwave range (the MIR frequency range is about 88 GHz and the ECEI frequency range is from 95 to 130 GHz). Consequently, it is feasible to combine the two imaging systems, which utilize state-of-the-art millimeter-wave planar arrays positioned at the focal point of the detection system. The MIR and ECEI systems share large collection optics for the reflected waves from the "cut-off layer" and for vertically (poloidally) extended electron cyclotron emission, respectively.

In an imaging diagnostic, it is essential to make use of as large an acceptance aperture as possible. In the TEXTOR system, the limiting aperture occurs at the vacuum window, which is 42-cm high, 30-cm wide, and is located 57 cm from the plasma boundary. All other optics have been adapted to make use of the full window aperture. Figure 13 shows the combined ECEI and MIR system on TEXTOR. It employs large optics and a beam splitter that reflects MIR frequencies below 95 GHz while transmitting the ECEI frequencies at 110 GHz or above. In the previous generation ECEI systems, the measurements were essentially one-dimensional in nature in that the detected radiation from each array element was sampled at only a single frequency at a time, resulting in measurements of vertically distributed plasma volumes. This

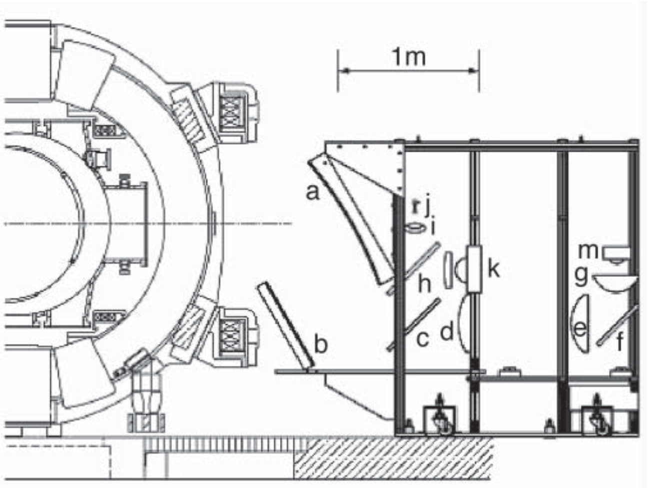

Figure 13. The detailed schematic of the TEXTOR Electron Cyclotron Emission Imaging (ECEI)/Microwave Imaging Reflectometry (MIR) system: (a) poloidal focusing mirror, (b) toroidal focusing mirror, (c) beam splitter for MIR and ECEI, (d) H-plane focusing mirror for ECEI system, (e) E-plane focusing mirror for ECEI system, (f) flat mirror, (g) moveable lens for the ECEI system focal depth change, (h) beam splitter for MIR source and signal, (i and j) MIR source beam and collimating lens, (k) MIR detection array, (m) ECEI array.

is in contrast to the conventional wideband electron cyclotron emission radiometer, in which multiple frequency elements are simultaneously detected from a single antenna resulting in a horizontally aligned sampling. The new generation, two-dimensional, electron cyclotron emission imaging system introduced two new technology advances: (1) a dual-dipole antenna array which has significantly improved sensitivity and antenna patterns, and (2) wideband transmission lines, which enable multiple simultaneous radial measurements for each vertical detection array element.

A logical test of the electron temperature fluctuation measurement capability for the new ECEI system is m=1 oscillations (sawteeth) which are well-established MHD phenomena in tokamaks. The fundamental magnetic reconnection process remains an outstanding issue, however, and requires two-dimensional measurement of electron temperature and plasma current. Primary outstanding issues are: (1) whether the reconnection process is partial (localized in poloidal and toroidal space) or full, and (2) whether the physics of the sawtooth crash follows the resistive time scale.

The test plasma conditions for the ECEI experiment were as follows: plasma current I_p = 400 kA, toroidal magnetic field B_t = 2.3–2.4 T, electron density $n_e(0) = 2–4 \times 10^{13}$ cm^{-3}, and electron temperature $T_e(0)$ ~ 1 keV. Since the radial coverage is limited to approximately 6 cm near the core, radial extensions of the image can be obtained by varying either the toroidal field or the local oscillator frequency on a shot-to-shot basis. To visualize the heat transfer out of the inversion radius to the mixing zone, a sequence of the heat transfer processes is illustrated in Figure 14 employing a composition of three images obtained from three plasma discharges with slightly different magnetic field strengths (2.3,

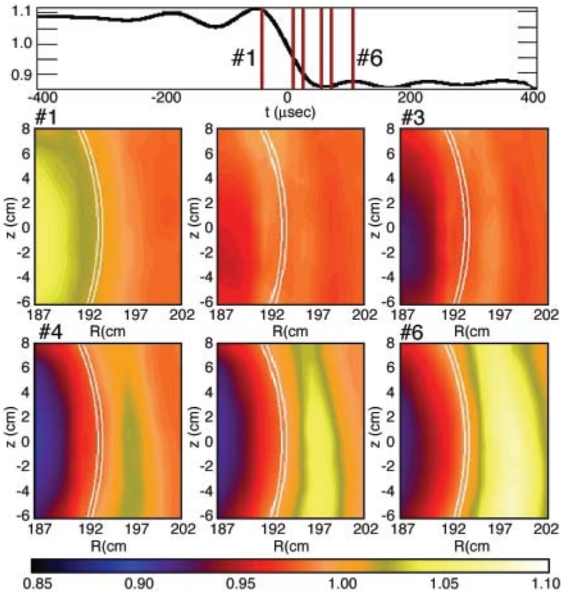

Figure 14. Six frames of the sawtooth crash processes, emphasizing heat transfer out of the inversion radius, are illustrated through a composition of the three two-dimensional images (384 pixels) obtained by varying the toroidal magnetic fields (2.3, 2.35, and 2.4 T). Note that the double white lines are an estimated inversion radius.

2.35, and 2.4 T). Since the change of magnetic field was less than ±2%, there was little change in plasma parameters such as temperature and density. It is also believed there was a minute change in the safety factor q ~ 1 layer, if any.

The preliminary analysis demonstrates that the temperature in the vicinity of the inversion radius is not perturbed through the crash whereas the hot spot is clearly present both before and after the crash. A detailed understanding of the poloidal mode number m=1 mode oscillation will be the immediate goal as soon as the core current profile measurement is available together with other important diagnostic information on TEXTOR. While a detailed physics study of the m=1 mode reconnection process is in progress, the present ECEI system with a relatively small image but with a high degree of spatial resolution is ideal for the study of smaller magnetic island structures, such as neoclassical tearing modes and double tearing modes which are harmful MHD phenomena for plasma stability near the q ~ 2 surface.

The MIR campaigns have yielded poloidally resolved spectra and assessments of the poloidal phase velocity of turbulent structures. Using the measured spectra from the MIR system, a preliminary spectral analysis was performed. The cross-coherency between channels yields a phase lag between each spectral component for each spatially separated channel pair. The magnitude of the cross-coherency, can be calculated against both the frequency (f) and the phase lag divided by the channel spacing (summed for all channel pairs $\Delta\phi/\Delta z$). The ration betwee f and $\Delta\phi/\Delta z$ yields the poloidal velocity of the turbulent structures over a wide spectral range, and is weighted by the channel pairs exhibiting the highest coherency. This type of plot is presented in Figures 15(c) and 15(d), for two time-slices taken during neutral-beam-injection heating and just after the turnoff of the neutral beam, respectively. The corresponding complex spectra for a central channel are shown in Figures 15(a) and 15(b). During neutral-beam injection, the frequency spectrum is broad and the derived rotation speed is +21 km/s [Figure 15(a)], corresponding to the ion diamagnetic direction as shown in Figure 15(c). Once the heating beam is turned off, the plasma slows down within a beam slowing down time scale and settles at -12 km/s [Figure 15(b)] in the electron diamagnetic direction as shown in Figure 15(d). This type of measurement will provide insight into the physics of “zonal flow” and fluctuation behavior in the vicinity of the internal transport barrier.

X-ray Imaging Crystal Spectrometer

The X-ray Imaging Crystal Spectrometer is a new kind of spectrometer, which consists of a spherically bent crystal and a 10-cm by 30-cm large, two-dimensional position-sensitive multi-wire proportional counter. It records spatially and temporally resolved X-ray spectra of helium-like ions from medium-Z elements, such as argon or krypton, from multiple lines of sight through the plasma for measurements of the radial profiles of the ion and electron temperatures, and the plasma rotation velocities. The spatial resolution in the plasma is solely determined by the height of the crystal and the Bragg angle and is of the order of one centimeter. Contrary to diagnostic techniques based on charge-exchange recombination spectroscopy, this instrument does not require the injection of a neutral beam and can produce data for all experimental conditions, which include plasmas with Ohmic heating and radio-frequency heating, as well as plasmas with neutral-beam injection. It will therefore also be of interest for future large tokamaks, such as ITER, where neutral beams may not penetrate to the plasma core. This new instrument is also expected to replace the presently used arrays of single-chord X-ray crystal spectrometers, which have only provid-

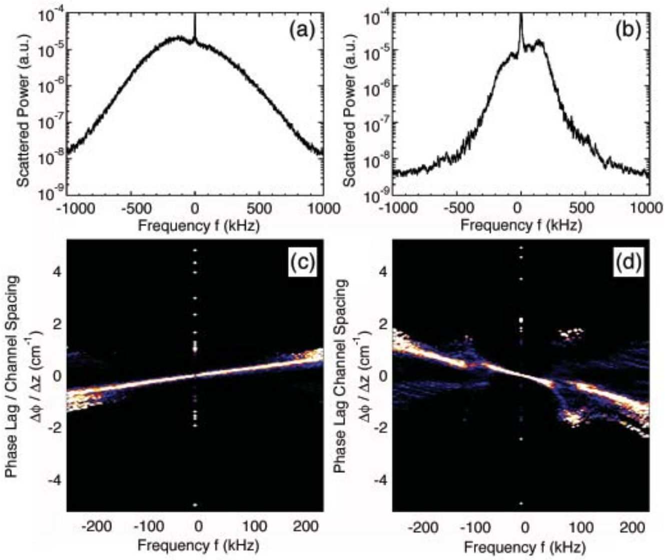

Figure 15. Poloidal velocity of turbulent spectra. Neutral-beam injection is turned off at 4.5 s. (a) broad frequency spectra and estimated initial velocity is +21 km/s during neutral-beam injection (co-beam) (4.4 s). (b) narrow frequency spectra after neutral-beam injection is turned off; rotation reverses and settles at -12 km/sec (4.8 s), (c) and (d) are the measured poloidal velocity for (a) and (b), respectively.

ed coarse information on the ion temperature profiles in tokamak plasmas.

The concept of the X-ray imaging crystal spectrometer was patented in 2001, and proof-of-principle experiments were conducted on the NSTX and the Alcator C-Mod tokamak (at the Massachusetts Institute of Technology). These were done in close collaboration with colleagues from the Korea Basic Science Institute and Brookhaven National Laboratory, both of whom developed two-dimensional X-ray detectors used alternately. Results from these experiments and new data analysis software were presented at the *15th Topical Conference on High-temperature Plasmas Diagnostics* in 2004. The X-ray imaging crystal spectrometer has been funded since FY02 by the U.S. Department of Energy Program Announcement LAB01-25: Development of Diagnostic Systems for Magnetic Fusion Energy Sciences. This funding has recently been renewed for three more years. Plans for the future include: (1) to develop new high-count rate detectors and electronics to increase the throughput of the spectrometer and to overcome the present count rate limit of 400 kHz and (2) to build a new dual X-ray crystal spectrometer, which will make it possible to measure profiles of the toroidal and poloidal rotation velocities simultaneously.

Liquid Metal Experiment

The Liquid Metal Experiment at PPPL is a small-scale laboratory experiment used to study the fundamental physics of magnetohydrodynamic (MHD) effects on surface waves and turbulence in liquid metal. MHD turbulence is regarded as an essential element of many intriguing phenomena observed in space and laboratory plasmas and it is a primary subject of basic plasma physics research. Also, recent interest in the application of liquid metal to fusion devices has added new demands for a better understanding of MHD physics of electrically conducting fluids. The Liquid Metal Experiment focuses on MHD effects on fluid turbulence and surface waves using liquid gallium, which can be well approximated by MHD models. Three basic physics issues are being addressed. (1) When and how do MHD effects modify surface stability, either in linear regimes or nonlinear regimes such as solitary waves? (2) When and how do MHD effects modify a free-surface flow, such as by surface deformation? (3) When and how do MHD effects modify thermal convection?

In neutral fluids such as water, depending on the wavelength, gravity and surface tension are dominant restoring forces for a surface wave. When a liquid metal is subjected to a magnetic and/or electric field, the Lorentz force adds to the wave complexity, leading to possible new instabilities. In PPPL's Liquid Metal Experiment, an external wave driver with varying frequency and amplitude is used to excite surface waves in the liquid metal. Reference cases are established using water and gallium without magnetic and electric fields. MHD effects can be examined by imposing an external magnetic field and/or electric current with varying amplitudes and angles with respect to wave propagation direction. A laser reflection system combined with a gated ICCD camera is used to measure dispersion relation and wave amplitudes.

It is found that the driven waves are not affected by a magnetic field applied 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, predicts magnetic damping of surface waves, in good agreement with

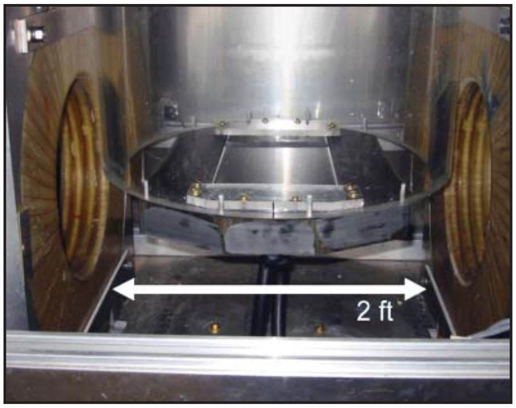

Figure 16. Initial apparatus for wide Hartman flow investigation.

the experimental results. Two-dimensional waves, made by shaking the liquid vertically (Faraday waves), have also been studied focusing on the MHD effects due to an imposed horizontal magnetic field.

Experiments have started on liquid gallium flow across an imposed magnetic field using a prototype gallium channel, as shown in Figure 16. The channel is 15.4 centimeters wide by 1.2 centimeters deep, with characteristic flow speeds of approximately 15 centimeters per second. The magnetic field is transverse and coplanar to the flow and is variable up to 1.2 kG. With these values fluid Reynolds numbers of approximately 5×10^4 and Hartman numbers of approximately 360 have been obtained. Internal velocity profiles were determined by two independent diagnostics: (1) by measuring the drag force on a submerged paddle, which is proportional to the square of flow velocity, and (2) by measuring the electric potential difference between two electrodes, i.e., by the induced Hall effect. The obtained results are qualitatively consistent with each other, and also with the (integrated) reading of a flow meter. Measured profiles by potential difference are shown in Figure 17 for three Hartman numbers. It is seen that the profiles become more peaked with increasing magnetic field. This is perhaps against the usual intuition of Hartman flow, which would typically flatten the velocity profile with increasing magnetic field. It turns out that this result can be understood as an effect of small channel aspect ratio of depth to width.

To illustrate this effect, Figure 18 shows the calculated flow profile using a two-dimensional incompressible MHD code for different combinations of magnetic field and aspect ratio. It is seen that when the width is less than or equal to

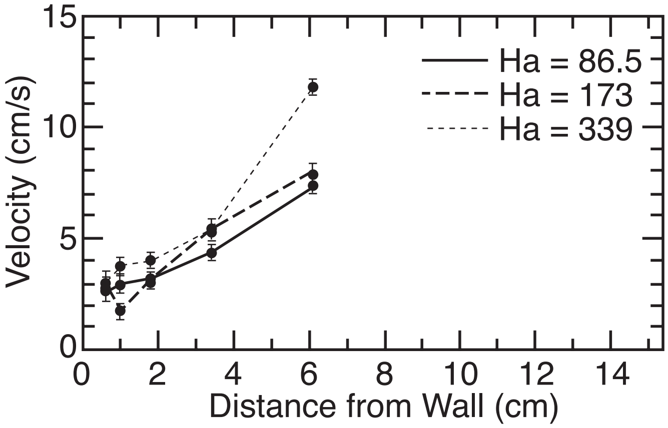

Figure 17. Initial results of the measured profiles by potential difference for three Hartman (Ha) numbers indicating a more peaked profile with higher magnetic field.

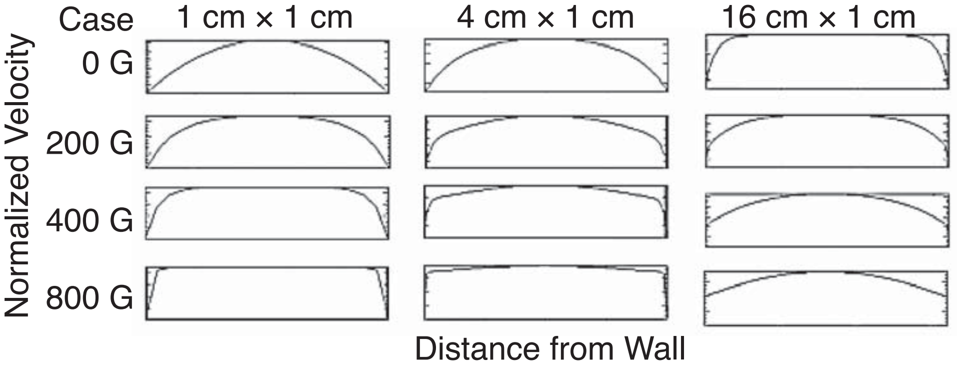

Figure 18. Effect of channel aspect ratio and magnetic field strength upon the velocity flow profile. The width of each rectangle represents the full channel breadth. The ordinate is normalized velocity.

the depth (i.e., for square and narrow or deep channels), the peaked profile flattens with increasing magnetic field. However, when the width is greater than the depth (i.e., wide or shallow channels), the originally flattened profile (at magnetic field B = 0) at first becomes more peaked with increasing magnetic field. In this case the electric current paths generated by the flow are localized near each side of the channel, leaving an essentially current-free region in the center. As the magnetic field increases further, these current paths (and attendant Lorentz forces) eventually grow to fully penetrate the central flow region, so that the profile ultimately flattens. Thus the flattening behavior typical of two-dimensional Hartman flow in narrow (deep) channels is displayed also in wide channels, but only above a minimum magnetic field that is dependent upon aspect ratio.

The effects due to small channel aspect ratios have important implications. In this case, an external transverse magnetic field can be introduced in the free-surface liquid metal flow without being dominated by boundary layers. And thus the flow can be subject to other types of instabilities, such as shear-driven surface instabilities, which may have important implications to the liquid metal wall applications in fusion devices. Dynamics of free-surface shear flows also have important connections to the observed energetic phenomena (such as X-ray bursts) in neutron stars, where newly accreted matter also drives free-surface, MHD shear flows.

To better study these phenomena, a larger, more refined experiment is under construction that will permit a higher flow rate in a stronger magnetic field, such that the Hartman number is approximately 2,000 and the Reynolds number is approximately 4×10^5. These dynamical parameters should allow for a MHD channel flow that is likely unstable and turbulent and is amenable to various flow and transport studies. Studies involving heat transport are also planned. Overall, the results of the Liquid Metal Experiment should prove useful in the understanding of free-surface MHD flows, in the design and control of these flows in fusion applications, as well as in the understanding of important astrophysical phenomena, such as X-ray bursts from neutron stars.

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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 staff 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 C- and D-site experimental facilities.

NSTX Engineering

A redesign of the National Spherical Torus Experiment (NSTX) demountable toroidal-field (TF) assembly was completed and implemented before the start of the FY04 experimental campaign. This new design provided an increase in the stiffness of the hub assemblies, utilizing steel boxes with epoxy filling rather than shims to contain the joint flags. The flags were mounted using larger diameter fasteners tightened to twice the force than the original design, and shear keys were added to resist the vertical electromagnetic force. In addition, voltage probes were added at all 72 TF joints to provide high-resolution real-time resistance measurements, and a fiber-optic-based instrumentation system was made available to take strain, temperature, and displacement measurements at select joints.

The FY04 experimental campaign started on schedule in January 2004, completing 21 weeks of operation in early August. During this period there were 844 hours of high-power operations with technical subsystems operating at an average of 92% availability. There were 2,701 plasma attempts during this operating period, resulting in 2,460 plasmas.

The NSTX operated under its best vacuum conditions to date due to implementation of systems to allow boronization of the vacuum vessel walls using trimethylboron while at vessel bakeout temperatures, and to provide a rapid daily boronization to meet experimental needs. Additional machine capabilities were added to support experiments on techniques to achieve solenoid-free plasma initiation. Poloidal-field coil 4 (PF4), which up to this year has not been used, was commissioned to operate at up to 15 kA via one of the Field Coil Power Conversion (FCPC) System's thyristor rectifiers, and successfully supported outer-PF-only induction operations. Also, a new capacitor bank was designed and installed and successfully supported transient Coaxial Helicity Injection start-up experiments (see Figure 1).

Two of the six error-field coils proposed for experiments to better characterize the limits of stability of spherical torus (ST) plasmas were mounted on

Figure 1. New capacitor bank for coaxial helicity injection start-up experiments on the National Spherical Torus Experiment.

NSTX and powered as a pair using an field coil power conversion thyristor rectifier. This arrangement provided initial data for future resistive wall mode experiments and set the stage for mounting the four remaining coils, completed after the experimental run this year. A new switching power amplifier capable of driving 3 kA, controllable to 7 kHz, in each of three pairs of error-field coils will be put into service for next year's run.

A lithium pellet injector (LPI) and new shoulder gas valve controls were designed and implemented to support particle control experiments. The lithium pellet injector is capable of solid or powder (micropellet) injection, and can fire from one to eight pellets per plasma discharge. It has a 400-pellet capacity for pellets ranging in mass from less than 1 to 5 mg (see Figure 2).

Upgrades to the SKYbolt computer that provides real-time controls of power supplies has reduced the system latency (time required for the system to respond to a change in an input signal) by a factor of four. Other control system upgrades this year include a real-time phase-control system for high harmonic fast wave (HHFW) feedback control of antenna loading, and radio-frequency filtering for the magnetic diagnostic system to allow real-time plasma control during high-power HHFW operations.

During the first four months of the experimental run, a small but gradual upward drift of the resistance of some of the more highly stressed TF joints was measured. Although all joint resistances measured well below 700 nano-ohms during all stages of a machine pulse, a TF operating limit of 3 kG was imposed while joint performance was analyzed. Subsequent measurements indicated larger than expected TF flag displacements at higher TF operating levels, and modeling sug-

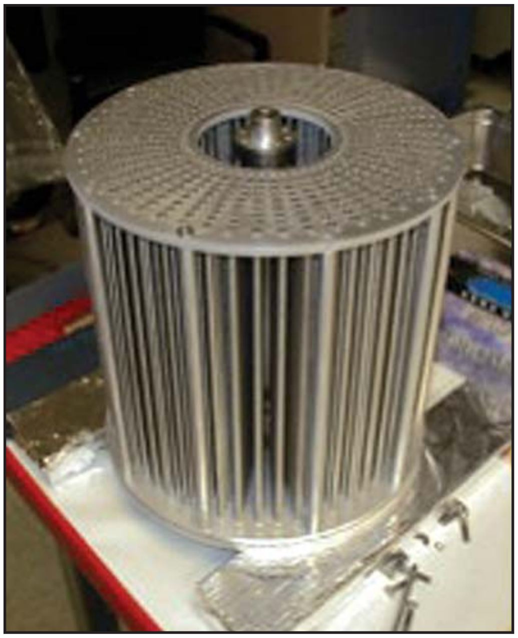

Figure 2. The 400-barrel turret on the National Spherical Torus Experiment's new lithium pellet injector.

gested that the epoxy potting in the flag boxes was softer than expected. Toroidal-field joint performance remained stable at 3 kG, and the FY04 experimental run was successfully completed.

At the end of the experimental campaign, the TF joints were dismantled and inspections indicated that there were voids in the epoxy potting due to inadequate impregnation of the fiberglass and premature curing of the epoxy. New techniques for the epoxy filling of the boxes were developed and a long pot life resin was identified to overcome these issues. Several plexiglass TF box replicas were built so that a demonstration of the potting process can be viewed in real time. Samples of the exact epoxy/glass composite proposed for use in the final assembly will be fabricated and tested to assure that the modulus of elasticity of the potting will effectively react to the moment applied to the flag. Prototype TF box and flag assemblies will be fabricated and tested to failure, and each of the 72 final units will be tested prior to normal operations.

NSST Engineering

Exploratory studies of a Next Step Spherical Torus (NSST) device have been underway since FY01, and continued during the past year, albeit at a relatively low level. The idea of the NSST is to advance ST research from the proof-of-principle 1-MA plasma-current regime of existing machines [NSTX, Mega Ampere Spherical Torus (MAST)] to a 10-MA regime. At this level the NSST would demonstrate ST physics relevant to future ST devices such as a Component Test Facility (CTF) that could be used as a neutron source and test bed for fusion technology. A key feature of all ST designs is the demountable and removable TF coil central conductor, which requires the implementation of a high-current electrical joint in a region of high electromagnetic loading.

Work on NSST in the past year focused on the structural behavior of the TF coil system and the design of a mechanical support structure that facilitates implementation of the high-current joint. Finite element analysis was performed to gain insight into the behavior of the system, which must account not only for the high electromagnetic loading but also for the axial displacement of the liquid-nitrogen-cooled central core due to its rise from 80 degrees Kelvin up to room temperature during a pulse. A support concept was developed which appears to be adequate for in-plane loading, and work is now underway to evaluate and further develop the design in the presence of both in-plane and out-of-plane loading.

NCSX Engineering

During FY04, the National Compact Stellarator Experiment (NCSX) project successfully completed several technical and cost and schedule reviews, leading to the U.S. Department of Energy's (DOE) authorization for start of fabrication. This very significant achievement permitted NCSX to enter its fabrication phase by the end of FY04 with the awarding of a $4.5 M subcontract for the vacuum vessel.

The NCSX Project Preliminary Design Review (PDR) was conducted in October 2003. The committee found that, "the NCSX design is technically sound, the management plans and budget are adequate, and the project is ready for CD-2 (i.e., establishment of the project's cost and schedule basis)." Accordingly, NCSX proceeded with two follow-up reviews conducted in parallel at PPPL November 18–20, 2003. The DOE Office of Science (SC) conducted the first, a Performance Baseline Review. The panel, chaired by Daniel Lehman, head of the DOE Office of Science Construction Management Support Division, included researchers and managers from fusion and other DOE/SC programs. Their goals were to examine the NCSX's design, cost, schedule, and management plans and to assess the project's readiness for CD-2 (Critical Decision 2). The DOE Office of Engineering and Construction Management conducted the second review, a Performance Baseline Validation, thereby satisfying DOE's requirement for an external independent review for a project of NCSX's magnitude. The team was comprised of outside consultants, led by Gerald Westerbeck of Logistics Management Institute, McLean, Virginia. The primary purpose of this review was to validate the proposed NCSX baseline and to provide reasonable assurance that the project could be successfully executed. Both review panels concluded that NCSX was ready for CD-2. Consequently, DOE approved the NCSX project baseline, which specifies a cost of $86.3 M and a first plasma date of May 2008.

The main NCSX technical efforts during FY04 were the completion of the final designs of the modular coil winding forms and vacuum vessel subassembly. The NCSX design calls for 18 modular coils, comprised of three coil types (see Figure 3). The completed coils bolt together at their flanges to form a stiff, continuous shell structure as shown in Figure 4. This structure reacts electromagnetic loads as high as 7,000 pounds per inch with a maximum deflection of 1.3 mm. The modular coil shell has numerous penetrations through which diagnostic devices will access the plasma for measurement of critical performance parameters, such as plasma temperature, density, and confinement characteristics.

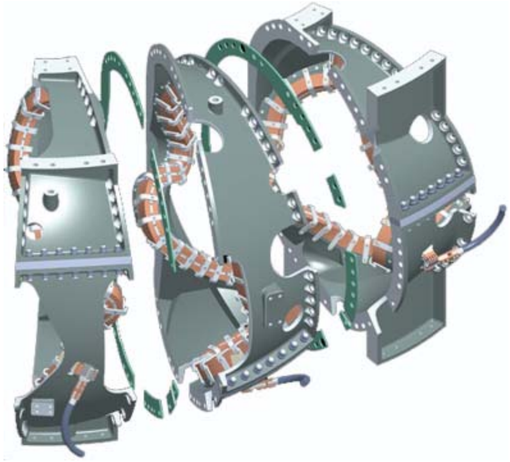

Figure 3. The National Compact Stellarator Experiment will utilize three modular coil types.

Figure 4. The National Compact Stellarator Experiment modular coils are bolted together to form a shell structure.

A large amount of design, analysis, and R&D was performed in preparation for the Final Design Review of the modular coil system, the most critical component of NCSX. Great care was taken in the coil designs to minimize magnetic field errors to achieve good plasma confinement. The modular coil design features cable conductor wound four-in-hand onto the winding form. A cross section of the winding pack in the lead area is shown in Figure 5. Subdividing the cable into a four-in-hand design was chosen to minimize cable distortions during

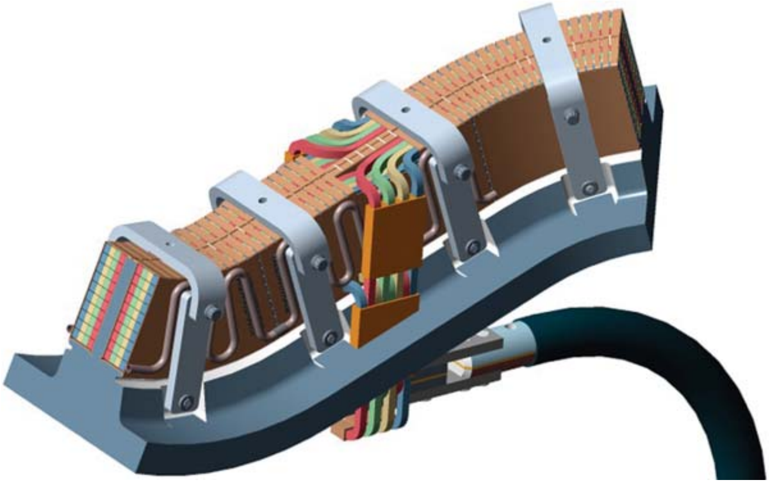

Figure 5. The National Compact Stellarator Experiment modular coil winding pack.

winding ("keystoning"), so the cable can be accurately located. The lead region details and their locations near the outboard midplane were also carefully chosen. Thermal analysis indicates that during a plasma pulse the coils will heat up adiabatically with a temperature rise of 40 degrees Kelvin and cool down within the 15 minutes between pulses. Liquid-nitrogen-cooled copper chill plates will provide the cooling.

During final design of the modular coil winding forms, manufacturing development efforts continued with two industrial teams, one lead by Energy Industries of Ohio, Inc. and the other by J.P. Pattern, Inc. of Wisconsin. Each team cast a prototype of the Type C winding form. Energy Industries of Ohio's prototype casting is shown in Figure 6.

The NCSX vacuum vessel will be comprised of three identical subassemblies, one for each field period. Final design of the vacuum vessel subassembly was completed concurrently with the modular coil winding forms. The vacuum vessel geometry is constrained to fit between the plasma and modular coils. It features numerous ports to provide diagnostic and heating access to the plasma, as shown in Figure 7. Magnetic diagnostics, cooling tubes, and thermal insulation will be installed after the vacuum vessel subassemblies are delivered to the Princeton Plasma Physics Laboratory.

Finite element analyses were performed to confirm the adequacy of the vacuum vessel's ability to withstand stresses and deflections. Concurrently, two industrial participants performed manufacturing development, Major Tool and Machine, Inc. and Rohwedder, Inc. Each team developed manufacturing processes and produced a prototype vacuum vessel segment. The prototype segment from Major Tool and Machine, Inc. is shown in Figure 8.

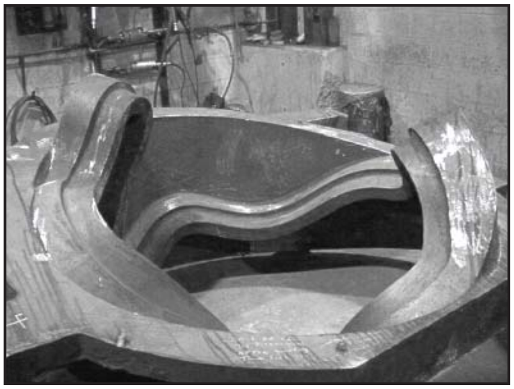

Figure 6. A prototype casting of an National Compact Stellarator Experiment modular coil winding form fabricated by Energy Industries of Ohio, Inc.

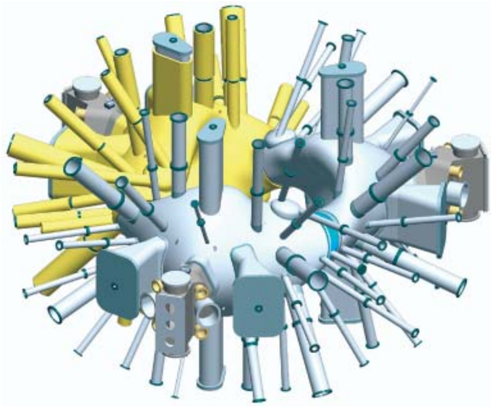

Figure 7. The National Compact Stellarator Experiment vacuum vessel assembly showing the ports that will provide diagnostic and heating access to the plasma.

Figure 8. A prototype National Compact Stellarator Experiment vacuum vessel subassembly manufactured by Major Tool and Machine, Inc.

The Final Design Review for the modular coil winding forms and vacuum vessel subassembly was successfully conducted in May 2004. The review committee concluded, "the designs for the vacuum vessel subassemblies and the modular coil winding forms satisfy the technical requirements and needs of the project and are ready to proceed with procurement and fabrication." Based on this successful technical review, a successful Independent Project Review in June 2004, and a successful DOE Office of Science Project Review in September 2004, DOE gave approval for the Start of Fabrication (CD-3). This decision authorized the NCSX project to commit all the resources necessary, within the funds provided, to execute the project. Subsequent to CD-3, an $8-million production contract for the modular coil winding forms was awarded to a team led by Energy Industries of Ohio, Inc., and a $4.5-million contract was awarded to Major Tool and Machine, Inc. for the vacuum vessel subassemblies.

NCSX Coil Winding R&D

During FY04 a number of R&D activities were completed to provide the information needed to fabricate the NCSX modular coils. This work included both materials testing and winding trials. Specimens were fabricated and tested at liquid nitrogen temperatures to determine the physical properties of the insulation/conductor scheme. Winding trials were performed on a complex geometric shape called "inch worm" (see Figure 9) that had features similar to the modular coils. These trials were used to gain invaluable experience in handling and winding the copper rope conductor and to develop related procedures.

A great deal of effort was spent on the design and fabrication of the tooling required to fabricate the modular coils. A coil manufacturing facility was set up in the former Tokamak Fusion Test Reactor (TFTR) Test Cell. This facility includes a winding-form preparation station, three winding stations, as well as an autoclave for vacuum epoxy-impregnating the wound coils. The autoclave is an

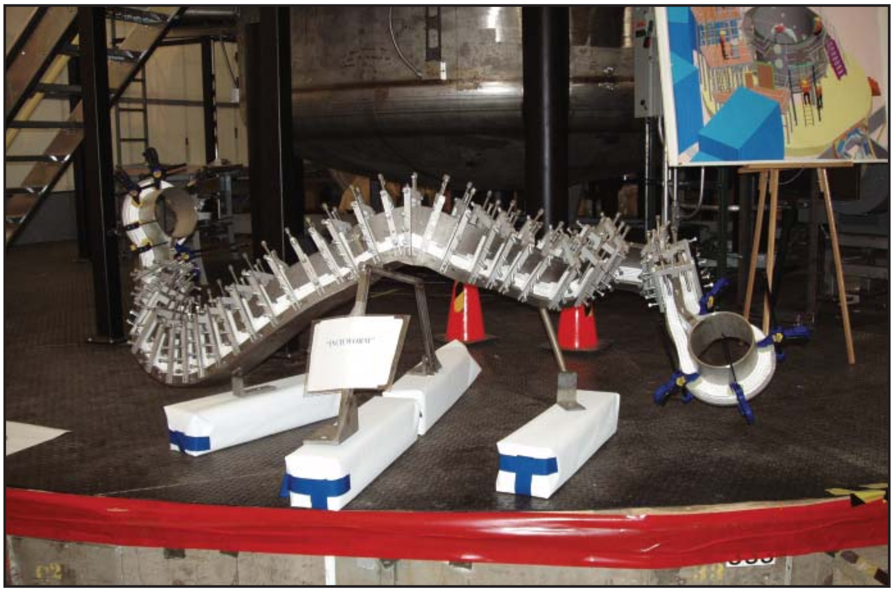

Figure 9. The National Compact Stellarator Experiment "inch worm" coil fabricated for winding tests.

oven that can operate under vacuum or pressure environments.

The coils will be wound onto the winding forms using vertical turning fixtures (see Figure 10) that allow the four-in-hand conductors to be positioned simultaneously onto the complex geometry with little distortion. A prototypical "twisted racetrack coil" (TRC) is being fabricated in the winding facility to demonstrate the manufacturability of the modular coils. The twisted racetrack coil (approximately one-third scale) incorporates all of the modular coils' basic design features, including complex geometry, conductors, insulation, as well as lead

Figure 10. Vertical turning fixture for the winding of National Compact Stellarator Experiment modular field coils.

Figure 11. The detectors for PPPL's Miniature Integrated Nuclear Detection System (MINDS) are enclosed in an aluminum case.

and cooling systems. Once completed, the twisted racetrack coil prototype will be tested at liquid nitrogen temperature and operating currents in the new test facility. Winding of the first production coil is scheduled for May 2005 with the arrival of the first winding form.

Miniature Integrated Nuclear Detection System

The PPPL Engineering Department's Fabrication, Operations and Maintenance Division has developed a real-time radionuclide identification system for homeland security applications (see Figure 11). The Miniature Integrated Nuclear Detection System (MINDS) has been designed to identify specific radionuclides at levels close to natural background radiation in real time. The system was successfully demonstrated in various deployments, including a mobile configuration, an office building location, and an automobile entry gate. Arrangements are underway for the deployment of multiple MINDS units at a military base in New Jersey and at locations associated with U.S. civil infrastructure.

NRL KrF Laser Engineering

During FY04, the PPPL Engineering Department's Fabrication, Operations and Maintenance Division collaborated with the Naval Research Laboratory (NRL) in the development of a silicon/nanocrystalline diamond hibachi window for use in a KrF laser (see Figure 12). The device is being developed in support of the NRL's inertial fusion energy program. Modeling and empirical tests conducted at the NRL Electra test bed have shown the novel hibachi window design to be robust and cost effective with a long duty cycle.

Excess Facilities Reclamation

During FY04, auxiliary systems related to the Princeton Large Torus (PLT) and the Princeton Beta Experiment-Modification (PBX-M) were removed to make way for the NCSX. In the former test cells, concrete blocks comprising the shield walls were removed and recycled. Cabling behind these walls was then removed, and the large steel base plates from the PBX-M device were removed and sent for recycling.

In the basement of the test cells, all equipment was removed, except for the PBX-M vacuum systems and the water and bus tunnels which will be used for NCSX. The removed items included the pulse discharge cleaning (PDC) power supplies, the pulse discharge cleaning and ohmic-heating transfer switches, the S1 and S2 transfer switches, the protected relaying control racks, getter power

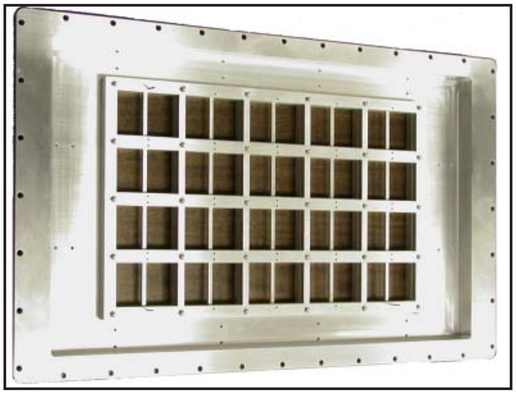

Figure 12. Hibachi window for the Naval Research Laboratory's KrF laser.

supplies, obsolete ac power items, a chiller and water conditioner, PLT vacuum equipment, the laser diagnostic stand, and the ohmic-heating and shaping-field power supply relay enclosures. On the first floor of the RF Building, the hard-tube amplifier was removed. On the first floor of the CS building, the ready rooms adjacent to the test cells were cleared out. Also during this period, the C-site cooling tower, built in 1958, was dismantled and removed.

Princeton University Cyclotron Decommissioning

During the last quarter of FY04, the decommissioning of the Princeton University Cyclotron, under Jadwin Hall, was started. The Fabrication, Operations and Maintenance Division, which had led the decommissioning of the Tokamak Fusion Test Reactor at PPPL, was funded by Princeton University to oversee this activity including generating plans for the Cyclotron decommissioning and selecting the contractors for the safing and removal of electrical components, as well as for the removal of the 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 under PPPL supervision, and by late September enough had been completed that the mechanical removal contractor could begin work. The goal is to have all of the removals completed by early January 2005 so the University can convert the area into a new physics research facility.

Computer Systems

Business and Financial Computing

PPPL's Business Computing consisted of legacy systems operating on an IBM 9121-210 mainframe computer. A project to replace the legacy systems with Great Plains e-Solutions Software commenced in early FY02. The e-Solutions Software utilizes client-server technology running on Microsoft's Windows 2000 Server and SQL Server 2000 as the database management system. Business Management International (BMI) was contracted to implement the Great Plains systems. The required degree of customization was initially estimated at 35%. However, after completing detailed specifications, it was determined that a higher degree, up to 83%, was required to meet DOE's evolving requirements and PPPL's business needs. Despite this, the changeover is being accomplished within its original budget. On April 27, 2004 transaction processing on the legacy systems was discontinued, and data were converted to the new systems and verified. The first transactions were entered into the new systems on May 5. Although the purchase card system and travel system were not part of the initial "Go-Live," temporary workarounds were put in place such that the mainframe supporting the legacy systems was decommissioned July 1. The Purchase Card System went live in July 2004. It is expected that the travel system will go live in the third quarter of FY05.

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 PPPL researchers and fusion community collaborators. The clusters were initially built at PPPL in late FY01 and FY02. Together these clusters include a mixture of 180 Intel and AMD dual processors, with an aggregate of nearly 400 gigabytes of memory, running Red Hat Linus.

In FY04 significant improvements were made to file services, environmental factors, and batch systems management (PBS-Pro). In particular, the implementation of one large batch system, where machines can be moved in or out of the clusters for maintenance, significantly contributed to the overall improved system stability, reliability and usability. Throughout the spring, a steady and rapid increase in utilization was enjoyed, with the cluster virtually saturated in late 2004. These clusters have become a critical and an essential resource to PPPL and off-site research staffs.

Also in late 2004 an additional compute engine, a 16-processor SGI Altrix machine, was benchmarked and procured. Further testing will be done in FY05 to determine how this technology is best applied to the PPPL suite of applications.

Computing Infrastructure

The Energy Science Network, ESnet, provides PPPL's with OC3 (155 megabytes per second) wide area connectivity. This past year, testing has shown that GRID computing can fully utilize the existing bandwidth and that as PPPL GRID use expands, the Laboratory will require an upgrade to at least OC12 (622 megabytes per second). ESnet has looked at several technical and financial scenarios for providing PPPL with this capability, including partnering with Princeton University and the Geophysical Fluid Dynamics Laboratory to provide all three with gegabytes per second connectivity to the wide area.

A new tape library, an 8-terabyte storage array and a storage area network, was procured in FY04. This system will provide PPPL with the basis for expansion to meet PPPL's storage needs. Although the new system will be primarily used to store experimental and theoretical data sets, plans include backup of PC's and Macintoshs to older PPPL tape libraries to provide easier and more complete restoration capabilities than are currently available.

Cyber Security

The Laboratory operates a proactive cyber security program and has an excellent cyber security record. The Laboratory's main networks are configured behind a firewall which is operated in default deny mode. Authorized users are required to authenticate with SecurID to access internal resources. Logs from the firewall are also sent daily to the Computer Incident Advisory Capability for post-processing against known threats.

Several initiatives were undertaken during FY04 to strengthen the Laboratory's cyber security program. The Cybergate project provides a separate network for laptops, visitors, and dial-in users. This network is continually scanned for machines infected with worms reducing the probability of an inadvertent infection of Laboratory computers.

A new Exchange e-mail server was brought up during the last year. This server not only provides enhanced features such as IMAP, encrypted authentication, and groupware, but also provides more secure off-site access to e-mail. Users no longer need to authenticate at our firewall to get their e-mail, thus greatly reducing the number of authentications from off-site locations. Access to e-mail, both for sending and receiving, requires encrypted authentication, greatly enhancing the security not only of e-mail, but also reducing the probability of a compromised password being used for further entry into the Laboratory systems.

The great majority of the Laboratory's PC users are now being managed centrally on PPPL's domain. This enables updates to be pushed out to machines more efficiently, as well as providing for centralized management of virus protection software. The Laboratory's ability to respond to Microsoft vulnerabilities has been greatly enhanced by this approach.

A revised Computer Use Policy, a Confidentiality Agreement for System Administrators, a Configuration Management Policy, and Cyber Security Threat Response Procedure were developed and issued. Although a handful of computers were infected with worms, no significant reportable incidents or system compromises occurred. Overall, the Laboratory's performance in this area continues to be excellent.

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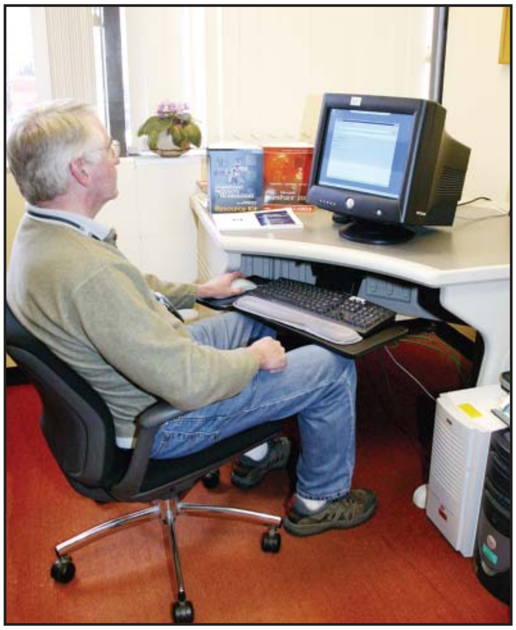
Environment, Safety, and Health

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

Initiatives begun in FY03 were continued or expanded in FY04. The Third Annual Safety Forum was held in January 2004, and the next is planned for February 2005. During FY04, the Laboratory experienced a moderate increase in its key worker safety metrics compared to FY03. The FY04 Total Recordable Case (TRC) and Days Away, Restricted, Transferred (DART) case rates were 1.63 and 1.02, respectively, compared with 1.34 and 0.76 in FY03. PPPL activities being performed or planned to increase employee safety awareness and to reduce work related injuries and illnesses are discussed below.



Tom Carroll of the Computer Division works at an ergonomically designed workstation.

Ergonomics

Workplace ergonomics is the study of workplace equipment design or how to arrange and design devices, machines, or the workplace so that people and things interact safely and most efficiently. The term "ergonomics" comes from the Greek words "ergos," meaning work, and "nomos," meaning natural laws of. Ergonomics considers the physical and mental capabilities and limits of the worker during interaction with tools, equipment, work methods, tasks, and the working environment. Activities during FY2004 included:

- Small group meetings with targeted populations (i.e., those at most risk due to their job duties) were conducted to review musculoskeletal safety issues, which have been involved in about 50% of the recordable cases over the past two years. From June through September 2004, fourteen work group sessions were held, involving a total of 174 PPPL staff.

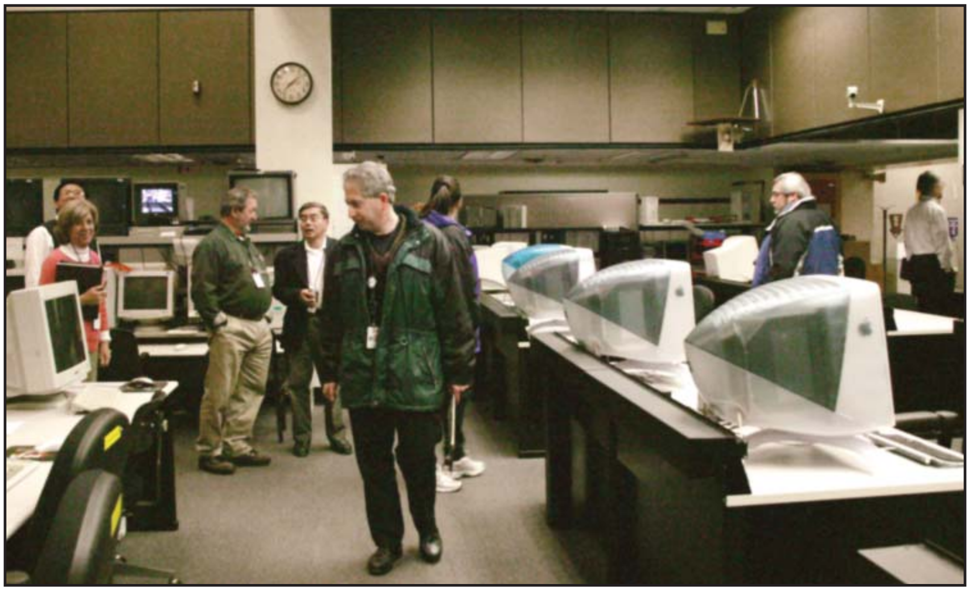
- A forum by the Princeton Medical Center was planned and organized and will be held in October 2004 dealing with the subject of "Avoiding Musculoskeletal Injuries on the Job." This talk will be available to the entire Lab population and will include presentations by the PPPL industrial hygienist and a physical therapist.
- Industrial hygiene ergonomic evaluations of workstations were conducted upon request and improvements recommended to help prevent worker injuries or illnesses.

Hazard Analysis

A formal Hazard Awareness course was implemented, focusing on the identification and mitigation of job hazards using classroom training and field exercises. The class size is limited to just 16 individuals to allow for direct interaction with the participants. During FY04, six sessions were held with attendance by a diverse group of about 60 employees, including senior managers. An additional 17 training sessions are scheduled for FY05. Other activities in FY04 include:

- Dedicated in-depth industrial hygiene, health physics, and construction safety engineering support were provided for the National Compact Stellarator Experiment (NCSX) coil fabrication and testing activities in the former Tokamak Fusion Test Reactor (TFTR) test cell.

The Hazard Awareness course involves classroom training and field exercises. Bill Slavin, class instructor (in back with blue jacket) listens as Sallie Meade (center in long dress) discusses possible hazards with the group in the Neutral Beam Power Conversion Building at D-site. Also in the photo are (l-r) Dave Moser, Shannon Belloni, John Boscoe (behind Belloni), Slavin, Meade, Harry Towner, Ed Gilsenan, and Phyllis Roney.



Twenty-four management safety walkthroughs were conducted in FY04. Here a team checks out the NSTX Control Room. Shown are (l-r) Dori Barnes, Masa Ono (partly hidden behind Barnes), Carl Potensky, Bob Kaita, Jerry Levine, Maria Pueyo, Bill Slavin, and Michael Williams.

- Safety evaluation reviews were coordinated for the National Spherical Torus Experiment (NSTX) low-Z lithium pellet injector, the NCSX coil test facility to be operated in the basement of the former TFTR test cell, the Magnetorotational Instability Experiment installed in Room L-114 of the C-Site Laboratory Building, power supply upgrades for the Magnetic Reconnection Experiment, and the NCSX modular-coil manufacturing facility located in the former TFTR Test Cell.

Workplace Improvements

Workplace improvement activities for FY04 include:

- Workplace safety improvements using the Occupational Safety and Health Administration (OSHA) inspection punch list were completed. More than 85% of the OSHA-identified items were corrected, and all items will be resolved well within the 24-month time frame established by DOE.
- The use of the web-based ES&H "Drop Box" for employees was highlighted and promoted. Safety items identified via the box were responded to promptly.
- Twenty-four management safety walkthroughs were conducted during FY04 to physically review the safety status 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 PPPL management, line managers, Department of Energy staff, Laboratory ES&H professionals, and workers. Additionally, ES&H action items are generated

based on frequent DOE Princeton Site Office surveillances of PPPL work areas.

Awareness of Worker Safety Issues and Performance

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

- Four editions of the ES&H Newsletter were published during FY04, providing timely information on topical safety issues.
- In October 2003, PPPL hosted a meeting of ten ITER safety specialists to discuss radiation exposure experiences at TFTR, the Joint European Torus (JET), and the DIII-D, and their relevance to ITER radiological planning. An International Energy Agency Task 5 meeting on risk assessments relevant to ITER with the same individuals in attendance was also hosted.
- Monthly reports were submitted to PPPL staff on safety performance and related ES&H issues.
- Internal and external lessons-learned reports were shared with the staff.
- "Safety Bulletins" were distributed to Laboratory staff to remind them of specific aspects of electrical safety, e.g., OSHA electrical safety standards, electrical working clearances, use of multi-outlet power strips, proper and improper electrical work practices and descriptions of the appropriate techniques, and the proper use of lockouts and tagout locks.
- A working group under the ES&H Executive Board was established to explore ideas and offer recommendations for work-group safety incentives.

It is believed that there is a strong worker safety culture at PPPL, and Laboratory management is committed to making it stronger. As a reaffirmation of this commitment, PPPL is applying to obtain a DOE Voluntary Protection Program (VPP) endorsement by the end of FY05. The VPP is a reinforcement of Integrated Safety Management, and it promotes effective worksite-based safety and health. In the VPP, management, labor, and DOE establish cooperative relationships at workplaces that have implemented a comprehensive safety and health management system. DOE's verification includes an application review and a rigorous on-site evaluation by a team of DOE safety and health experts. Acceptance into VPP is DOE's official recognition of the outstanding efforts of employers and employees who have achieved exemplary occupational safety and health. Statistical evidence for VPP's success is impressive. The average VPP worksite has a Days Away, Restricted, Transferred (DART) case rate 52% below the average for its industry.

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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 Laboratory 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. WFO 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.

Small Business Innovative Research Workshop

In August 2004, the PPPL Technology Transfer Office, in collaboration with the North East Region of the Federal Laboratory Consortium (FLC), hosted a one-day workshop for small businesses interested in the Small Business Innovative Research (SBIR) Program and the Small Business Technology Transfer (STTR) Program. The NASA Center for Technology Commercialization (CTC) jointly sponsored the workshop, which attracted 40 participants. The topics included:

- An overview of the SBIR/STTR programs.
- Services available through the FLC and the CTC for small businesses.
- Information on the U.S. Department of Energy's SBIR programs.
- The Army's and the Navy's SBIR programs.
- The SBIR programs at Picatinny Arsenal.
- Collaborative opportunities available at PPPL.
- Workshops on how to write effective SBIR and STTR abstracts.

Intellectual Property experts provided an overview of issues such as patents, trade secrets, copyrights, and trademarks. Other topics included government rights and legal issues related to intellectual property with respect to SBIRs, STTRs, CRADAs, and government contracts in general.

Data Grids for Large-scale Fusion Simulations

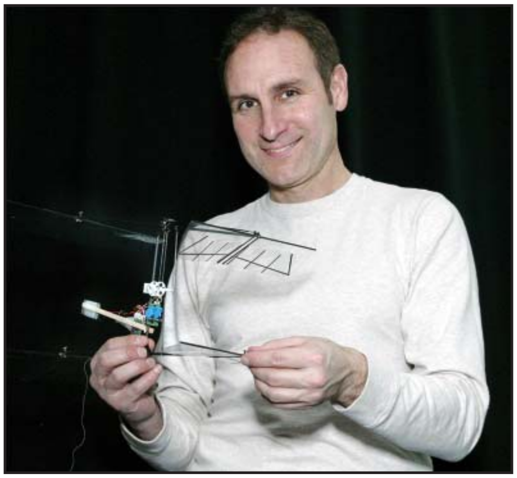
In this Phase II, Small Business Innovation Research CRADA project funded during FY04, Tech-X Corporation is implementing a FusionGrid Service for data transfer and access with PPPL collaboration. The service will connect heterogeneous data collections and provide transparent Interactive Data Language 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, experiments, and visualization along with its expertise in grid computing. The PPPL Computational Plasma Physics Group, which is responsible for this CRADA, has experience in developing data grids for large-scale fusion simulations from its work on the National Fusion Collaboratory project.

Micro Air Vehicles

During FY04, work continued on PPPL's Micro Air Vehicles (MAV) project in support of the Naval Research Laboratory (NRL) Micro Air Vehicle Program. The NRL MAV Program involves fundamental research and development on the aerodynamics of unconventional miniature air vehicles and feasibility demonstrations of mission-useful MAV's.

Ongoing efforts in this WFO project focused on upgrades to Samara development. The Samara is a hybrid aircraft that combines a helicopter's abilities of slow flying, and vertical ascent and descent, with the speed and efficiency of a fixed-wing aircraft. The FY04 work included an automatic mass shifting system to increase Samara's stability in the rotary wing operational mode. This sys-



Dave Cylinder holds a new version of the Tandem-winged Clapper Micro Air Vehicle dubbed the BITE-wing (Biplane Insectoid Travel Engine) by the Naval Research Laboratory.

MINDS deployed in a mobile configuration.

tem was bench tested with satisfactory results. A new variation of Samara called (Samara II) began development in FY04. This altered configuration is expected to be more compact, more stable with mass shifting, and have the ability of controlled hovering.

There were also ongoing improvements in flapping wing aircraft research. A smaller Tandem-winged Clapper (smaller than the FY03 model) was built using carbon fiber composite materials and an enhanced aerodynamic control system. Flight tests began in late FY04. A new variation of the Tandem-winged Clapper was also designed and built in FY04 and flight tests will begin in early FY05. Micro Air Vehicle experimental research was coupled with computation fluid dynamics and flight control system simulations that are continuing at NRL.

Miniature Integrated Nuclear Detection System

During FY04, 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.

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 entering a site, passing through a tollbooth, placed inside of a shipping container, or hidden in other ways, under realistic conditions. The full system, which employs mostly off-the-shelf components, will be capable of detecting x-rays, soft gammas, gammas, and neutrons. 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, thus eliminating false positive alarms resulting from the movement and transportation of approved radionuclides, such as 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 demonstrated the detection of 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, a mobile configuration of MINDS was developed and demonstrated for law enforcement agencies. The mobile MINDS was demonstrated to representatives of Picatinny Arsenal, the New York/New Jersey Port Authority, the New Jersey Office of Counter Terrorism, the New York City Metropolitan Transportation Bridge and Tunnel Authority, and other State and municipal representatives. Discussions are continuing with parties interested in licensing the technology for commercial development.

Plasma Sterilization Experiment

Tens of billions of plastic food and beverage containers are manufactured each year in the U.S. All of these packages must undergo sterilization, which at present is done using high temperatures or chemicals. Both of these methods have drawbacks. Chemicals often leave a residue that can affect the safety and taste of the product and produce undesirable waste. Heat is effective and sufficiently rapid, but necessitates the use of costly heat-resistant plastics that can withstand sterilization temperatures. Consequently, it would be of great benefit if a new method could be found that eliminated the need for chemicals or heat-resistant plastics.

During FY04, a team of PPPL scientists conducted a series of small-scale experiments studying plasma sterilization.

The plasma sterilization experiment at PPPL. Shown are, from left, Gary D'Amico, Nevell Greenough (kneeling and looking into sterilization apparatus) and Lewis Meixler.

The researchers used modified equipment that had once been used to study radio-frequency waves for fusion applications. It consists of a vacuum chamber equipped with a radio-frequency source. A brass sphere measuring one inch in diameter is mounted at the center of the chamber. In preparation for experiments, the sphere is removed and sent to a commercial biological testing laboratory where a known number of spores of bacillus subtilis, a nonpathogenic microbe commonly used as a standard in lab testing, is placed on its surface. Following an experiment, the sphere is returned to the testing laboratory where technicians determine the number of spores killed in the process.

Fusion experiments at PPPL have generated plasmas with temperatures in the hundreds of millions of degrees centigrade. For killing spores, the PPPL researchers start with "low-temperature" hydrogen plasmas in the range of 50,000 degrees centigrade. At that temperature, the hydrogen ions are moving much too slowly to kill spores quickly. Rapidly pulsing a 50-kilovolt potential between the sphere and the vacuum chamber solves the problem. The sphere is charged negatively and the vessel is at ground. Under these circumstances, the positively charged hydrogen ions accelerate toward the sphere in pulses energetic enough for the ions to pierce the hard outer shell and soft inner core of the spores. These high-energy hydrogen ions stop very quickly and consequently deposit all their energy over a very small distance, a few microns, which, as it turns out, is the size of the spores. So relatively modest currents of energetic hydrogen ions can do a large amount of damage to the spores.

The FY04 experiments were designed to evaluate the parameters under which spore destruction takes place by varying the accelerating voltage, type of background gas, number of pulses, gas pressure, pulse width, and pulse rise-time. A typical exposure employed 4,000 eight-microsecond pulses, which reduced the population of live spores to less than one colony-forming unit, or essentially 100% kill. The FY04 experiments reconfirmed the achievement of significant (i.e., 100–1,000) kill ratios. The experiments established that the spore damage occurred primarily during the first two microseconds of an eight-microsecond pulse. Voltage scans demonstrated that significant spore damage could be achieved at voltages as low as 35 kV. The background pressure dependence of the kill ratio was established.

Work For Others

Additional Work for Others projects funded during FY04 included:

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 waves and microwave heating. These heating techniques, also used to heat plasma in a fusion device, are being tested for pasteurizing raw liquid foods such as eggs, fruit juices, and milk.

Radio-frequency waves offer advantages over the traditional pasteurization method of directly heating raw liquid foods. The direct method often heats foods unevenly, possibly resulting in incomplete pasteurization in lower temperature regions and in denaturing foods in overheated regions. Using radio-frequency waves 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 studying the physics of magnetic reconnection — the topological breaking and reconnection of magnetic field lines in plasmas. Scientists hope to understand the governing principles of this important plasma physics process and gain a basic understanding of how it affects plasma characteristics such as confinement and heating. The results of these experiments will have relevance to solar physics, astrophysics, magnetospheric physics, and fusion energy research.

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 Center at the Korean Basic Science Institute in Taejon, Republic of Korea.

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

Sponsor: Naval Research Laboratory

Scope: Study, design, and produce thin "hibachi" windows fabricated from silicon or other novel materials for the Naval Research Laboratory Electra KrF Laser System and perform a systems engineering study for Electra.

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 the Princeton Plasma Physics Laboratory 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 non-local theory which 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 spacecraft measurements.

Title: Self-consistent Model for Regions of Downward Auroral Current

Sponsor: National Science Foundation

Scope: The objective of this program is to develop a self-consistent understanding of the plasma and field properties of downward auroral currents.

Title: Vacuum Ceramic Multi-window in Titanium Flange

Sponsor: Institute for Plasma Research

Scope: The Institute for Plasma Research (IPR) is enhancing its capability on the SST1 Tokamak in Gujarat, India, and has contacted PPPL to fabricate and supply two multi-channel, ceramic vacuum windows for them. PPPL staff are working with the staff at IPR to design, fabricate, and the test the ceramic window assemblies at PPPL before shipment to IPR.

Title: Testing of the Detritiation of the JET Tiles by Heating with the Oxy-Gas Burner

Sponsor: United Kingdom Atomic Energy Authority

Scope: The United Kingdom Atomic Energy Authority wants to investigate the removal of co-deposited tritium from the Joint European Torus (JET) graphite tiles employing localized heating. In general, the tile samples will first be characterized for tritium content and tritium depth profile. After such analysis, the tile sample will be subjected to direct heat from a burner to liberate the co-deposited tritium from the tile. After the application of localized heat, the tile will be reanalyzed to determine the effectiveness of the techniques employed.

Title: Kinetic Ballooning Instability as a Mechanism for Substorm Onset in the Near Earth Plasma Sheet

Sponsor: National Aeronautics and Space Administration

Scope: The objective of the project is to study the onset mechanism of substorms which occur in the near-Earth plasma sheet region of the magnetosphere. Theoretical predictions are being compared with satellite observations to clarify unresolved physics issues.

Title: Concept Exploration of Novel Hall Thruster Configurations: Staged Hall-ion Thruster with Cylindrical Configuration

Sponsor: Defense Advanced Research Projects Agency

Scope: The objective of this project is to explore several novel plasma propulsion configurations with an aim to evaluating potential performance, including high-power (10–20 kW), mid-power (1–5 kW), low-power (under 100 W), moderate specific impulse (1,500–2,500 sec), high specific impulse (over 3,000 sec), and desirable features such as throttling, lifetime, or variable thrust.

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 preeruption 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 three-dimensional current sheet structure in the near-Earth plasma sheet region during the substorm growth phase by combining the three-dimensional modeling with observations of magnetic field and plasma pressure from the POLAR satellite.

Title: Fabrication of a Hibachi Test Module to Evaluate the use of Edge-cooled Silicon/Nanocrystalline Diamond Films as Electron-beam Transmission Windows for a Repetitively Pulsed E-beam Pumped Laser

Sponsor: Naval Research Laboratory

Scope: Building upon recent successful prototyping and testing at Electra of a silicon/nanocrystalline diamond (electron-beam transmission) window for use in a KrF laser system, PPPL is fabricating a hibachi test module with 40 windows employing (active) internal cooling.

Title: Semi-Parametric Modeling of Kp and Dst from Solar Wind Measurements

Sponsor: Johns Hopkins University Applied Physics Laboratory

Scope: The purpose of this work is to determine the underlying nonlinear statistical dependencies of the planetary activity index (Kp) and the disturbance storm time index (Dst) on past history and solar wind data and to provide an algorithm that accurately predicts future planetary activity and disturbance storm time indices based on past time history of the planetary activity index, disturbance storm time index, and solar wind data.

Title: Fabrication of Electronic Preamplifier Modules for Thomson Polychromator Boxes at the Joint European Torus

Sponsor: General Atomics

Scope: PPPL is manufacturing electronic preamplifier modules to be used in conjunction with General Atomics polychromators, forming the detection system for the Joint European Torus high-resolution Thomson scattering diagnostic, which measures electron temperature and density profiles in fusion plasmas.

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Patents and Invention Disclosures

Patent Issued

Magnetic-field Sensing Coil Embedded in Ceramic for Measuring
Ambient Magnetic Field
— *Hironori Takahashi*

Invention Disclosures

Airflow Control by Ferroelectric Plasma Sources
— *Alexander Dunaevsky and Nathaniel J. Fisch*

Asymmetric Ponderomotive Current Drive with Reduced Cyclotron Heating
— *Nathaniel J. Fisch and Ilya Y. Dodin*

Center-post Plasma Start-up Concept
— *Masayuki Ono, Wonho Choe, Jayhyun Kim, Richard Hawryluk*

Electrostatic Dust Eliminator
— *Charles Skinner*

Homogeneous Plasma Source
— *Ernest Valeo and Nathaniel Fisch*

Laser-ionization-produced Plasma Source
— *Richard L. Berger, Ernest Valeo, and Nathaniel Fisch*

Lithium "Thick Film" First Wall
— *Richard Majeski*

Miniature Integrated Nuclear Detection System with Improved Detection Capability
— *Charles Gentile, Steve Langish, Lew Meixler, Rick Mammone, and Joseph Wilder*

Multi-step Backward Raman Amplifiers (BRA)
— *V.M. Malkin and N.J. Fisch*

Plasma Sterilization Process for Plastic Containers with Integral Pulse Modulatio Unit
— *Lewis Meixler*

Pump Side-scattering in Ultra-powerful Backward Raman Amplifiers
— *A.A. Solodov, V.M. Malkin, and N.J. Fisch*

RF Microdischarge Thruster
— *Alexander Dunaevsky and Nathaniel J. Fisch*

Tandem Clapper Air Vehicle
— *David A. Cylinder*

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Graduate Education

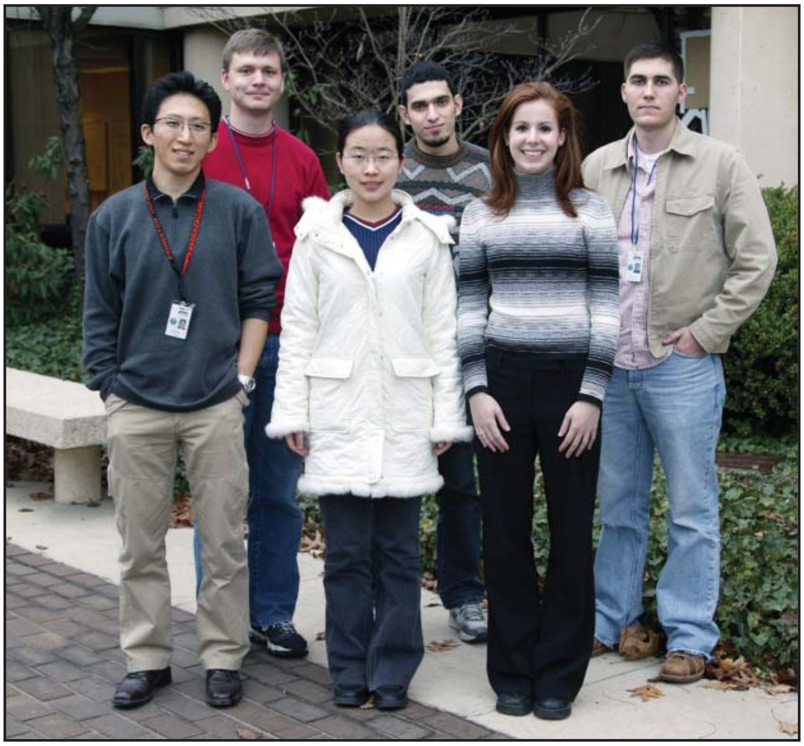
Program in Plasma Physics graduate students, fiscal year 2004. Program Administrator Barbara Sarfaty is seated at left.

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

Both basic physics and applications are emphasized in the Program. There are



First year graduate students from left to right are: Jong-Kyu Park, Sterling Smith, Xiaoyan Ma, Mikhail Dorf, Laura Berzak, and Brendan McGeehan (Andrei Zhmoginov not available).

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 FY04, 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 National Defense and Science Engineering Graduate Fellowship, and one Princeton University Honorific Fellowship.

Seven new students were admitted in FY04, one from China and Korea each, two from Russia, and three from the United States. Two students graduated in FY04, accepting positions at Los Alamos National Laboratory in New Mexico and the Institute for Defense Analyses (IDA) in Washington, D.C.

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 of toxic wastes, chemical synthesis, space propulsion, control system theory and experiment, 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. In fiscal year 2004, twelve graduate students received support from the PPST during the academic year and/or summer. They co-authored more than a dozen refereed publications. Four of the students received Ph.D. degrees from their respective departments.

Professor G. Mourou was the distinguished speaker at the PPST public lecture series held to inform the Princeton community of contributions made by plasma science and technology to our society. In a talk entitled, “Extreme Light: Relativistic Optics and Optics Horizon,” Dr. Mourou, A.D. Moore Distinguished University Professor, Director of the Center for Ultrafast Optical Science, University of Michigan, described methods for generating and studying extremely intense laser beams and their interactions with matter.

To develop and maintain a strong graduate program, increased efforts were made to develop appreciation for plasma physics in Princeton undergraduates. Through an summer internship program, four Princeton undergraduates worked on plasma-physics projects such as plasma thrusters, plasma modification of materials, and the manipulation of chemical reactions by laser light.

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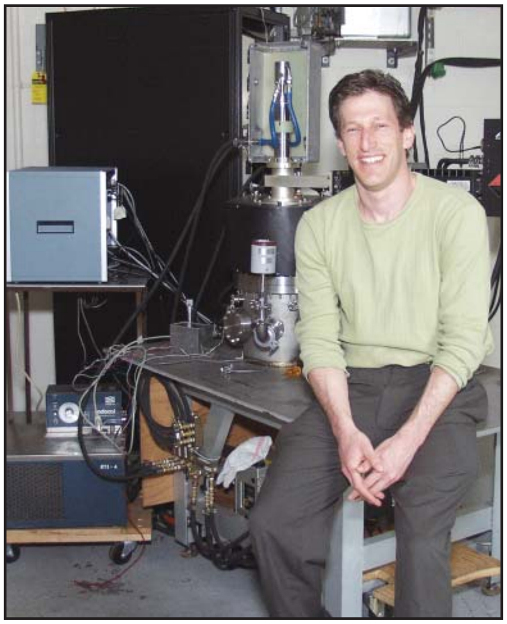
Science Education

The goals of the Princeton Plasma Physics Laboratory (PPPL) Science Education Program (SEP) are to provide a comprehensive portfolio of initiatives that leverage the unique resources of the Laboratory with an education strategy that recognizes that plasmas are superb for generating questions, stimulating curiosity, and increasing 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 American scientists and engineers. (2) Collaborate with K–12 teachers on ways to improve science teaching using an inquiry-based approach to learning. (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 Plasma Science Education Laboratory (PSEL). A fusion of research between education and plasma science, this unique facility includes a classroom, general laboratory space for educational workshops, and areas for advanced plasma physics research. The research performed in the PSEL simulates a research environment while remaining 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, and 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 FY04, funding from the U.S. Department of Energy (DOE) Office of Fusion Energy Sciences was approved to move the PSEL into a new and upgraded facility. Construction



Andrew Post-Zwicker was appointed Head of PPPL's Science Education Program during fiscal year 2004.

on the new laboratory and classroom will be completed in FY05.

In FY04, Andrew Post-Zwicker was appointed Head of PPPL's Science Education Program. Post-Zwicker joined SEP in 1997 as a Senior Program Leader and became Lead Scientist for the Program in 2000.

Undergraduate Research Programs

PPPL staff continued the tradition of training the next generation of scientists and engineers, as 38 students participated in the Laboratory's undergraduate research programs during FY04. This was the largest number of students accepted by these programs. Eleven students from the Summer Undergraduate Laboratory Internship (SULI) program and 27 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, University of Wisconsin-Madison, Los Alamos National Laboratory, General Atomics, Lawrence Livermore National Laboratory, and Columbia University. The U.S. Department of Energy's Office of Science Workforce Development and Office of Fusion Energy Sciences support the research programs, respectively. Before students travel to one of these sites for a nine-week research project, they attend a one-week introductory course at PPPL in the basic elements of plasma physics.

Three NUF students were recognized for their research at the annual American Physical Society's Division of Plasma Physics conference. Rick Wagner of the University of California, San Diego did his research with Dr. Mike Makowski at General Atomics. His poster was titled, "Fast Data Acquisition System for the DIII-D MSE Diagnostic Signal Processing Technique." Nathan Howard of the University of Illinois, Urbana-Champaign did research with Dr. Craig Petty at General Atomics. His poster was titled, "Analyzing Electron Transport on DIII-D Using the General Form of Heat Pulse Propagation." Ying Wu of the University of Illinois, Urbana-Champaign did research with Dr. Fred Levinton at

National Undergraduate Fellowship (NUF) and Summer Undergraduate Laboratory Internship (SULI) participants, summer 1994.

PPPL. His poster was titled, “High Voltage Ramp Generator for Electro-Optically Tunable Filter for the MSE-CIF Diagnostics on NSTX.”

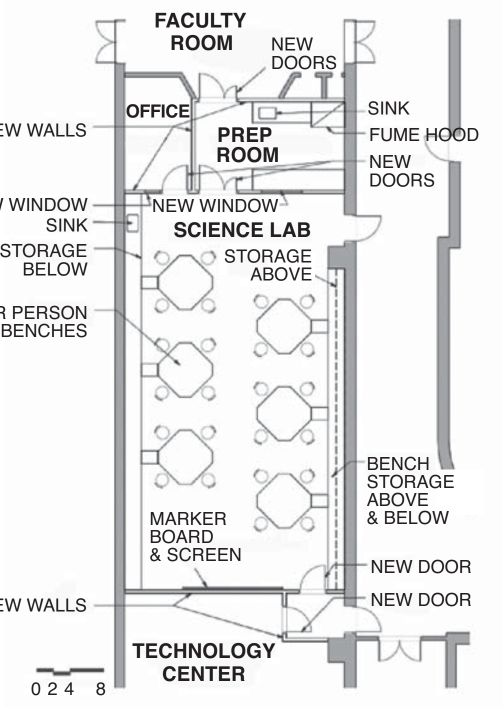
From FY92 to FY02, 227 students have received a National Undergraduate Fellowship (a total of 273 through FY04). Of those 227, forty-three are currently American Physical Society members. The list includes professors of physics at the University of California-Los Angeles and the University of Colorado, researchers at national laboratories and private industry, and graduate students at Princeton University and the University of Wisconsin-Madison.

Pre-college Activities

Trenton Partnership

PPPL has a long tradition of utilizing the unique resources of the laboratory to aid in the improvement of science instruction for students and teachers in the Trenton Public School District. Trenton, the state capitol of New Jersey, is a low-income community of 85,000 people with a minimal industrial base. Twenty-three percent of the population is school-age. Trenton has a large minority population with many students at risk of educational failure. The district consists of eighteen K–5 schools, four middle schools servicing grades 6–8, and one high school. Its 12,981 students are 67% African American, 29% Hispanic, and 4% Caucasian. The school system’s 712 teachers are 52% Caucasian, 38% African American, 8% Hispanic, and 2% Asian.

Hedgepath-Williams Middle School Partnership: Within the Trenton district only 14% of middle school students pass the state’s proficiency exam in mathematics and 22% in language. Science achievement is not tested. In FY04, PPPL entered into a strategic partnership with a Trenton middle school with no existing science-specific classroom or laboratory. The goal is to improve science learning within one school and use this as a model for the other mid-



Schematic of new science laboratory for Hedgepath-Williams Middle School.

dle schools. PPPL organized a meeting with an architect, the principal, and the assistant superintendent to design a new 1,500 square-foot state-of-the-art classroom and laboratory. A final design was approved and a proposal to the State of New Jersey to fund the construction was completed and funding was approved. Construction is expected to begin in 2005. Concurrently, PPPL is participating in curriculum design in support of this new facility. Professional development for the science teachers at the school will begin in 2005 at PPPL's Plasma Science Education Laboratory.

Middle School Science Bowl: In FY04, the Princeton Plasma Physics Laboratory sponsored the first New Jersey Regional Middle School Science Bowl as a pilot program for Trenton students. This DOE-sponsored, nation-wide program is based upon the successful National Science Bowl® for high school students. In this inaugural year, eight teams of five students each participated in an academic competition and a hydrogen fuel cell car challenge. 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.

High School Research Internships

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

Will Fisher, The Dalton School, New York City, New York — *Time-dependent Java-based Virtual Tokamak.*

Emily Margolis, Pennsbury High School, Pennsbury, Pennsylvania — *Ion Acoustic Waves in a Dusty Plasma.*

Laura Wong, Villa Victoria Academy, Ewing, New Jersey — *Low-speed Wind Tunnel for Micro-air Vehicles.*

Brian Zhao, West Windsor-Plainsboro High School, Plainsboro, New Jersey — *Start-up of an Electron Cyclotron Resonance Sputter Source.*

The Lewis School Collaboration

An ongoing collaboration for special-needs students of The Lewis School was

New Jersey Regional Middle School Science Bowl champions.

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 FY04, the 11th grade physics class visited the PSEL throughout the school year, designing and building solar-powered devices and learning about renewable energy.

Plasma Camp

Since 1998, PPPL's Plasma Science and Fusion Energy Institute ("Plasma Camp") has brought high school physics teachers from around the country and Canada to the Laboratory 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.

The 2004 Plasma Camp began, for the first time, with a mini-conference on plasma physics education during which returning participants gave talks and created posters about the use of plasmas within their curricula. After the mini-conference, first-time participants went into the Plasma Science Education Laboratory to begin hands-on investigations of typical classroom plasma sources and a DC glow discharge tube. Veterans spent the remainder of their week working on a piggy-back experiment on PPPL's National Spherical Torus Experiment (NSTX). At the end of the workshop, veterans presented their NSTX analysis while the new participants discussed the first draft of their plasma curricula. They also received a variety of classroom plasmas to take back to their schools and are also eligible to apply for up to $2,000 to purchase equipment for their plasma-related curricula.

A first-year "plasma camper" working with a dc glow discharge tube.

High School Science Bowl

The DOE established the National Science Bowl® to motivate high school students to pursue scientific and technical careers and promote science and mathematics literacy. 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 the fourteen years PPPL has hosted the competition, more than 2,000 New Jersey and Bucks County, Pennsylvania students have participated. Teams have come from science and math magnet schools, public and private schools, and home schools.

In FY04, PPPL hosted 24 teams from 17 schools across the state. More than 40 volunteers from PPPL, Princeton University, Merck, and local school districts helped facilitate the competition. East Brunswick High School won the New

PPPL Director Rob Goldston (seated right, dark coat) and PPPL physicist Daren Stotler (seated on Goldston's left) serve as the moderator and science judge during the final round of the New Jersey Regional Science Bowl held in PPPL's Auditorium. The scorekeeper (standing) is graduate student and former National Undergraduate Fellowship (NUF) program participant Patrick Ross. The competing teams are from East Brunswick High School and High Technology High School.

Jersey Regional Science Bowl competition. High Technology High School from Lincroft placed second and West-Windsor/Plainsboro-South placed third. Teams that did not advance to the later rounds were given a tour of the PPPL facility. The first place team, East Brunswick High School, won an all-expense paid trip to Washington, D.C. in early May. There they competed against 70 teams from around the country in the National Science Bowl®. The New Jersey team placed 8th overall and received a trophy and a $1,000 check for their school's science department.

Science-on-Saturday Lecture Series

The Science-on-Saturday Lecture Series Program began on February 18, 1984, with a lecture on "Robotics," by G.L. Miller. Back then it was called the "World of Science Seminars." That year, four lectures made up the series and 150 people were in attendance each Saturday. Twenty years later, Science-on-Saturday has expanded to eight lectures geared toward high school students, but open to everyone. Scientists and other professionals who are leaders in their respected fields give the talks. The program currently draws more than 300 students, teachers, parents, and community members each Saturday. The program has evolved from its 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.

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

The Science Education Program sponsored the third "Expand Your Horizons Mini-conference for Young Women in Science, Mathematics, and Technology" on March 24, 2004. Approximately 230 eighth through twelfth grade female students from schools throughout New Jersey participated. The goal of the conference is to: increase young women's interest in science and mathematics; provide students an opportunity to meet women working in traditional and non-traditional fields and; foster an awareness of varied career opportunities for women.

The conference included presentations by various women in the sciences, breakout sessions, exhibits, and lunch. The two keynote guest speakers were Professor Ainissa G. Ramirez from Yale University, New Haven, Connecticut, and Dr. Celeste Baines, Engineering Education Services Center, Eugene, Oregon. Staff members from the New Jersey Department of Environmental Protection, Rutgers University, and the State University of New York led the other sessions.

Bergen Academy for Math, Science, and Technology Partnership

Since FY03, PPPL has had a partnership with this science magnet high school in northern New Jersey. Each summer, juniors from the school spend a week at the PPPL Plasma Academy, a workshop centered on plasmas, fusion, and 21st century energy sources such as solar power and fuel cells. Beginning in the 2004-05 school year, the school is offering a concentration for students in "Energy Engineering." This program provides a unique curriculum and innovative scheduling that allows students to work off-campus for large blocks of time. Students study current and future sources of energy from a scientific, sociologic, and political perspective.

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Awards and Honors

2003 PPPL Employee Recognition Award Recipients

Honored by their co-workers for their "personal qualities and professional achievements," thirteen PPPL'ers received 2003 Employee Recognition Awards. Along with PPPL Director Rob Goldston and PPPL Deputy Director Rich Hawryluk are the recipients attending the awards ceremony. From left are: Hawryluk, Larry Nixon, Michael Bell, Al von Halle, Lane Roquemore, Goldston, Bob Tucker, Penny Neuman, Bobbie Forcier, Carl Scimeca, Bob Reed, and Mike Kalish.

Individual Honors

Arthur Brooks
PPPL Distinguished Engineering Fellow
Princeton Plasma Physics Laboratory

John DeLooper
Special Award
Fusion Power Associates

Russell Hulse
Fellow
American Association for the Advancement of Science

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

Robert Kaita
Fellow
American Physical Society

Jonathan Menard
Presidential Early Career Award
for Scientists and Engineers
President George Bush
and
Early Career Award in Science and Engineering
U.S. Department of Energy, Office of Science

Dennis Mueller
Distinguished Career Award
MacMurray College Alumni Association

Neil Pomphrey
Fellow
American Physical Society

Patrick Ross
William G. Bowen Merit Fellowship
Princeton University

Artem Smirnov
Harold W. Dodds Fellowship
Princeton University

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

Laboratory Honors

Resolution of Appreciation
Plainsboro Township Committee
for PPPL's "Commitment to the Community
through Its Emergency Services Mutual Aid Program"

PPPL physicist Jonathan Menard (center) receives the Presidential Early Career Award for Scientists and Engineers. Dr. John Marburger (right), Director of the Office of Science and Technology Policy, presented the awards to recipients at a ceremony at the Old Executive Office Building next to the White House. At left is DOE Office of Science Director Ray Orbach.

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The Year in Pictures

During the fall of 2003, the new center stack for the National Spherical Torus Experiment (NSTX) was completed. PPPL staff members who participated in the design, fabrication, and assembly of the stack included (front, from left) Bob Horner, H.M. Fan, Jack Mount, John Trafalski, Bruce Paul, Joe Rushinski, Frank Jones, Charlie Neumeyer, Mike Messineo, George Steill, Tom Kozub, Art Brooks, Chang Jun, Phil Heitzenroeder, Jim Chrzanowski, and Masa Ono; (behind, from left) John Edwards, Steve Jurczynski, Jack Hynes, Bob Marsala, Mike Kalish, Hans Schneider, John Desandro, Mike Hause, Buddy Kearns, Bob Herskowitz, Ed Bush, Joe Winston, John Boscoe, Mark Cropper, Ron Beyer, Scott Gifford, Jim Benchoff, Mike Duco, Frank Terlitz, Kris Gilton, Marty Wisowaty, Mike Anderson, Mike DiMattia, Bob Tucker, Jr., Ed Gilsenan, Jim Kukon, Jim Lane, Bill Slavin, Sylvester "the eagle" Vinson, and Tom Meighan. The stack was installed on NSTX in December.

PPPL Director Rob Goldston delivered his annual "State-of-the-Lab" address to staff on November 24, 2004, telling the overflow crowd in the Gottlieb Auditorium that PPPL has a "top crew" and is "on course." Said Goldston, "We have great people, an exciting program, and remarkable prospects."

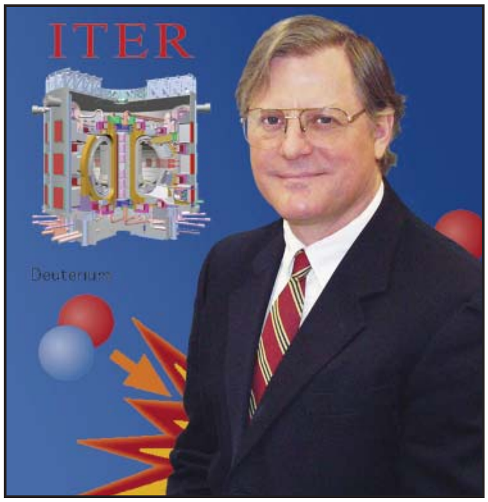
Seven area students exhibited their science projects in the LSB Lobby on April 7, 2004 during the annual Science Day Fair at PPPL. The Science Fair honored the winners of PPPL's Corporate Awards, who were chosen among student exhibitors in March at the Mercer Science and Engineering Fair at Rider University and the North Jersey Regional Science Fair at Rutgers University. Student exhibitor Katie E. O'Mara described her project, "How Effective is the Airborne Propagation of Maple Seeds?" to PPPL's Dave Cylinder at the Lab's Science Fair.

In April 2004, the vacuum vessel prototype for the National Compact Stellarator Experiment (NCSX) arrived at PPPL. Some PPPL members of the joint PPPL-Oak Ridge National Laboratory team checked out the new arrival — a curved piece of Inconel — displayed in the Lobby. From left were Mike Zarnstorff, Charlie Gentile, Hutch Neilson, Phil Heitzenroeder, H.M. Fan, Craig Priniski, Tom Brown, Lew Morris, Henry Carnevale, Marianne Tyrrell, Jerry Levine, Fred Dahlgren, Eric Fredrickson, Larry Dudek, Don Monticello, Chang Jun, Mike Viola (seated in prototype), Rob Goldston, Ron Strykowsky, Judy Malsbury, Art Brooks, Frank Malinowski, Wayne Reiersen, Bob Simmons, David Mikkelsen, Martha Redi, Irving Zatz, Mike Kalish, Allan Reiman, Erik Perry, Gary Oliaro, Neil Pomphrey, Mike Messineo, Rich Hawryluk, and Bruce Paul. Major Tool and Machine in Indianapolis manufactured the prototype.

In June 2004, the Laboratory honored 32 inventors for Fiscal Year 2003 during the annual Patent Awareness Program Recognition Dinner at Princeton University's Prospect House. Those attending the dinner and receiving awards were, from left, Charles Skinner, Scott Klasky, Margaret Lumia, Doug McCune, Kenneth Hill, Eliot Feibush, Manfred Bitter, Dana Mastrovito, Christopher Brunkhorst, Masayuki Ono, Andrew B.W. Bigley, Lewis Meixler, and John Desandro.

The chance to tour a fusion machine and play with plasma drew about 2,000 visitors to the Open House at PPPL on June 12, 2004. The Laboratory's visitors, ranging from tots to seniors, walked around the National Spherical Torus Experiment, learned about the physics behind sports games, and participated in tabletop demonstrations about electromagnetism, thermodynamics, and common plasmas, as well as in hands-on safety activities. PPPL engineer Ray Camp gave a cryogenics demonstration to a crowd in the Cafeteria.

The Laboratory named PPPL Employment Manager Andrea Moten as the Diversity Officer and Hispanic Employment Program Coordinator.



In July 2004, U.S. Department of Energy (DOE) officials announced that PPPL will host the U.S. project office for ITER, a major international fusion experiment. PPPL, in partnership with DOE's Oak Ridge National Laboratory, will be responsible for overseeing the U.S. ITER Project Office and providing it with the requisite staffing and facilities. PPPL's Ned Sauthoff (pictured) was named Project Manager for the Office.

The staff at PPPL celebrated the successful completion of the National Spherical Torus Experiment (NSTX) operations for Fiscal Year 2004. In August, the Laboratory held an Olympics-themed pizza party in honor of the NSTX 21-run-week accomplishment and of all who contributed to making the run a scientific success. In the top photo, PPPL'ers enjoyed the pizza party in the LSB Lobby under a series of flags reflecting the Olympics theme of the bash. Below, partygoers grabbed a slice or two. PPPL's John Jenner (left photo) led the line.

In September 2004, PPPL awarded two subcontracts for the fabrication of major components for the National Compact Stellarator Experiment (NCSX), now under construction at the Laboratory. PPPL is building the new experiment in partnership with the U.S. Department of Energy's Oak Ridge National Laboratory. PPPL Director Rob Goldston (center) signed the subcontracts for the NCSX components fabrication, joined by NCSX Project Head Hutch Neilson (right) and NCSX Deputy Project Head for Engineering Phil Heitzenroeder.

In observance of Fire Prevention Week, PPPL's Site Protection Division staff displayed emergency response equipment and handed out fire prevention materials in the LSB Lobby. The week's theme, "It's Fire Prevention Week: Test Your Smoke Alarms," highlighted the importance of all families installing and maintaining smoke alarms in the home. At the display were, from left, Mike Scafiro, Howard Caruso, Chris Snyder, and Dave Neuman.

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PPPL Financial Summary by Fiscal Year
(Thousands of Dollars)

	FY00	FY01	FY02	FY03	FY04
Operating Costs					
Fusion Energy Sciences					
NSTX	$18,248	$20,538	$19,894	$25,604	$27,203
NCSX	3,644	3,156	3,608	3,109	621
Theory and Computation	5,823	5,757	6,201	6,749	6,993
Off-site Collaborations	8,342	7,722	7,601	9,121	7,656
Off-site University Research Support	719	871	742	819	710
CDX-U/LTX	876	771	822	743	865
MRX/MRX Frontier Science Center	600	513	462	673	885
Heavy Ion Fusion	513	1,078	1,191	1,410	1,307
Next-step Options	900	771	749	589	536
ITER	–	–	–	705	647
Science Education Programs	515	593	624	667	685
TFTR	12,101	17,402	14,936	717	–
Waste Management*	–	3,086	2,790	–	–
Other Fusion	1,077	1,369	1,442	1,700	2,509
Total Fusion Energy Sciences	$53,358	$63,627	$61,062	$52,606	$50,617
Environmental Restoration and Waste Mgt	$3,036	$95	$123	–	–
Advanced Scientific Computing Research	21	72	547	437	231
Basic Energy Sciences	608	391	161	79	–
High Energy Physics	98	316	341	181	354
Safeguards and Security**	–	1,670	1,617	1,623	1,907
Science Laboratories Infrastructure	–	–	710	679	1,237
Other DOE	34	120	185	87	86
Total DOE Operating	$57,155	$66,291	$64,746	$55,692	$54,432
Work for Others					
Federal Sponsors	$596	$1,111	$1,424	$1,958	$1,661
Nonfederal Sponsors	515	596	130	170	523
Other DOE Facilities	150	425	235	103	51
Total Operating Costs	$58,416	$68,423	$66,535	$57,923	$56,667
Capital Equipment Costs					
NSTX	$5,532	$2,393	$1,995	$976	$2,365
NCSX	–	–	–	4,796	11,392
Off-site Collaborations	655	1,714	2,187	1,817	740
LTX	–	–	–	–	75
TFTR	1,273	870	34	–	–
All Other Fusion	242	917	966	200	850
All Other	1	177	–	–	68
Total Capital Equipment Costs	$7,703	$6,071	$5,182	$7,789	$15,490
Construction Costs					
General Plant Projects - Fusion	$2,070	$1,533	$2,170	$738	$1,696
General Plant Projects - S&S	–	–	–	49	1,265
Energy Management Projects	110	77	64	28	45
Other DOE Construction	7	–	–	–	2
Total Construction Costs	$2,187	$1,610	$2,234	$815	$3,008
TOTAL PPPL	$68,306	$76,104	$73,951	$66,527	$75,165

*Waste Management transferred to the Fusion Energy Sciences Program from Environmental Restoration/Waste Management in FY2001. Waste Management transferred to an indirect funded activity in FY2003.

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

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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

William Happer
Chair, Princeton University Research Board

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

Off-Site Research
Ned R. Sauthoff

Plasma Science and Technology
Philip C. Efthimion

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

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

Experiment
Joel C. Hosea

Engineering and Technical Infrastructure
Michael D. Williams

Business Operations
Edward H. Winkler

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

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

PPPL Staffing Summary by Fiscal Year

	FY00	FY01	FY02	FY03	FY04
Faculty	3	3	3	3	3
Physicists	91	97	95	94	90
Engineers	85	82	82	77	78
Technicians	197	210	166	157	170
Administrative	77	73	72	73	69
Office and Clerical Support	21	20	18	16	17
Total	474	485	436	420	427

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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 annually and reports to the University President through the Provost.

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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Publications

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*First author is from another institution. PPPL co-authors are underlined.
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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
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
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
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
EFDA	European Fusion Development Agreement
EFIT	An equilibrium code
E-LHDI	Electrostatic Lower-hybrid Drift Instability

ELM	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
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
FLC	Federal Laboratory Consortium (for Technology Transfer)
FLR	Field-line Resonance
FPT	Fusion Physics and Technology, Inc.
FRC	Field-reversed Configuration
FTP	File Transfer Protocol
FW	Fast Wave
FY	Fiscal Year

GA	General Atomics in San Diego, California
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
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
ITPA	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
LPDA	Laboratory Program Development Activities at the Princeton Plasma Physics Laboratory
LPI	Lithium Pellet Injector
LSN	Lower Single Null
LTX	Liquid Tokamak Experiment

MA	Megampere
MAST	Mega-Ampere Spherical Tokamak at the Culham Laboratory, Unted Kingdom
MAV	Micro Air Vehicle
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
MRX	Magnetic Reconnection Experiment at the Princeton Plasma Physics Laboratory
ms, msec	Millisecond
MSE	Motional Stark Effect (Diagnostic)
MW	Megawatt

NASA	National Aeronautics and Space Administration
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
NERSC	National Energy Research Supercomputer Center
NIFS	National Institute of Fusion Science (Japan)
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)
PF	Poloidal Field
PFC	Plasma-facing Component

PFRC	Princeton Field-reversed Configuration (Experiment) at the Princeton Plasma Physics Laboratory
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)
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

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
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	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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Editors: Carol A. Phillips and Anthony R. DeMeo

Contributors: S.A. Cohen, R.C. Davidson, A.R. DeMeo, N.J. Fisch, S. Gerhardt, E.P. Gilson, R.J. Goldston, L.R. Grisham, R.J. Hawryluk, M.T. Iseicz, S. Jardin, H. Ji, D.W. Johnson, J.R. Johnson, S.M. Kaye, J. Levine, R.P. Majeski, J. Manickam, D.M. Meade, L.D. Meixler, R. Nazikian, G.H. Neilson, C.A. Phillips, A. Post-Zwicker, B. Sarfaty, N.R. Sauthoff, G. Schilling, B. Sobel, P. Wieser, M.D. Williams, M. Yamada

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For additional information contact:
Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543
Phone: (609) 243-2750
Fax: (609) 243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov/