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, including the Center'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 (e.g., 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 development of environmental monitoring and remediation techniques based on plasma technology

The PSFC research and development (R&D) programs are supported principally by the Department of Energy's Office of Fusion Energy Sciences (DOE-OFES). Approximately 271 personnel are associated with PSFC research activities, including 20 faculty and senior academic staff; 52 graduate students and 22 undergraduates; 75 research scientists, engineers, postdoctoral associates, and technical staff; 37 visiting scientists, engineers, and research affiliates and 5 visiting students; 27 technical support personnel; and 27 administrative and support staff. Participating faculty and students come from the Departments of Aeronautics and Astronautics, Chemical Engineering, Electrical Engineering and Computer Science, Materials Science and Engineering, Mechanical Engineering, Nuclear Science and Engineering, and Physics.

The overall research budget in FY2006 for the PSFC's five research divisions was $33.0 million, a 1.8 percent increase over the FY2005 research budget of $32.5 million. Funding for the Center's single largest program, the Alcator C-Mod project, actually dropped slightly from FY2005, decreasing by 1.6 percent from $19.6 million to $19.2 million. Alcator funding is stable, however, and is expected to increase in FY2007. Funding was virtually unchanged (down 0.2 percent from FY2005) for the Physics Research Division at $5.1 million. At the same time, the Wave and Beams Division experienced a pronounced drop of nearly 35 percent in funding, from $2.5 million in FY2005 to $1.6

million in FY2006. This decline was due in part to a slowing of gyrotron development work in the United States, with most gyrotron funds passing through to industry. The Fusion Technology and Engineering Division, on the other hand, saw its funding rise by more than 37 percent from $4.5 million in FY2005 to $6.2 million in FY2006, making it PSFC's second largest division in FY2006. This increase was attributable to the strength of early funding for tasks related to the International Tokamak Experimental Reactor (ITER; see below), which may not continue in FY2007. Finally, funding for PSFC's smallest division, the Plasma Technology Division, increased by only 11 percent, from $0.85 million in FY2005 to $0.95 million in FY2006.

Given the steady budget projection for base fusion research in FY2007 and beyond, and a significant additional increase for ITER construction (the US contribution is expected to be about $1.134 billion during the next eight years), funding at PSFC is expected to remain nearly constant, in line with the national program. Alcator C-Mod remains one of the nation's three main magnetic fusion facilities. The go-ahead for the construction of ITER seems nearly certain now, and the final documents are expected to be "initialed" (signed according to US law) by December of this year at the ministerial level. The construction site will be at Cadarache, France, and the multi-billion-dollar international collaboration will lead to the implementation of the world's largest fusion energy experiment. DOE determined that US participation in ITER would be led by the newly established US ITER Project Office at the Oak Ridge National Laboratory (ORNL). The consequence of the focused project management plan is that the scope of PSFC's work in tasks related to magnet technology and microwave heating will be more modest than originally anticipated.

Alcator Division

The Alcator C-Mod tokamak 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 PSFC, is the principal investigator and project head. The C-Mod team includes full-time equivalent staff at MIT of approximately 50 scientists and engineers, including 6 faculty and senior academic staff, along with 25 graduate students and 28 technicians. In addition, we have collaborators from around the world, bringing the total number of scientific users of the facility 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 FY2006 funding for the project was about $21.8 million ($19.2 million direct funding at MIT).

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 (MHD) stability, as well as in the integrated topic areas of advanced-tokamak and burning plasma science.

Facility operation for research in FY2006 was planned to total 14 weeks (±10 percent). As of June 23, 2006, 14.4 weeks of research operations had been completed. Details of the day-by-day operation can be found at http://www-cmod.psfc.mit.edu/cmod/cmod_runs.

php, which includes links to run summaries, mini-proposals, and engineering shot logs. Alcator's operation is largely constrained by funding. Current guidance funding for the project in FY2007 ($22.9 million) would allow for 15 weeks of research operation next year. Highlights of recent research achievements are outlined in the following paragraphs.

Important progress was made with 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 that are long relative 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 3. The original titanium launchers were successfully replaced with stainless steel (see figure 1), and powers up to 900 kW were successfully coupled into target plasmas. More than 80 percent of the toroidal plasma current was driven by the microwaves, and the efficiencies appeared to be in good agreement with expectations from theoretical modeling. New diagnostics, aimed specifically at examining the nonthermal electron distributions driven by the microwaves, have been successfully commissioned, and measurements are revealing important details of the experiments for comparison with theory. The next step in this research will be to increase the power (and driven current) as we move toward fully noninductive conditions.

On rare occasions, tokamaks are subject to events leading to prompt and total loss of confinement (the so-called major disruption). Many aspects of the physics of major disruptions are understood from worldwide research conducted over the last 20 years. However, no reliable means to completely avoid them has yet been discovered. The consequences of major disruptions can be significant: Large forces result from eddy and halo currents induced in structures during the fast plasma decay; direct deposition of plasma energy can cause localized erosion; large inductive voltages are generated during the plasma current decay, which can accelerate some of the plasma electrons to very high energies (>10 MeV); and the interaction of these "runaway" electrons with material surfaces can be deleterious. Approaches to ameliorating the negative results of disruptions are urgently needed for next-step experiments, especially ITER. Currently, the most promising approach is to use a rapid injection into the disrupting plasma of noble gas at very high pressure. Results of studies on the DIII-D tokamak have shown that this can soften the impacts of the disruption, at least in plasmas with moderate pressure. These results have been tested with higher absolute pressure plasmas (on Alcator C-Mod).

The C-Mod experiments, in collaboration with the University of Wisconsin, have shown that the disruption time scale can be shortened and halo currents reduced. It is clear from the experiments that penetration of the gas as neutral atoms is not necessary. Instead, measurements and detailed modeling from fully three-dimensional MHD numerical simulations show that gas cooling of the edge plasma induces strong instabilities, destroying the magnetic flux surface and allowing rapid escape of plasma energy from the confined core. This cooling occurs on a time scale faster than the natural time for the plasma to lose its vertical position; as a result, the plasma remains near the midplane of the torus until nearly all of the plasma current has decayed, which prevents the generation of strong halo currents. With the correct species of gases, including mixtures of light (helium) and heavy (argon) atoms, the process is very fast and dissipation of close to 100 percent of the stored energy (kinetic plus magnetic) can be achieved, dramatically decreasing the energy density to the walls. Further experiments examining the scaling of such events with plasma conditions on C-Mod and extending the investigations to the world's largest tokamak, the Joint European Torus (JET) in the United Kingdom, will be undertaken in the coming year.

A key issue confronting tokamaks as we look forward to ITER, and ultimately to reactors, is the stability and confinement of energy, particles, and momentum of the core plasma in the absence of direct torque drives. In most modern tokamaks, strong momentum input is provided by the injection of fast neutral particles (beams), which are also used to heat, fuel, and drive current in the core plasma. In ITER, particle, momentum, and current input from beams will be substantially smaller than in most current experiments, and in reactors they may be entirely absent. C-Mod is among only a very few high-power tokamaks operating without neutral beams, relying instead entirely on radio frequency (RF) waves and microwaves for heating and current drive. It has been known for several years, mainly from experiments on C-Mod and the Tore-Supra experiment (in France), that as the plasma pressure and pressure gradient are increased, the core plasma begins to rotate spontaneously. Understanding of the underlying transport drive(s) for this rotation is rudimentary, with no model successfully providing quantitative predictions of the experimental results. These studies, largely pioneered on C-Mod, are now being expanded through coordinated experiments involving several facilities. Some of the key physics parameters have been identified, and additional experiments in the coming year should help to inform the related theoretical investigations.

Physics Research 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, new confinement concepts, and novel inertial fusion diagnostics.

Fusion Theory and Computations

The theory effort, led by Dr. Peter Catto and funded by DOE-OFES, focuses on basic and applied fusion plasma theory research. It supports Alcator C-Mod and other tokamak experiments worldwide, LDX (which is about to begin levitated operation), and VTF. In support of these efforts, new funding ($150K, shared equally by DOE and PSFC) will allow an upgrade of our computer cluster this year and next. The sections to follow highlight important contributions made by this group during the past year.

Tokamak Confinement and Transport

Using kinetic simulations of plasma turbulence, Dr. Darin Ernst has found that the nonlinear upshift of the critical density gradient for onset of trapped electron mode (TEM) turbulence increases with collisions. In addition, he and a summer student have implemented a synthetic phase contrast imaging diagnostic (in conjunction with the phase contrast imaging diagnostic group, led by Professor Porkolab and postdoctoral fellow Nils Basse) that has allowed a direct comparison of the measured wavelength spectra for density fluctuations from TEM turbulence with nonlinear gyrokinetic simulations, possibly leading to the first direct identification of TEMs in tokamaks.

Turbulence levels are often controlled by the plasma flow shear. Dr. Catto's student Yong Xiao completed a thesis on the residual zonal flow level in tokamaks that (1) extended the collisionless Rosenbluth-Hinton calculation from long to arbitrary perpendicular wavelengths, confirming observations that this level is larger for modes driven by electron temperature gradients than for modes driven by ion temperature gradients, and (2) generalized the circular flux surface result to shaped cross sections to demonstrate that the residual increases more strongly with ellipticity than with triangularity or Shafranov shift. He also evaluated the arbitrary collisionality residual zonal flow level to obtain an improved estimate of the poloidal flow damping rate and demonstrated that limiting forms typically provide inadequate approximations to the residual level.

Dr. Catto and Dr. Andrei Simakov of the Los Alamos National Laboratory considered the effect of general tokamak symmetries on flows by investigating the consequences of (1) the reversal of all magnetic fields and currents, (2) a switch from lower to upper X-point operation, (3) poloidal magnetic field or plasma current reversal, and (4) toroidal magnetic field reversal. They applied their results to the flux surface flows inside and outside the separatrix of C-Mod, leading to predictions of the magnitude of the electric fields that await experimental measurements.

Magnetohydrodynamics and Extended MHD

Dr. Jesus Ramos has used his participation in two Scientific Discovery Through Advanced Computing Initiative (SciDAC) projects, Center for Extended MHD Modeling and Center for Simulation of Wave Interactions with MHD, to advance modeling of magnetized plasmas at low collisionality under the general conditions of arbitrary magnetic geometry, fully electromagnetic nonlinear dynamics with arbitrary fluctuation amplitudes, and far from Maxwellian distribution functions. Some specific results are the dynamic evolution equations for the parallel heat fluxes, reduced systems without fast magnetosonic waves for small parallel gradients in a strong magnetic field, and representations of the moments of the complete Fokker-Planck operator.

Dr. Luca Guazzotto is at PSFC under a fellowship appointment to the Fusion Energy Postdoctoral Research Program. He works with Professor Jeff Freidberg on equilibrium beta limits in dipole configurations with toroidal flow and pressure anisotropy and on the stability of magnetic confinement devices in the presence of flows and resistive walls. Professor Freidberg's introductory plasma energy textbook from an engineering viewpoint, completed last year, is nearly ready for publication.

Heating, Current Drive, Advanced Tokamaks, and Nonlinear Dynamics

Drs. Paul Bonoli and John Wright participate in the Center for Simulation of Wave Plasma Interactions national SciDAC project. This year Dr. Bonoli was named the principal investigator of the project. Drs. Bonoli and Wright have modified their full wave solver to couple it to a three-dimensional electromagnetic antenna code developed with collaborators in Torino, Italy. Tests of the modified code successfully produced the desired impedance matrix. Also, collaborative work with scientists at General Atomics and ORNL has successfully simulated minority ion cyclotron heating experiments in Alcator C-Mod by retaining finite ion orbit effects such as spatial losses and energetic particle phase decorrelation. In addition, work with the Princeton Plasma Physics Laboratory incorporated model quasilinear electron distribution functions in modules for the plasma response. Drs. Bonoli and Wright also participate in the Center for Simulation of Wave Interactions with MHD SciDAC, where they have worked on defining an interface that could be used to couple their full wave spectral solver to a general integrated plasma simulator.

Dr. Abhay Ram, his former student Joan Decker, and senior scientist Yves Peysson (both of the latter at the French Atomic Energy Commission) are studying heating and current drive in the electron cyclotron range of frequencies. Their code solving the fully relativistic dispersion relation has been extended to include geometric optics ray tracing equations. It has been coupled to a drift kinetic Fokker-Planck code to study current drive in spherical tori using electron Bernstein waves. Current is generated in the core by asymmetric modification of the plasma resistivity and in the outer region by inducing asymmetric electron trapping. This allows current profile tailoring to control MHD instabilities and optimize confinement.

Levitated Dipole Experiment Stability, Heating, and Confinement

LDX theory research is led by Dr. Jay Kesner. The MHD interchange mode is thought to set the pressure limit in dipole confinement devices such as 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. Dr. Kesner is pursuing simulations in full dipole geometry of nonlinear stability but in the more tractable low beta limit. Also, LDX is heated by intense electron cyclotron heating, leading to hot electron generation. Dr. Catto and his former student Natalia Krasheninnikova evaluated the effect of hot electrons on interchange stability in dipoles and Z pinches. Importantly, the hot drift resonance was shown to be destabilizing if evolution of hot electron density and temperature profiles are not controlled.

Experimental Research

Levitated Dipole Experiment

LDX represents a new and innovative approach to magnetic fusion, one in which a levitated superconducting coil will be used to confine plasma in a dipole magnetic field. LDX, a joint collaborative project with Columbia University, is located in Building NW21 at MIT. The principal investigators of this project are Dr. Jay Kesner (MIT) and Professor Michael Mauel (Columbia University). The project was renewed in FY2004 by DOE as a three-year grant at an approximate annual budget of $1.4 million (shared between MIT and Columbia University).

The LDX facility was designed collaboratively by the LDX physics group and the PSFC engineering division under the leadership of Dr. Joseph Minervini. LDX utilizes three unique superconducting coils and is the only superconducting magnetic confinement experiment in the US fusion research program. The coils include a high-performance Nb_3Sn "floating coil" and cryostat, an 11 MJ "charging coil" (built in Russia), and a "levitation coil" that utilizes a high-temperature superconductor. The construction and assembly of the facility have been completed, and experimentation began in August 2004.

During the initial experimental campaign that is presently under way, the dipole coil is mechanically supported within the LDX vacuum chamber. Initial experiments indicate a clear transition into a high-pressure plasma regime, as had been predicted. These experiments also provide a database for supported operation to be compared with the later levitated experiments and an opportunity to test the coil operation, the diagnostic set, and the control system. Hardware upgrades that will permit levitation are presently being installed. In the next phase of operation, initiated in fall 2006, the dipole coil will be levitated. Because levitation eliminates plasma losses to the supports of the internal coil, we expect that levitation will lead to substantial improvements in plasma confinement and stored energy.

Magnetic Reconnection Experiments on the 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. The magnetic geometry of VTF was recently upgraded to a new closed configuration providing improved plasma confinement. The new configuration has already yielded the first measurements of spontaneous magnetic reconnection events in a dedicated experiment; a Physical Review Letter detailing these observations is currently under review. The present focus of the experimental program is on exploring the trigger of these spontaneous events. Dr. Jan Egedal, recently appointed as an assistant professor in the Physics Department, has been the VTF group leader since September 1, 2005. Dr. Egedal received a DOE junior faculty plasma physics award that will fund experimental activities at a level of $150,000 per year, with an additional $100,000 in equipment funds for the first year. Also, two physics graduate students working with Dr. Egedal (Will Fox and Noam Katz) both were awarded DOE fellowships to sponsor their thesis research on VTF.

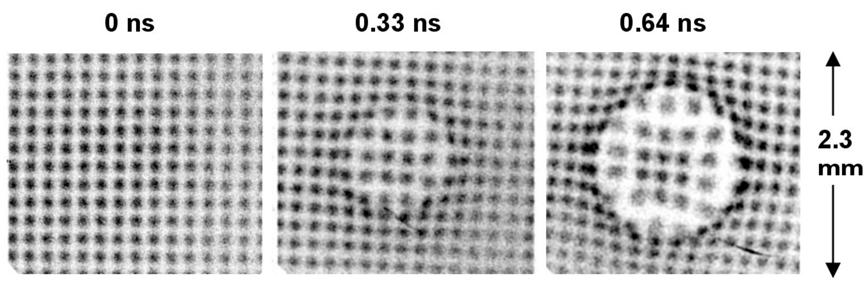
PSFC/JET/Centre de Recherches en Physique des Plasmas Collaboration on Alfvén Wave Propagation and Instabilities

Professor Porkolab leads this project, with active involvement by Dr. Joe Snipes of PSFC and a new MIT postdoctoral fellow, Alex Klein, located at the JET site near Oxford, England. This program conducts experiments at JET and involves collaboration with Professor Ambrogio Fasoli of the Centre de Recherches en Physique des Plasmas in Lausanne, Switzerland. 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 will be carried out in the coming year. 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 wherein the fusion process generates a substantial alpha particle component.

Inertial Confinement Fusion Experiments

MIT continues a major effort in inertial confinement fusion (ICF). Dr. Richard Petrasso and his group have 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, 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. MIT is designing one of the major diagnostic instruments for the NIF and plays an important part in the overall NIF diagnostic development program. In addition, the MIT group is a primary member of a Fusion Research Center of Excellence headquartered at the University of Rochester and will lead a number of experiments for that consortium next year.

Especially noteworthy in the last year have been experimental measurements on OMEGA of important aspects of fusion burn in ICF experiments and studies of the nature of laser-plasma interactions. In the second category, MIT-developed imaging techniques were used to study the time evolution and spatial distribution of electric and magnet fields generated by plasma arising from the interaction of a long-pulse (1-ns), low-intensity laser beam with a plastic foil. These images, taken with exposure times of 150 ps, are a modern version of the famous high-speed photographs made at MIT a half century ago by Harold Edgerton and students (except that they involve protons rather than photons). All ICF experiments involve the use of lasers, and scientists have begun to realize that electromagnetic fields generated by laser-plasma interactions can have important consequences and must be understood.



The figure above shows sample radiographic images of laser-foil interactions made with a monoenergetic proton source (the 14.7 MeV protons were produced by D^3He fusion reactions in an implosion of an ICF capsule). The protons were passed through a metal mesh to divide them into beamlets, and the images show how the beamlets (indicated by the dark areas) were deflected by magnetic fields at different times. The plastic foil was 5 microns thick, and the laser beam was about 800 microns in diameter. The images are each labeled by the time interval between the arrival at the foil of the interaction beam and the arrival at the foil of the imaging protons. The peak magnetic field inferred from these images was about 0.5 MG. These measurements are being used to provide the first tests of magnetic field generation in hydrodynamic simulation programs, and the experiments have also demonstrated that laser phase plates substantially reduce chaotic field structure. In addition to the senior staff, these research projects involve the direct participation of several graduate and undergraduate students.

Novel Diagnostics for Magnetic Fusion Research

Phase Contrast Imaging Diagnostic of 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 at DIII-D and C-Mod have upgraded phase contrast imaging diagnostics to detect short-wavelength (sub-cm), high-frequency (up to 5 MHz) modes. The shorter wavelength modes (the so-called electron temperature gradient [ETG] modes) should play a fundamental role in determining electron transport, one of the frontiers of fusion research. These experiments have commenced on C-Mod but had been delayed on DIII-D until recently, when the DIII-D tokamak resumed operation after a lengthy modification of the neutral beam system. New turbulence data have been obtained on both machines, and data analysis is in progress.

Collective Thomson Scattering of Ions in TEXTOR and ASDEX Upgrade

An international partnership consisting of PSFC, the Risø National Laboratory (Denmark), the Institut für Plasmaphysik (Jülich, Germany), and the Max-Planck-Institut für Plasmaphysik (Garching, Germany) is pursuing the development of fast ion collective Thomson scattering (CTS) diagnostics. Experiments have been implemented at the TEXTOR (Jülich) and ASDEX Upgrade (Garching) tokamaks with the powerful millimeter-wave gyrotron sources available at these facilities. In FY2006, several CTS diagnostic campaigns were carried out at TEXTOR, and detailed frequency measurements were made of the two frequency tunable gyrotron at ASDEX Upgrade in preparation for the start of CTS measurements there. At TEXTOR, data were obtained during neutral beam heated discharges, and the first tests were done with ion cyclotron resonance heating. At ASDEX Upgrade, a failure of one of the motor generator sets has delayed the first CTS experiments into FY2007. 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

PSFC's Ionospheric Plasma Research Group (visiting scientist Min-Chang Lee and MIT Undergraduate Research Opportunities Program students) conducted wave injection space plasma experiments at Arecibo, Puerto Rico, and Gakona, Alaska, using UHF (430 MHz or 440 MHz) incoherent scatter radar together with PSFC's optical and radio plasma diagnostic instruments to investigate ionospheric plasma turbulence. Continuing efforts have been made to collaborate with the Air Force Research Lab and the MIT Lincoln Laboratory/Haystack Observatory for the purpose of investigating the intense space plasma turbulence detected on December 26, 2004, at Arecibo about 26 hours after the occurrence of the disastrous tsunami associated with the magnitude 9.0 earthquake off the west coast of northern Sumatra, Indonesia. Intriguing results were also acquired from Arecibo experiments aimed at examining whistler wave-particle interactions in the earth's radiation belts over Puerto Rico. Intense E- and F-region plasma line enhancement has shown that a broad range of short-scale plasma turbulence can be created by the precipitated energetic charged particles in the ionosphere. After the expiration of the present Air Force Office of Scientific Research contract in 2007, this program will be transferred to Boston University, Professor Lee's home institution.

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 the division.

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 of 90 to 500 GHz at power levels of up to several megawatts. In 2005–2006, the Gyrotron Group, headed by Dr. Michael Shapiro, demonstrated operation of a 110 GHz gyrotron with an internal mode converter at an efficiency of more than 50 percent using a depressed collector. These results are in very good agreement with theoretical results obtained with the MAGY code at the University of Maryland. The research at MIT is the basis for a development program for a continuous wave gyrotron built by an industrial vendor, Communications and Power Industries (Palo Alto, CA). That tube will be tested soon at General Atomics in San Diego. We have also recently initiated a research program on low loss microwave transmission lines in support of the ITER program.

Intensive research continues on 250 to 500 GHz gyrotrons for use in electron spin resonance and nuclear magnetic resonance (NMR) studies. This research, funded by the National Institutes of Health, is a collaboration with Professor Robert Griffin at the Francis Bitter Magnet Laboratory. In 2005–2006, we demonstrated continuous wave operation of our 460 GHz gyrotron for 24 hours under computer control. We are now building both a 100 W, 140 GHz pulsed amplifier and a tunable 330 GHz gyrotron source for enhancing NMR signals.

PSFC research on high-gradient accelerators is focused on high-frequency linear accelerators for application to future multi-TeV electron colliders. In 2005–2006, the High Gradient Accelerator 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 measured, on an absolute scale, the power of frequency-locked terahertz coherent transition radiation from a train of electron bunches produced by the accelerator. The emitted radiation was observed to be a combination of frequencies that are harmonics of the accelerator frequency; the highest harmonic observed with the available equipment was n = 22 at 377 GHz. The emitted power was compared with calculations made via an electric field integral equation formulation, and very good agreement was obtained.

The Intense Beam Theoretical Group, led by Dr. Chiping Chen, has contributed to our understanding of coherent radiation generation and particle acceleration. Topics covered include control of halo formation in intense electron and ion beam transport and a new theory describing the formation and transport of sheet electron beams.

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 source of research support is DOE-OFES. The Fusion Technology Program and, subsequently, the Enabling Magnet Technology Program have undergone significant redirection over the past several years. Basic technology R&D funding has been decreased, while technology development efforts have been redirected to the construction of ITER. During FY2006, our base funding was reduced by more than half to $0.89 million, although we received a substantial increase in funding directly related to the ITER project. During the first half of FY2006, we received $1.57 million for ITER preparation work directly from DOE. During the second half of FY2006, all ITER-related funding was transferred to the US ITER Project Office, headquartered at ORNL. We received $1.75 million in funding for the second half of FY2006. In the future (FY2007 and beyond), all ITER project funding will come to MIT in the form of a subcontract from ORNL.

Budget guidance for FY2007 from DOE-OFES has not been good. All base program work has nominally be zeroed out for FY2007 and beyond. This would be catastrophic for our fundamental research and work done by our graduate research assistants. DOE-OFES has, however, recognized the difficulty it created regarding support of our graduate student research and has agreed to restore $410K in funding for FY2007. This amount will be sufficient to maintain our present four graduate students. Location of the US ITER Project Office at ORNL has also resulted in centralized control of all ITER project work, meaning that all magnet work is done under the direction of an ORNL employee (the work breakdown structure manager for ITER magnets).

Another important development has been the sudden decision last summer, by the National Science Foundation's National Science Board, to terminate the Muon-to-Electron-Conversion Experiment (MECO), which is part of the Rare Symmetry Violating Processes (RSVP) project. Fabrication and assembly of the experiment were scheduled to begin this fiscal year, with the experiment eventually being installed at Brookhaven National Laboratory in conjunction with the Alternating Gradient Synchrotron facility. FT&E Division staff member Bradford Smith served as the MECO magnets subsystem manager and also served at the L1 project manager level. The FT&E Division received about $0.75 million in MECO project close-out funding in FY2006, and these funds were used to successfully transfer all MIT personnel to either ITER-related work or the Synchrocyclotron Project.

PSFC continued its collaboration with Brookhaven National Laboratory, Princeton University, ORNL, and other institutions that are developing mercury jets as targets for a muon collider or neutrino factory. Peter Titus leads the MIT effort. During FY2006, the pulsed, cryogenically cooled magnet he designed was delivered to PSFC from industry. It passed its acceptance test with several successive pulses to a 15 Tesla central field. The project will continue in FY2007 when ORNL delivers and installs the mercury jet cartridge for testing in the pulsed, high-field magnet.

The division continues to make substantial progress on the privately funded project to develop a 250 MeV synchrocyclotron for proton beam radiotherapy. This work is carried out 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. During this fiscal year, funding has been increased to approximately $0.95 million. The project has moved forward into final design, and procurement of the superconducting wire has been initiated. The project will continue through FY2007 with development of magnet and cryogenic system components and tests, culminating in testing of the first magnet cold mass in 2007.

Responding to MIT's Energy Research Initiative, the FT&E Division has developed a proposal for the MIT Energy Research Council for a program designed to develop high-efficiency power and energy systems using superconducting and cryogenic technology. In addition to contributions from several members of the PSFC staff, other collaborators include faculty and staff from the departments of Nuclear Science and Engineering, Electrical Engineering and Computer Science, and Mechanical Engineering and the Laboratory for Electromagnetic and Electronic Systems. We see this new project as being a major contributor to increased energy efficiency and advanced power technology. This interdepartmental collaboration will draw on the interdisciplinary resources and facilities required to make a substantial impact in a relatively short period of time.

Plasma Technology Division

The objectives of the Plasma Technology Division, led by Drs. Daniel Cohn and Paul Woskov, are (1) to develop new spin-off applications from plasma science and technology in areas such as clean, high-efficiency vehicles; monitoring devices relevant to homeland security; and nuclear waste treatment and (2) to develop new environmental technology diagnostics and fusion diagnostics (see the Collective Thomson Scattering of Ions in TEXTOR and ASDEX Upgrade section).

From 1995 to 2005, under the direction of Drs. Leslie Bromberg and Daniel Cohn, a major research area for the division was plasma-enhanced conversion of hydrocarbon fuels into hydrogen. Hydrogen has potential environmental advantages as a fuel additive that can substantially reduce pollution from motor vehicles and stationary electricity generation systems. It can also be used to increase the efficiency of converting hydrocarbon fuels into mechanical power or electrical power. Special plasma technology, referred to as plasmatron reformers, can provide important technical advantages for enhancing the generation of hydrogen from hydrocarbon fuels. This work has been licensed by ArvinMeritor, a major automotive parts supplier; ArvinMeritor is continuing to develop and commercialize the invention, but, as a result of a lack of funding, without PSFC participation.

In the area of diagnostic development, in FY2006 the DOE Environmental Management Science Program funded a program for millimeter-wave measurements of high-level and low-level activity in glass melts, but funding will not be renewed in FY2007 because of changes in the priorities of the funding agency. Millimeter-wave glass melt research achievements included measurements of the millimeter-wave emissivity of molten salts to better characterize this fluid at high temperatures. Salt is a major contaminant found in nuclear waste, and it can damage a nuclear waste glass melter and lower the quality of the storage glass product.

A trace metals monitoring development project was supported by a Lincoln Laboratory Advanced Concepts Committee grant and is being carried out primarily by PSFC's Dr. Kamal Hadidi. In this project, the plasmatron previously developed for hydrogen fuel reforming is being tested for application to a low-cost trace metals monitoring instrument that could be used to monitor turbine blade wear. The plasmatron is 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 are being studied. Funding for this project is for one year only, but the division has submitted a proposal based on the results of the current program for a subsequent three-year program.

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. Drs. Bromberg and Cohn received funding in FY2006 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 is expected to continue in FY2007.

Overall, the division, which has received a number of R&D 100 Awards in the past for its technical innovations (including one this year), most notably the development of the plasmatron and diagnostics in the area of pollution detection, has struggled in recent years to cultivate timely new funding opportunities with private or government sponsors. As a result, the division has experienced a gradual erosion of its research volume, and this 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, might provide the vehicle to secure new funding in this area of research. The division has submitted an important "white paper" for new research to the council.

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 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 real laboratory and research environments. The hope is that this kind of interaction will encourage young people to consider science and engineering careers. Tours of our facilities are also available for the general public. Annual visitors include participants from 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 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 more than 67 schools and other events, reaching kindergartners through college freshmen. He makes a special effort to excite young people about the beauty and wonder of science. In addition to his program on magnetism, he is offering 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 equipmen. The Plasma Lab is offered two weeks during the academic year. In April 2006, at the request of DOE, Thomas traveled with his truckload of equipment to Washington, DC, for the DOE-sponsored National Science Bowl. He has made this trek annually for the past six years to present his magnet and plasma demonstrations to high school teams from across the nation.

Beyond the classroom, the History Channel approached Thomas this year to help the channel update its one-hour program about magnetism. Thomas spent a day discussing magnetism with a film crew, allowing them to film him in action with the kinds of experiments he typically brings to schools. The program aired in June 2006. He was also contacted in September 2005 by the Boston Museum of Science to provide technical training to its staff prior to the debut of the museum's Star Wars exhibit.

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. This year PSFC has collaborated on educational events with the MIT Energy Club, bringing a variety of interactive plasma demonstrations to the club's very successful "Energy Night" at the MIT Museum in February. Hundreds of MIT students attended and learned about the latest directions in fusion research. PSFC graduate students also participated in the MIT Energy Poster Session, held at the Stata Center on May 13.

PSFC continues to collaborate with other national laboratories on educational events. Teacher's Day (intended to educate middle school and high school teachers about plasmas) and the Plasma Sciences Expo (to which teachers can bring their students) have become traditions at each year's American Physical Society–Division of Plasma Physics meeting. This year Paul Rivenberg contributed to the effort in Denver, CO, which attracted 108 teachers and more than 1,500 students. Paul Thomas and Valerie Censabella, Department of Nuclear Science and Engineering administrator, were also involved, along with numerous PSFC graduate students.

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 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 US state. 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. Rivenberg also heads a subcommittee that created and maintains a website intended to help teachers bring the topic of plasma into their classrooms. In addition, he works with the coalition's Technical Materials Subcommittee to develop material introducing laypeople to different aspects of plasma science.

Awards, Appointments, and Promotions

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

Awards

Professor Miklos Porkolab, director of PSFC, was awarded the distinction of fellow by the American Association for the Advancement of Science for "pioneering experimental and theoretical research in nonlinear dynamics of plasmas and for leadership in advancing controlled fusion." Principal research scientists Paul Bonoli (Physics Research) and Brian LaBombard (Alcator) were awarded fellowships by the American Physical Society. Dr. Jesus Ramos of the Theory Group was appointed as a visiting professor at the National Institute for Fusion Studies in Japan.

Gary Dekow, operations and engineering coordinator, and George MacKay, project technician, were winners of 2006 MIT Infinite Mile Awards for their contributions to the Alcator project. Evgenya Smirnova, a recent graduate in physics, received the award for the Outstanding Doctoral Thesis Research in Beam Physics from the American Physical Society in April 2006. Eunmi Choi, a graduate student in physics, received the best Student Paper Award and Prize in April 2006 at the International Vacuum Electronics Conference, sponsored by the Electron Devices Society of the Institute of Electrical and Electronics Engineers. Roark Marsh, also a graduate student in physics, received the Distinguished Performance Award at the International Accelerator School for Linear Colliders, held in Hayama, Japan, in June 2006.

Appointments

Alcator Division: T. Brandon Savage was appointed IT administrator, Patrick MacGibbon and Alan Binus were appointed RF engineers, Atma Kanojia was appointed lower hybrid controls engineer, and Dr. Jerry Hughes was appointed postdoctoral associate.

Waves and Beams Division: Dr. Seong Tae Han and Dr. Yoshiteru Hidaka were appointed postdoctoral associates.

Fusion Technology and Engineering Division: Stanislaw Sobczynski was appointed superconducting magnet lead engineer.

Physics Research Division: Dr. Alexander Klein was appointed postdoctoral associate.

Promotions

Alcator Division: Dr. Amanda Hubbard was promoted to principal research scientist, Dr. James Irby was promoted to principal research engineer, Dr. Brian LaBombard was promoted to principal research scientist, Dr. James Terry was promoted to principal research scientist, and Henry Bergler was promoted to IT and network administrator.

Waves and Beams Division: Dr. Amit Kesar was promoted to research scientist.

Physics Research Division: Theodore Baker was promoted to computer systems and fiscal administrator.

Fusion Technology and Engineering Division: Joel Schultz was promoted to principal research engineer.

PSFC Fiscal Office: Lee Keating was promoted to fiscal officer.

Graduate Degrees

During the past year, four departments awarded students degrees with theses in plasma fusion and related areas.

Nuclear Science and Engineering	Marco Ferrara, MS Timothy Graves, PhD John Liptac Jr., PhD Natalia Krasheninnikova, PhD Chaiyod Soontrapa, SM Xiao Yong, PhD
Physics	Bo Bai, PhD Ronak Bhatt, PhD Enrique Henestroza, PhD Ryan Rygg, PhD David Strozzi, PhD Jing Zhou, PhD
Electrical Engineering and Computer Science	Chad Marchewka, MS
Mechanical Engineering	David Harris, MS

Miklos Porkolab
Director
Professor of Physics

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