Plasma Science and Fusion Center

MIT's Plasma Science and Fusion Center (PSFC) is known internationally as a leading university research center for the study of plasma and fusion science and technology with research activities in six major areas:

- The science of magnetically confined plasmas in the development of fusion energy, in particular the Alcator-C-Mod tokamak project
- The basic physics of plasmas, including magnetic reconnection experiments on the Versatile Toroidal Facility (VTF), new confinement concepts such as the Levitated Dipole Experiment (LDX), development of novel high-temperature plasma diagnostics, basic laboratory and ionospheric plasma physics experiments, and theoretical plasma physics and fusion science research
- The physics of high-energy density plasmas, which includes PSFC's activity on inertial confinement laser-plasma fusion interactions
- The physics of waves and beams (gyrotron and high gradient accelerator research, beam theory development, nonneutral plasmas, and coherent wave generation)
- A broad program in fusion technology and engineering development that addresses problems in several areas (for example, magnet systems, superconducting materials, and system studies of fusion reactors)
- Research into plasma technologies, such as plasma-assisted conversion of hydrocarbon fuels into hydrogen, and the development of environmental monitoring and remediation techniques based on plasma technology

Administratively, each of these six major research areas constitutes a separate research division. The PSFC's research divisions are Alcator, Physics Research, High-Energy Density Plasma Physics (HEDP), Waves and Beams, Fusion Technology and Engineering, and Plasma Technology. Note that the newest of these divisions, HEDP, led by Dr. Richard Petrasso, was created this past year to recognize the growth in HEDP research at the center over the last ten years. Previously, the center's HEDP program resided in the Physics Research division.

PSFC research and development (R&D) programs are supported principally by the Department of Energy's Office of Fusion Energy Sciences (DOE-OFES). There are approximately 260 personnel associated with PSFC research activities. These include 21 faculty and senior academic staff; 52 graduate and 12 undergraduate students, with participating faculty and students from Aeronautics and Astronautics, Chemical Engineering, Electrical Engineering and Computer Science, Materials Science and Engineering, Mechanical Engineering, Nuclear Science and Engineering, and Physics; 80 research scientists, engineers, postdoctoral associates, and technical staff; 36 visiting scientists, engineers, and research affiliates; three visiting students; 26 technical support personnel; and 30 administrative and support staff.

Total FY07 funding for the PSFC's six research divisions was $32.03 million, slightly lower than the FY06 funding level of $32.34 million. Funding for the center's single largest program, the Alcator C-Mod project, increased by 4.2 percent from $19.22 million in FY06 to $20.02 million in FY07. Funding for the Physics Research division also increased, though only slightly, from $3.46 million in FY06 to $3.49 million in FY07. (Note that the research volume reported here for the Physics Research division in FY06 *excludes* the research volume of the PSFC's HEDP program, formerly considered part of the Physics Research division but now reported separately for the new HEDP division.) The research programs that now make up the new HEDP actually decreased by 3.70 percent over last year, from $1.73 million in FY06 to about $1.67 million in FY07.

Two PSFC research divisions experienced more significant declines in their research volumes. Fusion Technology and Engineering, for instance, saw its funding drop by 11.6 percent, from $5.23 million in FY06 to $4.62 million in FY07. Funding for the Wave and Beams division dropped by more than 15 percent, from $2.06 million in FY06 to about $1.75 million in FY07. The decreases are a consequence of the US Department Of Energy's (DOE) decision to reduce some ITER-related R&D activities so as to keep the total US ITER budget within the congressionally authorized limit of $1.12 billion. Finally, due to lack of sponsors (both government and private sector), funding of the PSFC's smallest division, Plasma Technology, continued to decrease, by 25 percent from $0.64 million in FY06 to $0.48 million in FY07.

With the construction phase of the International Thermonuclear Experimental Reactor (ITER) Program now underway, the House's proposed budget for the US national fusion program in FY08 would increase to $428 million, up from $312 million in FY07, an increase of about 37 percent. The Senate budget request is similar, with some differences in funding HEDP physics. Most of the funding increase will go toward the US government's commitment to ITER. We are encouraged that DOE will continue to support the US base program for fusion R&D at least at the same level of funding as prior to ITER. We believe that a continued strong base program is essential if the US is to capitalize on the success of ITER to develop fusion energy in the long term.

Alcator

The Alcator C-Mod tokamak (see figure 1) is a major international fusion experimental facility and is recognized as one of three major US national fusion facilities. Dr. Earl Marmar, senior research scientist in the Department of Physics and the PSFC, is the principal investigator and project head.

The C-Mod team includes MIT full-time equivalent staff of approximately 50 scientists and engineers, including eight faculty and senior academic staff, plus 27 graduate students and 25 technicians. Additionally we have collaborators from around the world, bringing the total number of scientific facility users to about 200. The cooperative agreement with DOE-OFES, which funds the C-Mod project, was renewed effective November 1, 2003 for a five-year period. Including major collaborators, total FY07 funding for the project is about $22.4 million ($20.0 million direct funding at MIT). Planning for the next five-year grant period (November 2008 through October 2013) has started, and a proposal will be submitted to the DOE in the spring of 2008.

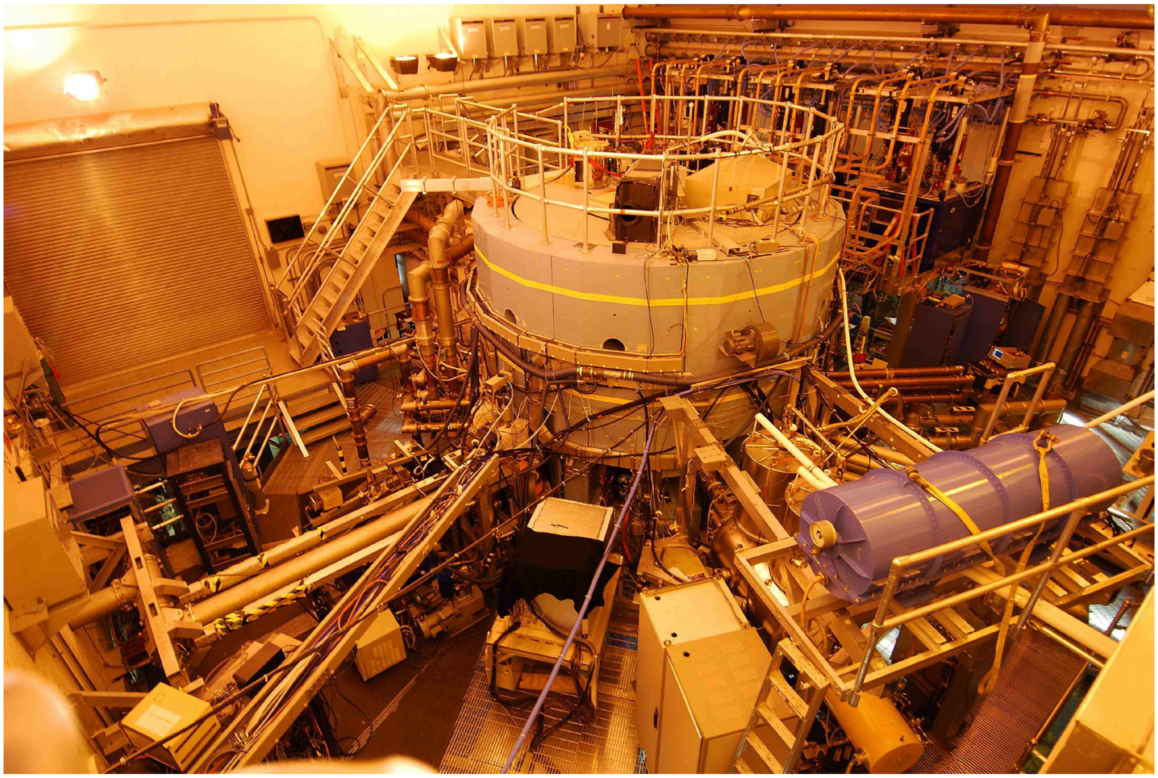

Figure 1. This picture shows the Alcator C-Mod experimental facility, with the tokamak at the center.

Research on C-Mod continued during the past year in high-performance compact magnetic plasma confinement. Experiments this year are being carried out in the topical science areas of transport, wave-plasma interactions, boundary physics, and magnetohydrodynamic stability, as well as in the integrated topical areas of advanced tokamak and burning plasma science.

Facility operation for research this fiscal year (FY2007) is planned to total 15 weeks (±10 percent). As of June 27, 2007, 9.3 weeks of the research operations have been completed. Details of the day-to-day operation can be found at http://www-cmod.psfc.mit.edu/cmod/cmod_runs.php, which includes links to run summaries, miniproposals, and engineering shot logs. Alcator's operation is largely constrained by funding. Current guidance funding for the project in FY2008 ($23.6 million) would allow for 15 weeks of research operation again next year.

Recent Research Achievement Highlights

Important progress was made using the lower hybrid microwave system, which is a key tool for control of current profiles in advanced scenarios. The long-term goals of this research are to demonstrate and develop predictive models for current profile control, leading to full noninductive current drive for pulse lengths long compared to current profile relaxation times; produce, understand, and control core transport barriers with strongly coupled electrons and ions; and attain and optimize plasma pressure up to the no-wall β (plasma pressure to magnetic pressure ratio) limits, with normalized β_N of at least three. Lower hybrid RF power has been coupled into ion-cyclotron heated plasmas, including plasmas operating in the H-mode regime. The coupling efficiency is found to be consistent with expectations based on the relationship between coupling efficiency and density at the grill face developed for L-Mode regimes. There is a marked difference in this density, and therefore the coupling efficiency, in pre- and post-boronization plasmas. Prior to the first boronization of the FY07 campaign, application of waves in the ion-cyclotron range of frequencies caused the density at the grill to drop to levels that resulted in relatively poor lower hybrid coupling; after boronization, the drop in density at the grill was much reduced, resulting in conditions more typical of those found in L-Modes, and the coupling efficiency improved significantly. It is not yet understood why boronization had this effect, or if it was the sole reason for this change in behavior. These studies are continuing, with emphasis on evaluation of the current drive efficiency and measurement of the spatial deposition of the driven current in H-Modes, in particular with synergies made possible by cryopump operation. These experiments are attracting international interest, as lower hybrid current drive (LHCD) is being actively considered for installation in ITER and the C-Mod results will be important in making a decision on whether to install LHCD for “day 1” operation on ITER.

Major disruptions are potentially risky events in tokamaks because the escaping pressure caused by the plasma instability can damage the containment vessel. Rapidly injecting inert gas into the unstable plasma greatly lowers the risks by making the thermonuclear plasma lose its pressure through releasing a relatively uniform emission of photons. Recently this mitigation technique has been experimentally demonstrated on Alcator C-Mod at the plasma and magnetic pressures comparable to those expected in ITER. The instability was detected and the disruption caught in a few thousandths of a second by real-time computer monitoring of the plasma, and the gas mitigation system was automatically triggered in time to ameliorate the effects of the disruption. For the first time, a state-of-the-art 3-D instability numerical model (NIMROD) of these experiments has shown how the plasma helps itself by mixing around the injected gas particles via the plasma instabilities themselves, a key insight into projecting this method to ITER and ultimately to reactors.

C-Mod is a unique high-power diverted tokamak with molybdenum refractory metal armor. Research on C-Mod has shown that its molybdenum walls have the surprising ability, in some cases, to retain about 30 percent of the hydrogenic (deuterium) gas fuel injected into the device. Large fractions of retention are not tolerated in a burning plasma device because they affect the tritium (hydrogen isotope) inventory available for burning. Refractory metals are typically favored for ITER and future reactors due to their high melt temperature and strength and their usually low capacity for H storage as compared to graphite (the material commonly used in present-day tokamaks). The research has identified new mechanisms by which exposure to the harsh, high heat and particle flux environment of a burning plasma tokamak can actually modify the metal properties to allow it to retain more of the fuel. These new experiments, and related modeling, could be critical to the successful use of refractory metals in ITER and beyond, where fuel retention must be about a factor of 100 lower than is seen in present fusion devices.

Physics Reseach Division

The goal of the Physics Research Division, headed by Professor Miklos Porkolab, is to improve theoretical and experimental understanding of plasma physics and fusion science. This division maintains a strong basic and applied plasma theory and computation program while developing basic plasma physics experiments and new confinement concepts.

Fusion Theory and Computations

The theory effort, led by Dr. Peter Catto and funded by the DOE-OFES, focuses on basic and applied fusion plasma theory research. It supports Alcator C-Mod and other tokamak experiments worldwide, the LDX (which has begun levitated operation), and the VTF. In support of these efforts, additional funding is allowing us to upgrade our computer cluster. To follow are highlights of contributions made by this group during the past year.

Professor Jeff Freidberg's new introductory plasma energy textbook is now available.

Tokamak Confinement and Transport

Dr. Darin Ernst and students continued first principles gyrokinetic simulations of trapped electron mode (TEM) turbulence. During studies of the impact of collisions on the upshift of the TEM threshold it was discovered that zonal flow-dominated states arise from nonlinear secondary instability. In comparing theoretical predictions with density fluctuation measurements, utilizing the new synthetic phase contrast imaging diagnostic, the first direct observation of TEM turbulence was made in C-Mod. This mode is thought to be the main candidate to explain electron heat and particle transport in tokamaks. Regarding new code development, finite gyroradius effects and energy scattering were implemented in the collision operator of the GS2 gyrokinetic code (only pitch angle scattering had been previously included). The finite gyroradius terms strongly stabilize short wavelength TEM's, while energy scattering greatly reduces resolution requirements.

Tokamak turbulence levels are regulated by plasma flow shear, referred to as zonal flow. Catto and coworkers analytically evaluated the residual zonal flow level in a PhD thesis by his former student Yong Xiao and then performed comparisons with the gyrokinetic code GS2. They found good agreement between their analytic results and the GS2 code predictions in the following areas:

- the residual zonal flow level is larger for electron temperature gradient drive than for ion temperature gradient drive
- the residual flow level increases more strongly with ellipticity than triangularity
- the poloidal flow damping rate for an improved ion-ion collision operator that conserved momentum

Magnetohydrodynamics and Extended MHD

Dr. Jesus Ramos participates in two Scientific Discovery through Advanced Computing (SciDAC) projects, the Center for Extended MHD Modeling and the Center for Simulation of Wave Interactions with MHD, with the purpose of implementing an advanced fluid description of magnetized plasmas in large-scale nonlinear simulations. During FY06, a gyroviscous contribution to the ion momentum equation was successfully included in the M3D and NIMROD codes. Also, as part of an ongoing collaboration with members of the National Institute for Fusion Science in Japan, a novel reduced two-fluid system was proposed to investigate multiscale nonlinear plasma dynamics. The basic properties of the equilibrium equations for axisymmetric plasmas with large flows and pressure anisotropies were obtained within the framework of this collaboration.

Existing nonlinear gyrokinetic and extended MHD codes are unable to predict the evolution of tokamak plasma on transport time scales requiring a simultaneous knowledge of the global axisymmetric radial electric field and its associated flow. To predict long time-scale plasma evolution along with the superimposed zonal flow established on shorter time scales and at shorter radial scale lengths, hybrid fluid-kinetic descriptions are required. In collaboration with Andre Simakov (Los Alamos National Laboratory), the PSFC theory group developed such descriptions for arbitrary collisionality by closing moment equations with solutions to kinetic equations. Descriptions have been developed with a Maxwellian lowest-order distribution function and a drift kinetic equation closure, and an arbitrary lowest-order distribution with a full Fokker-Planck closure.

Heating, Current Drive, Advanced Tokamaks, and Nonlinear Dynamics

Dr. Paul Bonoli and Dr. John Wright participate in the multi-institutional SciDAC Center for Simulation of Wave Plasma Interactions. Bonoli serves as the principal investigator of this SciDAC project. This year they completed changes to a full-wave electromagnetic field solver for waves in the ion cyclotron and lower hybrid (LH) range of frequencies so the code could be run on a leadership-class computer at Oak Ridge National Laboratory (ORNL) using as many as 9000 processor cores. This has allowed simulations to be performed in less than an hour of wall clock time, simulations that normally required a week of wall clock time on a much smaller Beowulf cluster. They also worked extensively on simulating the radial and velocity space structure of nonthermal fast electrons produced in LH current drive experiments on Alcator C-Mod. The integrated LH currents have been found to be in quantitative agreement with the experiment, but the predicted profiles of hard x-ray emission have been found to be narrower than the measured profiles. Physics explanations for the broader measured emission include fast electron diffusion or broader deposition than what is predicted from ray tracing, perhaps due to diffraction effects. These effects are under investigation. Bonoli and Wright also participate in the Fusion Simulation Project “Simulation of Wave Interactions with MHD (SWIM),” where they completed work on an interface for coupling a full-wave field solver to a general integrated plasma simulator.

An analytical description correctly including relativistic effects on the propagation and damping of electron Bernstein waves was formulated for the first time by Joan Decker (Cadarache) and Abhay Ram as an outgrowth of Joan's MIT thesis. They have recently shown that the physics of electron Bernstein wave propagation and damping in spherical tori is similar to that of ordinary electromagnetic wave propagation and damping in ITER plasmas. Thus, the results for electron Bernstein waves may be useful in understanding electron cyclotron current drive in ITER.

Levitated Dipole Experiment Stability, Heating, and Confinement

The MHD interchange mode is thought to set the pressure limit in dipole confinement devices like LDX. A Z-pinch provides a large aspect ratio approximation to a dipole and in this limit finite beta nonlinear modeling indicates the development of a stiff pressure gradient limit accompanied by convective cells that reduce particle, but not necessarily energy, confinement. A recently completed PhD thesis by Alexei Kouznetsov, advised by Professor Freidberg and LDX theory research head Jay Kesner, indicates that toroidal flow has only a weak effect on the MHD stability limit. A quasilinear MHD theory developed showed that density as well as pressure may be expected to attain a stiff profile. Finally, PSFC theorists completed a study of equilibrium beta limits in dipole configurations with toroidal rotation and pressure anisotropy. Existence of an equilibrium limit was proved using numerical and analytical tools. Analytic study of magnetic confinement devices in the presence of flow and resistive walls continues with the purpose of formulating the problem in a form attractive for code development.

Experimental Research

Levitated Dipole Experiment

LDX is a joint collaborative project with Columbia University located in Building NW21 at MIT (see figure 2). Principal investigators of this project are Dr. Jay Kesner of MIT and Professor Michael Mauel of Columbia University.

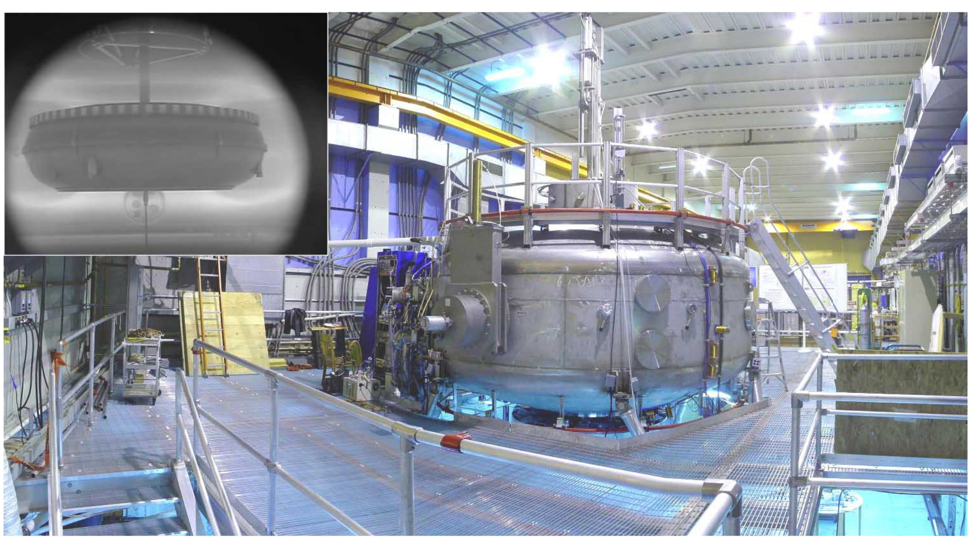

Figure 2. Picture of the LDX with insert showing floating coil magnetically levitated and surrounded by plasma.

During the initial experimental campaign in the past year, the dipole coil was mechanically supported within the LDX vacuum chamber. The experiments indicated a clear transition into a high-pressure plasma regime, as had been predicted. These experiments also provided a database for supported operations to be compared with future levitated experiments and have provided an opportunity to test the coil operation, the diagnostic set, and the control system. Because levitation eliminates plasma losses to the supports of the internal coil we expect that levitation will lead to substantial improvement of plasma confinement and stored energy.

In order to permit levitation, the launcher was replaced to permit the floating coil to lift off from it, and a feedback system was developed. Levitation was demonstrated in February 2007. Unfortunately the levitation coil, which sits above the vacuum chamber and creates the upward force necessary for levitation and feedback, was damaged during this trial. It is presently being replaced with a normal copper coil and experiments with the floating coil-levitated operation are expected to resume in September. In the next phase of operation, beginning in fall 2007, the dipole coil will be levitated.

Magnetic Reconnection Experiments on the Versatile Toroidal Facility

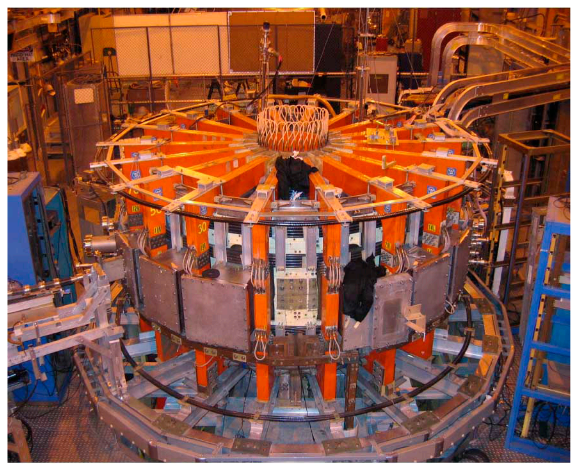

Figure 3. The PSFC's Versatile Toroidal Facility.

Magnetic reconnection plays a fundamental role in magnetized plasmas as it permits rapid release of magnetic stress and energy through changes in the magnetic field line topology. It controls the spatial and temporal evolution of explosive events such as solar flares, coronal mass ejections, and magnetic storms in the earth's magnetotail, driving the auroral phenomena. Magnetic reconnection is studied in the VTF (see figure 3) under the leadership of Dr. Jan Egedal, appointed assistant professor in 2005. The new magnetic geometry of VTF is providing insight into what controls the onset of the explosive magnetic reconnection event observed in nature. This January a *Physical Review Letter* was published detailing the first observation of a spontaneous reconnection event in a toroidal geometry (see figure 4). The focus of the experiment is now to explore the physics of the three-dimensional mechanism that initiates these events. To aid this study new analog-to-digital converters have been installed, which allow simultaneous measurements of 900 diagnostic signals. The diagnostics are being built mainly by four UROP students and three graduate students. Besides the work on VTF, Dr. Egedal enjoys a strong collaboration with the Space Science Lab at the University of California, Berkeley on the analysis of electron data obtained in situ by spacecraft in the Earth's magnetotail. New results on magnetotail reconnection are currently under review for publication in *Physical Review Letters*.

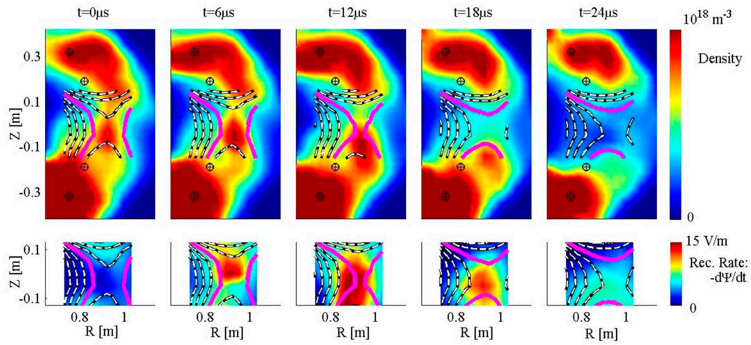

Figure 4. First measurements of plasma density, magnetic fields, and reconnection rate during a spontaneous reconnection event in the VTF.

MIT-PSFC/JET/CRPP Collaboration on Alfvén Wave Propagation and Instabilities

Professor Porkolab leads this project from MIT, with active involvement by Dr. Joe Snipes of PSFC and MIT postdoctoral fellow Alex Klein, located at the Joint European Tokamak (JET) site near Oxford, England. This program conducts experiments at JET, the world's largest tokamak, and involves collaboration with Professor Ambrogio Fasoli of the Plasma Physics Research Center (CRPP) in Lausanne. In these experiments, waves are launched by specially built antennas, the most recent of which has just been installed in JET. Studies of wave propagation and damping processes have been carried out in the past year. A large database has been obtained in recent experiments and it is presently being analyzed. Further antenna components will be installed next year to improve on the spectral resolution of launched waves. In addition, instabilities driven by high-energy particles, such as neutral beam ions, RF-driven energetic ions, and ultimately, alpha particles, are studied. These studies lead to an improved understanding of plasma stability and transport that will be important in future burning plasma experiments where the fusion process generates a substantial alpha particle component.

Novel Diagnostics for Magnetic Fusion Research

Phase Contrast Imaging Diagnostic of Waves and Turbulence on DIII-D and C-Mod

Under the leadership of Professor Porkolab, PSFC research scientist Dr. Chris Rost (at DIII-D in San Diego) and graduate students on DIII-D and C-Mod have upgraded the phase contrast imaging (PCI) diagnostics to detect short wavelength (cm to sub-cm), high frequency (up to 5 MHz) modes. The shorter wavelength modes (the so-called TEM and ETG modes) should play a fundamental role in determining particle and energy transport, one of the frontiers of fusion research. Meanwhile, localization measurements of modes along the laser beam have also been carried out with the aid of a rotating mask. These experiments are providing important new information on short wavelength instabilities related to transport, and various instabilities in the Alfven wave regime (Reversed Shear Alfven waves, or RSA). New turbulence data has been obtained on both machines and data analysis is in progress.

Collective Thomson Scattering of Ions in Textor and Asdex-U

An international partnership consisting of PSFC, Risø National Laboratory (Denmark), Institut für Plasmaphysik (Jülich, Germany), and Max-Planck-Institut für Plasmaphysik, (Garching, Germany) is pursuing the development of fast ion collective Thomson scattering (CTS) diagnostics. CTS experiments have been implemented at the TEXTOR

(Jülich) and ASDEX-Upgrade (Garching) tokamaks using the available high-power gyrotron infrastructure at these facilities, with the addition of sensitive scattered signal receiver systems. In FY2007 several CTS diagnostic campaigns were carried out at TEXTOR with neutral beam heating of the plasma. Measurements of fast ion dynamics were obtained during neutral beam turn on and off, and during sawtooth activity. Initial comparisons of these measurements with Fokker-Plank modeling calculations look to be in good agreement. At ASDEX-Upgrade, initial CTS plasma measurements will begin in FY2008. The higher performance plasmas of ASDEX-Upgrade are expected to provide a more definitive test of CTS for fast ion studies. The development of fast ion diagnostics is considered essential for the advancement of fusion burning science to study energetic product alpha particles during fusion burn. This activity also involves the design and application of CTS to ITER fusion alpha product diagnostics.

Ionospheric Plasma Research

These experiments were conducted by several undergraduate and graduate students under the leadership of Professor Min-Chang Lee. The experiments will be concluded at the end of 2007 and the equipment will be transferred to Boston University where Professor Lee is a tenured professor. This event is based on the decision of the previous vice-president for research, Professor Alice Gast. The impact of loss of this funding on the PSFC is minimal.

High-energy Density Plasma Physics Division

MIT continues a major effort in inertial-confinement fusion (ICF). The newly formed HEDP (formerly part of the Physics Research division) is led by Dr. Richard Petrasso and has carried out pioneering and important studies of ICF physics with the development and use of novel diagnostic techniques, with experiments and interpretation, and with theory. MIT collaborates with the University of Rochester Laboratory for Laser Energetics, where the 30-kJ, 60-beam OMEGA laser provides the most important current test bed for ICF experiments worldwide, and with the Lawrence Livermore National Laboratory, where the huge National Ignition Facility (NIF) under construction will host the next generation of ICF experiments expected to achieve ignition (self-sustaining burn and net energy gain) by imploding fuel capsules with a 2-MJ, 192-beam laser. Fusion ignition experiments will commence in 2010.

A major new initiative in the last year was the development of a major NIF diagnostic instrument (called the Magnetic Recoil Spectrometer, or MRS) that will measure high-resolution spectra of 14.1-MeV DT neutrons by determining the spectra of protons or deuterons scattered by the neutrons in a special foil. Spectra of direct neutrons will give information about fusion yield and plasma temperature, while spectra of "downscattered" neutrons that have lost energy through interactions with fuel ions will provide a measure of the level of compression of the fuel. A prototype of that instrument has been built and is now being installed on OMEGA (see figure 5). This spectrometer, which will be qualified and commissioned this fall, will enable workers to make the first measurements of fusion products under the extreme conditions–200 g/cc–achieved in fusion implosions.

In other work this year at OMEGA, MIT scientists have done a wide range of important experiments utilizing charged fusion products to study the dynamics of imploded ICF fuel capsules. In addition, proton radiography utilizing MIT-developed methods with monoenergetic proton sources has been used for the first time to study magnetic reconnection in laser-plasma interactions and to observe and quantify the spatial structures of compressed ICF capsules and the electric and magnetic fields that form around them during implosions. Several papers were published in the prestigious *Physical Review Letters* in this area of research. In addition to the senior staff, these research projects involve the direct participation of several graduate students pursuing PhDs in the field, as well as that of undergraduate students.

Figure 5. The spectrometer magnet enclosure just before being hoisted and interfaced to the OMEGA target chamber.

Waves and Beams Division

The Waves and Beams division, headed by Dr. Richard Temkin, conducts research on novel sources of electromagnetic radiation and on the generation and acceleration of particle beams. Substantial graduate student involvement is emphasized in all research programs within Waves and Beams.

Gyrotrons are under development for electron cyclotron heating of present day and future plasmas, including the ITER plasma; for high frequency radar; and for spectroscopy. These applications require gyrotron tubes operating at frequencies in the range 90–500 GHz at power levels of up to several megawatts. In 2006–2007, the Gyrotron Group, headed by Dr. Michael Shapiro, conducted research on the efficiency of a 1.5 MW, 110 GHz gyrotron with an internal mode converter and a depressed collector. New theoretical research identified that the gyrotron efficiency may be limited to 50 percent by an unwanted interaction that occurs after the cavity. Experimental results on the limits of the voltage that can be reached with the depressed collector agree with this theory. Research is also continuing on the origin of low frequency oscillations, in the 50–200 MHz range, found in the beam tunnel of the gyrotron. The research at MIT is the basis for a development program for a continuous wave gyrotron, which has been built by an industrial vendor, Communications and Power Industries (Palo Alto, CA).

That tube was tested at General Atomics in San Diego but is being returned due to a vacuum failure. We are also continuing research on low-loss microwave transmission lines in support of the ITER project (see figure 6). Intensive research, under the direction of Dr. Jagadishwar Sirigiri, continues on 140–500 GHz gyrotrons for use in electron spin resonance and nuclear magnetic resonance studies. In 2006–2007, we have rebuilt the 460 GHz gyrotron for improved efficiency. We also obtained first operation of a 140 GHz pulsed amplifier at the 500 watt power level and are continuing to construct a tunable 330 GHz gyrotron source.

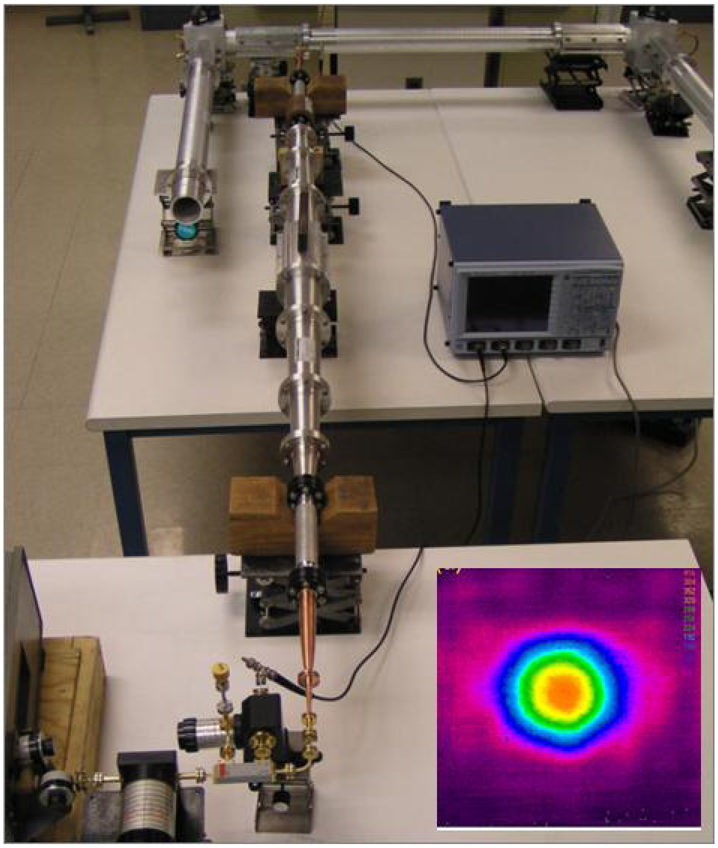

Figure 6. ITER transmission line components built by General Atomics under initial testing at PSFC. The inset shows the Gaussian mode transmitted by the line.

Our research effort on high-gradient accelerators is focused on high-frequency linear accelerators for application to future multi-TeV electron colliders. In 2006–2007, the Accelerator Research Group continued operation of the Haimson Research Corporation/MIT 25 MeV, 17 GHz electron accelerator. This is the highest power accelerator on the MIT campus and the highest frequency stand-alone accelerator in the world. We have recently installed our photonic bandgap accelerator cavity to measure the wakefields generated when the intense electron beam passes through the structure. Wakefields in parasitic modes are being calculated by our collaborators at Stanford Linear Accelerator Center and at STAR, Inc. and the results will be compared with our data. We are also installing a power amplifier test system from Haimson Research, which will test the capability of novel materials, such as stainless steel, to withstand breakdown at high microwave power levels. An upgrade of this facility to higher repetition rate operation, up to 20 Hz, is funded and will be carried out in the next year.

Fusion Technology and Engineering Division

The Fusion Technology and Engineering (FT&E) division, headed by Dr. Joseph Minervini, conducts research on conventional and superconducting magnets for fusion devices and other large-scale power and energy systems. The division's major research support has historically been from DOE-OFES. The OFES Fusion Technology

Program and, subsequently, the Enabling Magnet Technology Program, have undergone significant redirection over the past several years. The OFES has continued in this direction, reducing the magnet technology budget at MIT to only $619,000 in FY2007 from a previous steady funding level of about $2.0 million per year. This has been a consequence of redirecting most of the magnet technology funds toward ITER-related fabrication efforts at the ORNL. After requests to OFES to allow three in-progress PhD students to continue, funding for FY2008 has been decreased to $410,000. This will allow these students to graduate, but further research assistantship positions in FY2009 and beyond are in jeopardy.

In 2006, all ITER-related funding was transferred to the US ITER Project Office headquartered at ORNL. MIT received approximately $1.5 million for most of FY2007 as a subcontract from ORNL toward ITER-relevant engineering design and R&D work. We expect that this level of funding will be renewed in FY2008. Funding beyond that is questionable and at present not in the DOE plans.

MIT-PSFC completed its collaboration with Brookhaven National Laboratory, Princeton University, ORNL, and other institutions in developing mercury jets as targets for a muon collider or neutrino factory. Peter Titus successfully tested the MERIT magnet this year in the West Cell of NW21. This cryogenically cooled magnet delivered 15 tesla pulsed magnetic fields to a flowing mercury jet cartridge, developed at ORNL. After successful completion of this test campaign, the MERIT magnet and mercury jet systems were shipped to the European Organization for Nuclear Research (CERN) in Geneva. The systems were installed in the TT2/TT2A tunnel at CERN (see figure 7) and are presently being readied for the first experimental scientific campaign.

Figure 7. MERIT magnet and mercury jet target being installed at CERN.

Work on a privately funded project to develop a 250 MeV synchrocyclotron for proton beam radiotherapy continued this year under the direction of Dr. Timothy Antaya of the FT&E Division. The Clinatron-250 is a synchrocyclotron with the capability of accelerating protons to 250 MeV and delivering a continuous current of up to 100 nA to a cancer patient. The system is now in the manufacturing phase. Division personnel are deeply engaged in finalizing the design and overseeing certain aspects of the component fabrication, especially for the superconductor, the superconducting magnet, and the cryostat. Under direction of Dr. Antaya, the team has been developing tools for beam dynamic simulations. These tools are used to investigate magnetic field optimization and beam extraction design. We expect to perform the cryogenic operation testing of the first magnet cold mass later this calendar year. The future funding of this project at the PSFC is in question once the project enters a commercialization phase in FY2008.

FT&E continued to further develop a detailed proposal for the MIT Energy Initiative for a "Program to Develop High Efficiency Power and Energy Systems Using Superconducting and Cryogenic Technology." Collaborators include PSFC staff, and faculty and staff from the Departments of Nuclear Science and Engineering, Electrical Engineering and Computer Science, Mechanical Engineering, and the Laboratory for Electromagnetic and Electronic Systems. We have received no indication from the MITEI that this work will be supported through this initiative, although we are ever hopeful.

Plasma Technology Division

The objectives of the Plasma Technology division, led by Daniel Cohn and Paul Woskov, are to develop new spinoff applications from plasma science and technology in areas including clean, high-efficiency vehicles, homeland security relevant monitoring devices, and nuclear waste treatment, and to develop new environmental technology diagnostics and fusion diagnostics (see the section on collective Thomson scattering of ions in Textor and Asdex-U).

From 1995 to 2005, under direction of Leslie Bromberg and Daniel Cohn, a major research area for the division was plasma-enhanced conversion of hydrocarbon fuels into hydrogen by the plasmatron reformer device. This work was licensed by ArvinMeritor, a major automotive parts supplier, who continued to develop and commercialize this invention—however, without PSFC participation, due to lack of funding. Recent sale of part of ArvinMeritor to a private equity group may provide opportunity for reinvolvement of PSFC in plasmatron-related technology development. Areas for potential reinvolvement include plasmatron-enhanced diesel exhaust aftertreatment systems for reduction of nitrogen oxides (NOx) and particulate emissions.

In addition to diesel exhaust aftertreatment, another potential area of application of the plasmatron reformer was its use to provide hydrogen-rich gas as a second fuel to increase the efficiency of gasoline engines. This second fuel approach, along with PSFC research in conversion of ethanol into hydrogen-rich gas, stimulated thinking that eventually led to creation of a concept to use directly injected ethanol as a second fuel to provide a major increase to the efficiency of gasoline engines at low cost. This ethanol-boosted gasoline engine concept was developed by Daniel Cohn and Leslie Bromberg in collaboration with Professor John Heywood. A patent on this concept was awarded to MIT in June 2007.

In the area of diagnostic development, from 1999–2006 the DOE Environmental Management Science Program funded a program for millimeter wave measurements of high-level and low-level activity waste glass melts, but funding was not renewed in FY2007 due to changes in the priorities of the funding agency. A small contract has been obtained from the Pacific Northwest National Laboratory (PNNL) in FY2007 to build an instrument based on the millimeter-wave glass melt research achievements for research into cogeneration coal gasification research at PNNL. The unique capabilities of the millimeter-waves to make in situ measurements in hot environments that are inaccessible to other measurement approaches are expected to provide new insights into the internal processes of this energy technology. If initial tests of the millimeter-wave thermal analysis instrumentation look encouraging, then follow-on support to fully develop this new diagnostic approach for cogeneration coal gasification is likely.

A trace metals monitoring development project, supported by a Lincoln Laboratory Advanced Concepts Committee grant, was carried out primarily by Dr. Kamal Hadidi in 2006–2007. In this project, the plasmatron reformer was tested for application to a low-cost trace metals monitoring instrument that could be used to monitor turbine blade wear. The plasmatron was used as an atomic emission excitation source for spectroscopic detection of the trace elements entrained in the plasma gas flow. Measurements of the plasma electron excitation temperature and molecular rotation temperature were studied. Funding for this project was for one year only, but the division is looking for support to continue trace metals monitoring development.

In a program led by Dr. Leslie Bromberg, the Plasma Technology division is developing a promising new approach for substantially increasing the sensitivity and selectivity for detection of explosives and chemical agents. Dr. Bromberg and Dr. Cohn received funding in FY06 from the Department of Homeland Security for research on a compact, low-cost sensor for explosives and chemical warfare agents using the plasma ion mobility spectrometer approach. This work continued in FY2007 but is being terminated due to a change in Department of Homeland Security funding priorities.

Overall, the division, which received the Discover Award for Technological Innovation and a number of R&D 100 Awards in past for its technical innovations (including one last year), most notably for development of the plasmatron and diagnostics in the area of pollution detection,struggled in recent years to cultivate timely new funding opportunities with private or government sponsors. As a result, the division experienced a gradual erosion of its research volume and this now threatens its viability. It is hoped that the new MIT initiative on energy research, through the activities of MIT's Energy Research Council directed by professors Ernie Moniz and Bob Armstrong, may provide the vehicle to secure new funding in this area of research. An important white paper for new research has been submitted to the council from the division.

Educational Outreach Programs

The Plasma Science and Fusion Center's educational outreach program is planned and organized under the direction of Paul Rivenberg, communications and outreach administrator of the PSFC. The program focuses on heightening the interest of K-12 students in scientific and technical subjects by bringing them together with scientists, engineers, and graduate students in laboratory and research environments. This kind of interaction, it is hoped, encourages young people to consider science and engineering careers. Tours of our facilities are also available for the general public. This year the PSFC was part of the citywide Cambridge Science Festival, offering a tour to the general public and a general seminar about some of the PSFC's recent environmental research. Annual visitors to the PSFC include participants from the Keys to Empowering Youth and the National Youth Leadership Forum.

Outreach Days are held twice a year, encouraging high school and middle school students from around Massachusetts to visit the PSFC for hands-on demonstrations and tours. PSFC graduate students who volunteer to assist are key to the success of our tour programs. The experience helps them develop the skill of communicating complex scientific principles to those who do not have advanced science backgrounds.

The Mr. Magnet Program, headed by Paul Thomas, has been bringing lively demonstrations on magnetism into local elementary and middle schools for 15 years. This year Mr. Magnet presented the program to nearly 30,000 students at over 75 schools and other events, reaching kindergartners through college freshmen. In addition to his program on magnetism, he offers an interactive lecture about plasma to high schools. The Traveling Plasma Lab encourages students to learn more about plasma science while having fun investigating plasma properties using actual laboratory techniques and equipment. The Plasma Lab is offered two weeks during the academic year. In April 2007, at the request of the DOE, Paul traveled with his truckload of equipment to Washington, DC, for the DOE-sponsored National Science Bowl. Paul has made this trek annually for the past eight years to present his magnet and plasma demonstrations to high school teams from across the nation.

PSFC's associate director, Professor Jeffrey Freidberg, has helped organize educational events oriented toward the MIT community, including the PSFC's annual IAP Open House. The PSFC has continued its educational collaboration with the MIT Energy Club, bringing a variety of interactive plasma demonstrations to their very successful Energy Night at the MIT Museum in October, and the MIT New England Energy Showcase at the Kendall Marriott in March. These events were attended by hundreds of MIT students, as well as business entrepreneurs, who learned about the latest directions of plasma and fusion research.

The PSFC continues to collaborate with other national laboratories on educational events. An annual Teacher's Day (to educate middle school and high school teachers about plasmas) and Plasma Sciences Expo (to which teachers can bring their students) has become a tradition at each year's American Physical Society (APS)-Division of Plasma Physics meeting. This year Mr. Rivenberg contributed to the effort in Philadelphia, PA, which attracted 61 teachers.

The PSFC also continues to be involved with educational efforts sponsored by the Coalition for Plasma Science (CPS), an organization formed by members of universities and national laboratories to promote understanding of the field of plasma science. PSFC associate director Dr. Richard Temkin is working with this group on goals that include requesting support from Congress and funding agencies, strengthening appreciation of the plasma sciences by obtaining endorsements from industries involved in plasma applications, and addressing environmental concerns about plasma science. Like Dr. Temkin, Paul Rivenberg is a member of the CPS Steering Committee. He works with CPS on new initiatives, including an effort to have the study of plasma placed in the science standards of every state in the US. He continues his duties as editor of the Coalition's Plasma Page, which summarizes CPS news and accomplishments of interest to members and the media. Mr. Rivenberg also heads a subcommittee that created and maintains a website to help teachers bring the topic of plasma into their classrooms. He also works with the Coalition's Technical Materials subcommittee to develop material that introduces the layman to different aspects of plasma science.

Awards, Appointments, and Promotions

During the past year, a number of PSFC staff have received awards, received appointments, or have been promoted.

Awards

Associate division head Paul Woskov has been honored with his sixth R&D 100 Award for his work on the MilliWaveThermal Analyzer. Principal research scientists Chikang Li (High-Energy-Density Plasma Physics) and John Rice (Alcator), and associate professor Dennis Whyte (Alcator) were awarded fellowships by the APS.

Andrew Pfeiffer, engineering and diagnostics shop supervisor, and Thomas Toland, electromechanical project technician, received 2007 MIT Infinite Mile Awards for their contributions to the Alcator Project.

Appointments

Alcator: Jeffrey Doody was appointed mechanical engineer.

Physics Research: Dr. Fredrick Seguin was appointed research scientist.

PSFC Fiscal Office: Jane Jackson, Edward Conroy, and Galina Ostrovsky were appointed assistant fiscal officers.

Promotions

Alcator: Dr. Jerry Hughes was promoted to research scientist. Dr. Stephen Wukitch was promoted to principal research scientist.

Waves and Beams: Dr. Jing Zhou was promoted to postdoctoral associate.

Physics Research: Dr. Chikang Li was promoted to principal research scientist. Dr. James Ryan Rygg was promoted to postdoctoral associate.

Fusion Technology and Engineering: Dr. Ji Hyun Kim was promoted to research engineer, Dr. Timothy Antaya was promoted to principal research engineer.

Graduate Degrees

During the past year, two departments awarded students degrees with theses in plasma fusion and related areas. Nuclear Science and Engineering awarded degrees to Alexei Kouznetsov, PhD; Daniel Rokusek, MS; Kelly Robert Smith, MS; and Ishtak Karim, PhD. Electrical Engineering and Computer Science awarded degrees to Alexandre Parisot, PhD, and Laurence Lyons, MS.

Miklos Porkolab
Director
Professor of Physics

More information about the Plasma Science and Fusion Center can be found on the web at http://www.psfc.mit.edu/.