Plasma Science and Fusion Center

MIT's Plasma Science and Fusion Center (PSFC) is known internationally as a leading university research center. The primary focus of its research is the study of plasma physics and fusion technology with strong research activities in five major areas: (1) the science of magnetically confined plasmas for the development of fusion energy, with the Alcator C-Mod tokamak project being PSFC's flagship facility; (2) basic plasma physics including magnetic reconnection experiments on the Versatile Toroidal Facility (VTF), magnetic confinement by a dipole magnetic field as is being tested in the Levitated Dipole Experiment (LDX), the development of novel high-temperature plasma diagnostics, and theoretical plasma physics and fusion science research; (3) the physics of high-energy-density plasmas (HEDP), which includes PSFC's world-class diagnostic program on inertial fusion energy produced by high-powered lasers; (4) the physics of waves and beams including gyrotron and high-gradient accelerator research, beam theory development, non-neutral plasmas, and coherent wave generation; and (5) a broad program in that addresses problems in several areas that are critical to the development of commercial fusion electricity (e.g., magnet systems, superconducting materials, and system studies of fusion reactors). Administratively, each of these areas constitutes a separate research division. In the order of areas described above, PSFC's research divisions are the Alcator Division, the Physics Research Division, the High-Energy-Density Plasma Physics Division, the Waves and Beams Division, and the Fusion Technology and Engineering (FT&E) Division.

PSFC research and development programs are supported principally by the Department of Energy Office of Fusion Energy Sciences (DOE-OFES). Approximately 248 personnel are associated with PSFC research activities, including 23 faculty and senior academic staff, 48 graduate students, and 14 undergraduates. The participating faculty and students are from the following departments (in alphabetical order): Aeronautics and Astronautics, Electrical Engineering and Computer Science, Mechanical Engineering, Nuclear Science and Engineering, and Physics. In addition, there are 64 research scientists, engineers, postdoctoral associates, and technical staff; 42 visiting scientists, engineers, and research affiliates; 5 visiting students; 26 technical support personnel; and 26 administrative and support staff.

Total PSFC funding for (FY2010) is projected to be $33.43 million. This amount includes $0.56 million of stimulus funding from the American Recovery and Reinvestment Act (ARRA) of 2009. ARRA was meant to be a one-time government stimulus in response to the global fiscal crisis that began in late 2008. Excluding FY2010 ARRA funds, PSFC's base FY2010 sponsored research funding is projected to be $32.87 million. The base FY2010 budget represents an increase of 7.6%, or $2.32 million, over PSFC's FY2009 base research funding of $30.55 million (excluding $8.86 million in ARRA funds in FY2009).

More than 70% of the center's $2.32 million funding increase—$1.70 million—will go to the Alcator Division, the center's largest research division. With this increase, Alcator funding will grow by 8.10% in FY2010 to $22.72 million. The remaining significant increase—$0.78 million—will go to the FT&E Division, a 41% increase over last year, bringing the division's FY2010 funding to $2.64 million. The FT&E Division has been very active in seeking new sources of research funding since it experienced a precipitous loss of funding in FY2008. This loss was due to the transition of the US International Thermonuclear Experimental Reactor (ITER) funding from research to construction as well as the loss of a major industrial program.

FY2010 funding for the Waves and Beams Division will grow by 2.22% this year to $1.84 million, while funding for the High-Energy-Density Physics Division will remain essentially unchanged at $1.99 million. Only the Physics Research Division, with FY2010 funding of $3.68 million will experience a decrease in FY2010 funding relative to FY2009—a decrease of $0.20 million, or 5.15%.

Alcator Division

The Alcator C-Mod tokamak is a major international fusion experimental facility, which 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 consists of an MIT full-time equivalent staff of approximately 50 scientists and engineers, including nine faculty and senior academic staff plus 29 graduate students (see figure 1) and 25 technicians. Additionally a large number of Alcator collaborators from around the world bring the total number of scientific facility users to more than 200. The cooperative agreement with DOE-OFES, which funds the C-Mod project, was renewed effective November 1, 2008, for a five-year period. Including major collaborators, total FY2010 funding for the project is about $26.5 million ($22.7 million of direct funding at MIT).

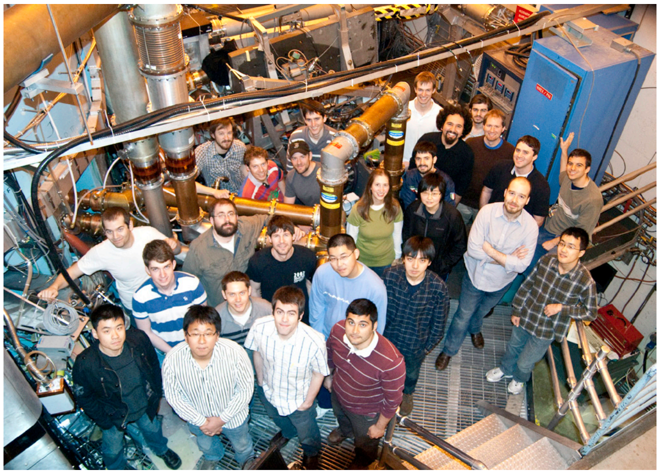

Figure 1. *Graduate students doing their PhD research on Alcator C-Mod.*

Research on C-Mod continued during the past year in high-performance, high-magnetic-field, plasma confinement. State-of-the-art experiments are being carried out this year in the critical science areas of transport, wave-plasma interactions, edge pedestal, boundary physics, and magnetohydrodynamic stability as well as in plasma integration areas involving advanced tokamak and burning plasma science.

A significant number of facility and diagnostic upgrades have been completed in the last year or are in progress. With support from MIT, an alternator water-cooling upgrade has been completed. Before the upgrade, river water was used to cool the oil/water heat exchangers. The upgrade uses the MIT chilled water supply to pre-cool the river water and also isolates river water from the cooling oil. These changes allow for operation of the alternator into the hot summer months while also providing greater environmental safety. Upgrades to solid-state drivers for our ion cyclotron range of frequency transmitters allow more reliable power delivery to the plasma. An outer divertor upgrade that will greatly improve heat-flux handling and allow operation at high temperature is being designed. A new antenna for the lower hybrid microwave current drive system has been installed on Alcator C-Mod. This new antenna utilizes a novel four-way splitting concept to distribute power across the outer midplane of the plasma. Initial operation of the new system is progressing smoothly with a net power coupled to the plasma of 675 kW for 0.5 s by the end of the second day of operation. We anticipate net power levels of approximately 1.0 MW for 0.5-s pulses once commissioning is completed. We are also upgrading the lower hybrid system to increase the number of klystrons available from 12 to 16 (source power from 3 to 4 MW). A new polarimeter diagnostic is being developed for making plasma current density and fluctuation measurements on C-Mod. Upgrades have also been implemented for a number of other important plasma diagnostics, including bolometry, the motional Stark effect imaging system, emissive probes, reflectometry, and visible imaging fluctuation diagnostics.

Facility operation for research this fiscal year (FY2010) is planned to total 18 weeks, a doubling from the 9 weeks in FY2009. 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.

Recent Research Achievement Highlights

One focus of the 2009–2010 research campaign is an operational regime exhibiting strongly suppressed energy transport across the last closed magnetic flux surface near the edge of the plasma, combined with significant cross-field particle transport, the so-called I-mode (“improved” mode). This approach to tokamak operation has many favorable properties, including energy confinement comparable to the best achieved but with no need for intermittent flushing of particles and impurities through the edge transport barrier. In more conventional high-confinement regimes, the particles and impurities can cause significant erosion of material surfaces at the plasma boundary. Possible applicability of the I-mode to the operation of future burning plasma experiments, including ITER, is under intense investigation.

As part of a nationally coordinated joint research program, C-Mod is studying the scaling of power exhaust along open field lines, which involves plasma flow to the material surfaces of the divertor. Significant diagnostic upgrades have been implemented to aid in these studies, including infrared imaging and extensive additions of probes and thermocouples. C-Mod’s divertor heat flux footprints are found to exhibit a two-zone structure: a narrow channel at the strike point locations and a tail feature that extends into the far scrape-off layer. In combination with complementary studies on the DIII-D and NSTX facilities, these experiments will be used to test numerical models of the plasma behavior and to aid in extrapolations to make predictions for ITER.

C-Mod operates with the highest power densities of any tokamak in the world, comparable to those expected on ITER. One important technique for spreading the heat loads, and thus reducing the power density impinging on material surfaces, is to seed the plasma with radiating impurities. Efficacy of this approach has been studied on C-Mod, including quantitative evaluations of heat load reductions, effects on plasma energy confinement quality, and optimization with respect to the choices of radiating impurity species, including argon, neon, and nitrogen. Results to date indicate that the higher Z impurity (argon), while effective in reducing divertor heat loading, results in substantial decreases in overall performance in high-confinement modes of operation. Conversely, nitrogen and neon can also be effective in reducing heat load, while overall energy confinement can remain high.

A key tool available for noninductive current drive, required to maintain the tokamak configuration in steady state, is the use of high-powered microwaves, which can be injected into the torus with phase velocity strongly directed along the toroidal direction. Under the right circumstances of wave frequency, plasma temperature and density, and magnetic field, the waves will penetrate into the hot plasma and preferentially damp on epithermal electrons (i.e., those with energies about a factor of 10 higher than the average thermal energy). The resulting transfer of momentum to the electron distribution is primarily toroidal, causing a net current drive. Detailed studies of the x-rays emitted by the driven electrons as they collide with the background plasma reveal that, in accordance with theory and modeling, the wave damping is a strong function of the parallel wave number imposed by the phasing of the microwaves in the launching structure. An anomalous reduction of current drive efficiency as the plasma density is increased, also observed quantitatively with the x-ray imaging camera, is not explained by conventional theory, and possible loss mechanisms in the plasma scrape-off layer are under investigation.

Physics Reseach Division

The goal of the Physics Research Division, headed by professor Miklos Porkolab, is to improve the theoretical and experimental understanding of plasma physics and fusion science. This division maintains a strong basic and applied plasma theory and computational program while developing novel plasma physics diagnostic experiments and investigating new confinement concepts. Students are an essential component of all aspects of the research.

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 and computational plasma physics research. It supports Alcator C-Mod and other tokamak experiments worldwide, along with the LDX and VTF experiments at MIT. The division's high-performance, 600-processor, computer cluster is heavily utilized by students, staff, and collaborators and is the main computational resource for PSFC experimental and theory research. The cluster was upgraded from 520 to 600 cores this year, primarily to provide improved operational flexibility. The cluster has now been in operation for almost three years and we are beginning the long-range planning process of examining technologies that might provide for our future computational needs.

Tokamak and Stellarator Confinement and Transport

Gyrokinetic descriptions retain gyromotion and magnetic drift departures from constant pressure surfaces and are used throughout the magnetic fusion program to simulate turbulence in tokamaks. Dr. Catto and his former student Dr. Felix Parra (Christ Church College, University of Oxford) demonstrated that existing gyrokinetic treatments are unable to correctly evaluate and evolve the axisymmetric radial electric field whose shear normally regulates turbulence levels. They have also given an implementable prescription for removing this limitation. In addition, Dr. Catto, his former student Dr. Grigory Kagan (Los Alamos National Laboratory), and Istvan Pusztai (a visiting student from Chalmers University of Technology, Göteborg, Sweden) have evaluated the effect of the strong edge radial electric field on ion transport, ion flow, and the bootstrap current generated by gradients in (1) the weak collision limit known as the banana regime and (2) the somewhat stronger collisional limit known as the plateau regime. The ion flow modification is observed on Alcator C-Mod and will enhance the edge bootstrap current that plays a key role in performance and stability. Dr. Catto and his student Matt Landreman are investigating electric field effects on transport in stellarators, which, unlike tokamaks, are inherently steady-state devices but not axisymmetric. Moreover, they have evaluated its role in the zonal flow regulation of turbulence in tokamaks and stellarators with a sheared electric field.

Dr. Darin Ernst, PSFC research staff member, completed a study of zonal flows in trapped electron mode (TEM) turbulence, involving colleagues from the SciDAC Center for the Study of Plasma Microturbulence (CSPM), resulting in publication of an invited American Physical Society paper. Dr. Ernst recently led an experiment on Alcator C-Mod utilizing modulated on-axis ion cyclotron resonance heating to modulate the core electron temperature, stimulating driven TEM turbulence in an internal transport barrier. Highly resolved profile measurements for both ions and electrons, including rotation, and several simultaneous edge and core fluctuation measurements will make quantitative comparisons with gyrokinetic turbulence simulations possible. Through an INCITE grant for the CSPM SciDAC project, Dr. Ernst will simulate these experiments on what is currently the most powerful computer in the world, using synthetic diagnostics to compare with fluctuation measurements and transport fluxes, toward a definitive observation of density gradient driven TEMs. Ernst recently collaborated with Dr. Catherine Fiore (Alcator C-Mod) to show that sheared flows appear to play a strong role in internal transport barrier formation with no external momentum input.

Magnetohydrodynamics and Extended Magnetohydrodynamic Simulations

Dr. Jesus Ramos, PSFC principal research scientist, participates in two SciDAC projects, the Center for Extended Magnetohydrodynamic (MHD) Modeling (CEMM) and the Center for Simulation of Wave Interactions with MHD (CSWIM), with the purpose of implementing an advanced fluid description of magnetized plasmas in large-scale nonlinear simulations. During the past year, he completed a fluid and drift-kinetic electron model applicable for slow dynamics in weakly collisional, magnetically confined plasmas. This model rigorously takes into account the physical effects needed to describe important macroscopic phenomena, such as the “sawtooth internal disruption” and the “neoclassical tearing mode,” that affect the performance of magnetic fusion devices. It has been implemented as a closure module for the fluid system of equations in the NIMROD code, which represents the state of the art for numerical simulation of macroscopic processes in magnetized plasmas.

Plasma equilibria in toroidally axisymmetric magnetic confinement concepts are fully determined by the solution of a second-order, nonlinear, elliptic partial differential equation known as the Grad–Shafranov equation. Because of its complexity, this equation is usually solved numerically. However, analytic solutions are desirable and useful for studying equilibrium, stability, and transport properties in toroidally axisymmetric fusion devices as well as for benchmarking MHD equilibrium codes. Professor Jeffrey Freidberg and his student Antoine Cerfon found new analytic solutions to the Grad–Shafranov equation and developed a streamlined procedure to use these solutions to calculate equilibria in several configurations of fusion interest (tokamaks, spherical tokamaks, spheromaks, and field reversed configurations) for arbitrary plasma shaping and plasma pressure.

Heating, Current Drive, Advanced Tokamaks, and Nonlinear Dynamics

Dr. Abhay Ram, PSFC principal research scientist, along with professor Kyriakos Hizanidis and Dr. Yannis Kominis of the National Technical University of Athens, Greece, developed a Fokker–Planck theory for the scattering of radio frequency (RF) waves by density blobs at the edge. There are two effects on wave propagation: a refractive deviation causing waves to deposit their energy and momentum away from the intended region in plasmas and diffusion in wave vector space that leads to a decrease in the current drive efficiency as well as broadening of the spatial region of wave damping. Calculations show that the spatial scattering of electron cyclotron waves in ITER is substantial enough to be of concern. In a separate study, they consider how RF electromagnetic waves impart their energy and momentum to plasma particles. Previous treatments of wave–particle interactions have been similar to the ones used for studying Brownian phenomena whereby a set of tracer particles move about randomly due to collisions. However, in fusion plasmas the temperatures are so high that collisions occur over very long timescales. The kinetic formulation shows that the interaction of electrons and ions with coherent electromagnetic RF waves bears no similarity to Brownian motion. The formalism illustrates the difference between complexity and randomness—wave-induced particle motion is complex but not random.

SciDAC Center for Simulation of Wave–Plasma Interactions and CSWIM Fusion Simulation Project

During 2010, MIT continued to serve as the lead laboratory for the multi-institutional SciDAC Center for Simulation of Wave-Plasma Interactions (CSWPI) with Dr. Paul Bonoli, a PSFC senior research scientist, serving as the principal investigator for the center. Dr. Bonoli and PSFC research staff member Dr. John Wright also participate in the prototype CSWIM fusion simulation project (FSP), which aims to perform multiphysics and multiscale simulations between short timescale plasma wave simulations and large-scale plasma fluid models. During the past year, members of CSWPI (John Wright and graduate student J- P. Lee) successfully implemented a new matrix inversion technique in the TORIC full-wave electromagnetic field solver that utilizes a parallel "divide and conquer" algorithm. The new solver demonstrates improved performance for large numbers of processors for large problems, but it also increases the number of processors that may be used for more modest-sized simulations. This versatile solver will be especially useful in the TRANSP transport analysis project and the SWIM prototype FSP, in which TORIC may be called hundreds of times as well as in facilitating three-dimensional electromagnetic field reconstructions. As part of the SWIM FSP, MIT also carried out time-dependent simulations for the proposed ITER thermonuclear reactor device using a parallel framework called the Integrated Plasma Simulator (IPS). In these simulations it was shown that a Monte Carlo code for neutral beam injection heating (NUBEAM) and the TORIC solver for ion cyclotron resonance heating could be run with high physics fidelity (excellent Monte Carlo statistics and high spectral mode resolution) by using the IPS and that the turnaround time for results could be reduced by an order of magnitude.

Experimental Research

Levitated Dipole Experiment

LDX is a joint collaborative project with Columbia University and is located in Building NW21 at MIT. The principal investigators of this project are Dr. Jay Kesner (MIT) and Professor Michael Mauel (Columbia University). LDX now operates regularly in the fully levitated configuration with the 1,200-lb coil floating for up to 2-1/2 hours. LDX plasmas are heated by electron cyclotron resonance heating with sources available at five frequencies, permitting a spatial control of the heating profile (LDX now applies up to 26 kW of heating power at frequencies of 2.45, 6.4, 10.5, and 28 GHz). Levitation eliminates field-aligned losses to supports that are present in a "supported-mode" operation. The diagnostic capability of LDX continues to improve.

During levitation, a strong particle pinch was observed, which was the basis of a recent article in *Nature Physics* [Volume 6 (2010) 207–212] and an accompanying press release. The pinch appears to be the result of plasma turbulence, which is observed in LDX. Such a turbulent pinch may have been observed in other confinement devices and is important for improving plasma confinement, but the effect is much more dramatic in a dipole. The pinch is observed to produce stationary density profiles with a peak-to-edge density ratio of up to 30. Until now, we have utilized only electron cyclotron resonance heating techniques, but we are preparing an ion cyclotron resonance heating system (ICRH) that will heat ions directly. This effort will utilize a 1-MW transmitter that has been obtained by PSFC.

Plasma Science Center on Plasma-Surface Interactions

A new Plasma Science Center on Plasma-Surface Interactions was successfully launched. The center was awarded $6.9 million from DOE for five years. Professor Dennis Whyte is director of the multi-institutional center, which works in collaboration with the University of California, San Diego (UCSD), University of California, Berkeley, and Sandia National Laboratories. The scientific goal of the center is to advance plasma–surface interaction (PSI) science through an approach that equally emphasizes material exposure to fusion-relevant conditions, cutting-edge plasma and surface diagnosis, and high-fidelity surface and material modeling. A centerpiece of the center is the MIT CLASS accelerator laboratory and associated DIONISOS experiment, which allows for real-time ion beam surface diagnosis of materials undergoing plasma bombardment.

The PSFC PSI center has hired a research scientist and a postdoc as well as several graduate and undergraduate students to work on PSI research topics.

The center team has collaborated with Alcator C-Mod to measure tungsten migration patterns after a toroidal continuous row of bulk tungsten tiles was tested in C-Mod. This research showed that tungsten erosion and migration were minimal if physical sputtering was the cause of tungsten removal. However, if the tungsten removal was caused by thermal damage—for example, the melting of a misaligned tungsten tile—then the migration pattern was substantially different, with tungsten found far from the original location. This step is a beginning toward understanding the consequences of melting for the use of tungsten in fusion reactors. The center team, collaborating primarily with UCSD and the FOM group in the Netherlands, has also made first measurements of helium concentrations in tungsten that formed surface "nanotendrils" as a consequence of exposure to helium plasmas at high temperatures. These tendrils are of great concern for the use of tungsten in hot-wall fusion reactors since they will not be thermally stable. The helium depth profiles are a challenging measurement, but can be obtained with heavy-ion elastic recoil detection using the CLASS accelerator. We find that the helium is present at very high and constant concentrations in the tungsten, about one percent helium atom per tungsten, despite the very high temperatures. This indicates a mechanism that is saturating and trapping the helium in the tungsten nanostructures. Further experiments are being planned for DIONISOS.

Magnetic Reconnection Experiments on the Versatile Toroidal Facility

Magnetic reconnection is a fundamental process in plasmas that converts magnetic energy into particle energy while changing the topology of the magnetic field lines. 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. The latter drive the auroral phenomena. Although reconnection occurs in microscopic diffusion regions, it often governs the macroscopic properties and behavior of the system. Magnetic reconnection is studied in the VTF under the leadership of associate professor Jan Egedal. Other participants in this work include professor Miklos Porkolab and a number of graduate and undergraduate students.

During the past year, excellent progress has been attained in understanding the three-dimensional dynamics of spontaneous reconnection events observed in VTF. By applying the information of more than 1,000 probe channels, a new model was developed that accurately accounts for the explosive growth rate of reconnection observed in the VTF experiments. The model was recently published in *Physical Review Letters*.

Regarding more theoretical aspects of reconnection, a new fluid model was derived to account for the strong temperature anisotropy that develops within the reconnection region. On the basis of this work, a scaling law for the strength of the parallel electric fields around the reconnection region has been obtained. In certain parameter regimes, these fields become very strong and may be a major heating source for the superthermal electrons observed during reconnection. The combined experimental and theoretical results of 2009–2010 have so far been documented in nine journal publications.

In 2009 Professor Egedal won a National Science Foundation Junior Faculty Award providing funding for the VTF experiment at the level of $150,000 per year until 2014. In addition, Professor Egedal secured funding from the National Aeronautics and Space Administration (NASA) at the level of $165,000 per year for the analysis of spacecraft data. This is the first time NASA is funding research within PSFC.

MIT PSFC/Joint European Torus/Centre de Recherches en Physiques des Plasmas Collaboration on Alfvén Wave Propagation and Instabilities

Professor Porkolab leads this project from MIT, with significant participation by Dr. Paul Woskov, PSFC senior research engineer. This program supports experiments at Joint European Torus (JET), the world's largest tokamak located near the Culham Laboratories in the United Kingdom, and involves collaboration with professor Ambrogio Fasoli of Centre de Recherches en Physiques des Plasmas in Lausanne, Switzerland. In these experiments, Alfvén waves are launched by a specially built antenna array, consisting of eight phase-locked loops, all of which have been installed in JET during the past two years. These studies are expected to 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 that may drive Alfvén waves unstable. A new proposal was submitted last summer to DOE for continuing financial support of this project for another 3 years. The proposal was reviewed and approved and funding was obtained at the level of $126,000 per year to design as well as procure eight new amplifiers to upgrade the JET phase array RF power drive system. This year JET is shut down for major upgrades; therefore, only two prototype amplifiers will be procured and installed and tested on Alcator C-Mod with the available two-strap Alfvén wave antenna system.

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 (centimeter to subcentimeter), high-frequency (up to 5 MHz) modes. The shorter wavelength modes (the so-called ion temperature gradient, TEM, and electron temperature gradient 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, which can be modeled with a "synthetic diagnostic" software package. These experiments are providing important new information on short-wavelength turbulence related to energy transport and various instabilities in the Alfvén wave regime during plasma current evolution. In addition, in Alcator C-Mod, mode-converted ion cyclotron waves have been detected during flow drive (both toroidal and poloidal) associated with intense ICRH heating (see earlier Alcator C-Mod section). Two students on Alcator (Liang Lin and Eric Edlund) and one student on DII-D (Jim Dorris) have successfully defended their PhD theses in the past year and this year, and several papers related to this research have been published, including one invited talk at each of the November 2008 and 2009 Division of Plasma Physics American Physical Society meetings. One new student has joined the Alcator PCI project to continue this work with two others.

Other Research

Applications of Fusion Technology to Engineered Geothermal Systems

Successful development of engineered geothermal systems (EGS) as a source of energy depends most strongly on the availability of a natural or artificially created underground fracture system that does not deteriorate with time and that circulates the fluid to heat exchangers. The economic and technical feasibility of EGS depend very much on drilling cost and speed. At present, the well costs can account for 60% or more of the total capital cost. A significant advance in rock penetration rates over conventional rotary drilling systems at lower cost could enable rapid exploitation of sustainable geothermal energy. Such an advance in rock penetration systems may now be possible with efficient (>50%) high -energy millimeter-wave (MMW) gyrotron sources originally developed for fusion energy research. During FY2010 Dr. Paul Woskov, sponsored by the MIT Energy Initiative, completed a study of the thermodynamics of rock ablation. This study supports the possibility that MMW-directed energy penetration rates in hot crystalline rock formations could greatly exceed the limits of mechanical drilling technology using currently available megawatt gyrotron sources. Dr. Woskov has won a second MIT Energy Initiative grant that will continue into FY2011 to experimentally study MMW rock ablation using a high average power gyrotron system at PSFC. Work has commenced to modify a water load for the rock specimen MMW irradiation experiments.

Thermal Analysis of Generation IV Nuclear Reactor Materials

The development of Generation IV very-high-temperature nuclear reactor (VHTR) technology depends on the development and characterization of high-temperature materials that can reliably meet the diverse fuel and structural requirements in extreme VHTR environments. During FY2010 Dr. Woskov with Dr. S. K. Sundaram of Pacific Northwest National Laboratory commenced work on a DOE grant aimed at the development and use of novel MMW thermal analysis tools to address VHTR needs for materials analysis. A pair of 137-GHz heterodyne receivers with orthogonal polarization have been set up to view specimens inside a furnace for high-temperature materials studies. Experiments have started with graphite and silicon carbide samples. The ability to observe anisotropic material behavior in real time is being demonstrated.

High-Energy-Density Plasma Physics Division

Led by Dr. Richard Petrasso, this division continues to expand on its two decades of pioneering work in inertial-confinement fusion (ICF) and HEDP. Its development and use of novel diagnostic techniques for understanding ICF implosion physics and basic plasma physics in the high-energy-density regime have led to important research accomplishments, publications in major journals, and contributions to the National Ignition Campaign (NIC) during the past year.

The division collaborated extensively with the NIC team at the Lawrence Livermore National Laboratory, where the huge National Ignition Facility (NIF) is expected to achieve ignition (self-sustaining burn) in the next few years by imploding fuel capsules with a 2-MJ, 192-beam laser. During the past year, MIT was the only university playing a major role in the first NIF campaigns, providing two MIT-developed diagnostic methods for measuring proton spectra and neutron yields. During the upcoming NIF campaign this fall, MIT will provide two additional major diagnostic instruments: a high-resolution neutron spectrometer called the magnetic-recoil spectrometer and an instrument for measuring the time history of nuclear burn. The four MIT-developed instruments will collectively form an essential part of the ignition diagnostics set for studying implosion dynamics.

MIT also collaborates and does its own original research at the University of Rochester Laboratory for Laser Energetics (LLE), where the 30-kJ, 60-beam OMEGA laser provides an important ICF test bed. An important series of MIT experiments performed there involved the use of monoenergetic, charged-particle radiography to study electric and magnetic fields as well as plasma flows in indirect-drive ICF experiments. These experiments are scaled-down versions of those to be performed at the NIF, which involve laser beams incident on the inner walls of a small container called a hohlraum to generate x-rays that cause an ICF fuel capsule to implode. Results of this work, published in *Science*, are shown in figure 2. MIT-developed diagnostics were also used on a regular basis to support the research programs of LLE scientists and other external users of the OMEGA laser facility from universities and national laboratories around the world. MIT also undertook a major effort to organize all external OMEGA researchers for the second time in the now annual OMEGA Laser Users' Group Workshop. This workshop brought scientists and students from all over the world together to discuss current research and to help LLE enhance its facility and procedures for outside scientists.

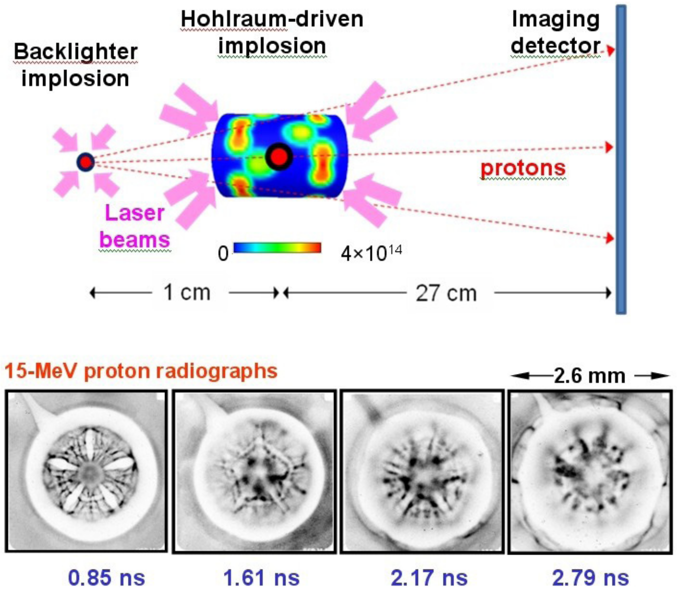

Figure 2. In an experiment at the OMEGA laser facility, a laser-driven ICF capsule produced monoenergetic 3- and 15-MeV protons through fusion reactions and the protons were used to make radiographs of another ICF capsule imploded by X rays generated by the interaction of 30 laser beams with the inner wall of a gold hohlraum. The colors inside the hohlraum wall indicate laser intensity in units of watts per cm2. In the 15-MeV radiographs shown here, the capsule is in the center, the gold hohlraum is the light-colored outer ring, and the patterns between capsule and hohlraum are due to electromagnetic fields and plasma jets. This work is discussed in Science, vol. 327, pages 1228–1231 (2010).

Besides the research results, the HEDP division places equal importance on the training and accomplishments of its seven PhD students, who were intensely involved in every project. In addition, Dr. Maria Gatu Johnson was just hired as a postdoctoral associate.

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 Waves and Beams Division.

Gyrotron and Accelerator Research

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 90–500 GHz at power levels up to several megawatts. In 2009–2010, the Gyrotron Group, headed by Dr. Michael Shapiro, conducted a program of research aimed at increasing the efficiency of a 1.5-MW, 110-GHz gyrotron with an internal mode converter and a depressed collector. The gyrotron, a form of electron cyclotron maser operated at high frequency, is needed for heating large-scale plasmas in the fusion energy research program. The 1.5-MW power level gyrotron is needed to upgrade the heating system of the DIII-D tokamak at the General Atomics Corp. in San Diego, CA; that system now uses 1-MW power level gyrotrons. Our current research is aimed at increasing the efficiency of the internal mode converter of the gyrotron. The converter changes the high-order waveguide mode into a Gaussian-like mode in free space. We have completed the testing of a novel converter with simple, smooth mirrors developed by the University of Wisconsin, Calabazas Creek Research, and MIT. This mode converter replaces the existing designs, which use phase-correcting mirrors that have major ripples across the surface on the wavelength scale. Smooth mirrors are easier to fabricate and much more forgiving of alignment errors. The gyrotron was operated at megawatt power levels, producing a Gaussian-like output mode of very high optical quality. The research at MIT serves as the basis for a development program for a continuous wave 1.3- to 1.5-MW, 110-GHz gyrotron, which is being developed by an industrial vendor, Communications and Power Industries (Palo Alto, CA). The gyrotron group is using the 1.5-MW, 110-GHz power level pulsed gyrotron to study breakdown in air and in other gases, including the discovery of filaments in air breakdown. In 2009–2010, Dr. Alan Cook measured the breakdown threshold in air and argon at pressures ranging from atmospheric down to a few torr, mapping out a Paschen-like curve of threshold electric field versus pressure. These are the first measurements of this breakdown threshold in the W-band (90 to 140 GHz) frequency range. The results are of great interest in planning future radars.

We are continuing research on low-loss microwave transmission lines in support of the ITER project. In 2009–2010, we collaborated with the Japan Atomic Energy Agency (JAEA) laboratory in Naka, Japan, on testing high-power transmission lines. JAEA has a 1-MW, 170-GHz gyrotron that could generate 1-MW pulses of 60 to 800 seconds, with power directed onto a 40-m test line. The excitation of high-order modes on the line and their transmission, as measured at JAEA, were found to be in good agreement with a theory developed at MIT. We also collaborate with the US ITER team at Oak Ridge National Laboratory on planning the ITER transmission lines. One of the graduate students working on testing the ITER transmission lines, Ms. Elizabeth Kowalski, was awarded a DOE Office of Science Fellowship (see figure 3). Her research includes the first complete description of the basis set of linearly polarized modes of a corrugated metallic waveguide. We are also working with General Atomics on characterizing and increasing the efficiency of their 110-GHz transmission lines.

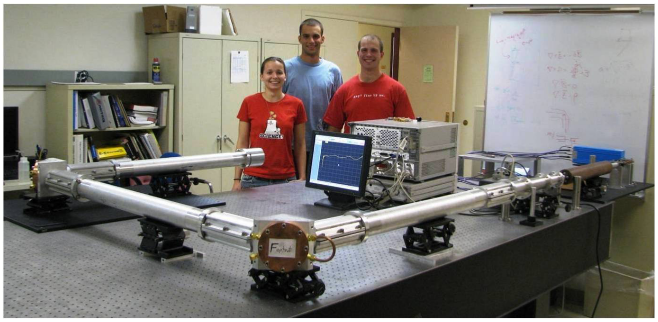

Figure 3. Left to right: Students Elizabeth Kowalski, Emilio Nanni and Brian Munroe testing the prototype ITER 170 GHz transmission line components in the PSFC Millimeter Wave test lab in NW16.

Research on high-gradient accelerators is focused on high-frequency linear accelerators for application to future multi-TeV electron colliders. The Accelerator Research Group operates the Haimson Research Corporation/MIT 25-MeV, 17-GHz electron accelerator. It is the highest power accelerator on the MIT campus and the highest frequency stand-alone accelerator in the world. The group also participates in a high-gradient collaboration headed by SLAC that includes major labs in the United States as well as the CERN (European Organization for Nuclear Research) and KEK labs. In 2009–2010, the MIT accelerator laboratory continued the upgrade of the facility. We have installed a novel high-power microwave tube called a Choppertron, built by Haimson Research, with a goal of producing 15 MW of pulsed power at 17.14 GHz. In 2009–2010, we completed the design of the next photonic accelerator structure. This new structure will have elliptical rods that reduce wall heating and will be tested at SLAC in July and August 2010. The accelerator group will also be collaborating with Dr. Evgenya Smirnova of Los Alamos National Laboratory, who is the recipient of a DOE Office of Science Early Career Award to conduct research on these photonic structures. In October 2009, Dr. William Brinkman, director of the Office of Science at DOE, identified photonic band-gap structures as a key emerging area of research at the symposium on accelerators for America's Future.

Fusion Technology and Engineering Division

The 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. In FY2010, the base program in fusion magnets was funded at the level of $0.71 million. The division did receive supplemental funding this fiscal year of $0.21 million to bring the total to the equivalent sum we received in FY2009. Our funding guidance for FY2011 is back to the $0.71 million level. This supports about three engineering research staff members who continue to perform research and development directed at developing high-temperature superconductors for fusion magnet applications.

As described in last year’s report, the efforts of Dr. Timothy Antaya, a principal research engineer in the division, have been very successful in developing new programmatic funding based on research and development of very compact cyclotron accelerators for detection of strategic nuclear materials (SNM). This new type of inspection system will result in a rapidly movable system for the active interrogation of objects at a distance to help detect concealed SNM. The Defense Threat Reduction Agency (DTRA) is the primary funding source for these projects. DTRA funding for one of these projects has been received from Raytheon for the Integrated Standoff Inspection System, or ISIS. This is an active interrogation nuclear radiation detection system that will provide the government with an accurate and reliable inspection system that is fully integrated and automated.

A second project funded by DTRA was just awarded as a subcontract from the Los Alamos National Laboratory. Under this funding, the division will develop a conceptual design for the construction of a 250-MeV, 1-mA, high-extraction-efficiency superconducting proton accelerator. A third and continuing project funded by DTRA is for a frontier studies program aimed at sensing fissile materials at long range. This is the second year of a five-year program for basic research with a total value of $2.2 million.

A fourth major contract is now being negotiated with Penn State University (again under DTRA sourced funding) for related work on small-scale superconducting cyclotron proton accelerators for portable deployment in unmanned underwater vehicles, unmanned aerial vehicles, and land-based applications.

The DTRA-funded programs now support two PhD candidate students with funding for an additional three students plus a postdoc to begin this fall. All projects are unclassified, unrestricted basic research type grants.

Other smaller research grants have been awarded through two phase I small business innovation research grants and one phase II small business technology transfer grant. The Princeton Plasma Physics Laboratory is funding two small projects related to fusion magnet applications.

With the establishment of several multiyear, stably funded programs, we now find the division short-staffed and will rapidly add new research staff over the next two years as the funding warrants.

Educational Outreach Programs

PSFC’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 laboratory and research environments. This kind of interaction, it is hoped, will encourage young people to consider science and engineering careers.

Tours of our facilities can be arranged for the general public as well as for corporations and political representatives. Massachusetts Congressman Edward J. Markey toured the center on February 5, 2010, to learn more about fusion as a future energy source (see figure 4). A group from Pixar also toured PSFC to see what an actual energy laboratory looks like in preparation for an animated film to be released in 2012. Visitors, students, and potential incoming graduate students are also able to get an educational overview of the fusion process and of the Alcator C-Mod project by watching a video on the PSFC home page.

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 the tour programs. The experience helps them develop the skill of communicating complex scientific principles to those who do not have an advanced science background.

Figure 4. Representative Edward J. Markey (far right) views a monitor recording the interior of the Alcator C-Mod tokamak in anticipation of the next plasma shot. Accompanying him (left to right) are senior research scientist Martin Greenwald, PSFC director Miklos Porkolab, congressional aide Sarah Butler, Nancy Beeuwkes and her husband, MIT alumnus Reiner Beeuwkes. Nuclear science and engineering graduate student Matthew Reinke (seated) was running the experiment that day.

Paul Thomas, whose Mr. Magnet in-school program was retired last year, continues to be involved in outreach days. He has also created three portable hands-on experiments focused on measuring voltage, building circuits, and testing electromagnets. Thomas, plus other staff and alumni have used these experiments to engage elementary school students in individual classrooms.

PSFC associate director Professor Jeffrey Freidberg has helped organize educational events oriented toward the MIT community, including PSFC's annual Independent Activities Period open house. PSFC has continued its educational collaboration with the MIT Energy Club, participating in their very successful energy night at the MIT Museum in October 2009 and supporting the MIT New England energy showcase at the Sheraton Boston in March 2010. These events were attended by hundreds of MIT students, as well as business entrepreneurs, affording them the opportunity to learn about the latest directions of plasma and fusion research.

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 a plasma sciences expo (to which teachers can bring their students) is a tradition at each year's American Physical Society Division of Plasma Physics meeting (see figure 5). Paul Rivenberg oversees the PSFC contributions to these events and leads the overall effort every four years. He is also part of the recently formed Fusion Communications Group (FCG). Composed of communication professionals from magnetic fusion energy institutions, the FCG seeks to improve awareness and understanding of magnetic fusion energy, targeting the media, teachers, students, and the general public.

PSFC 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, edits their educational publications, and heads a subcommittee that created and maintains a website to help teachers bring the topic of plasma into their classrooms.

Figure 5: Encouraged by PSFC graduate student Zach Hartwig, students attending the Plasma Sciences Expo at the APS-DPP meeting in Atlanta enjoy the challenge of confining plasma in the Alcator C-Mod video game.

PSFC also hosted a film crew from National Geographic, who interviewed staff and students about fusion as background for a program about the sun and the solar eclipse. The footage is to be edited into a live broadcast from Easter Island on July 11, during the next solar eclipse.

Awards, Appointments, and Promotions

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

Awards

Dr. Darren Garnier, a visiting scientist from Columbia University, received a 2009 Fusion Power Associates (FPA) Excellence in Fusion Engineering Award. In selecting Dr. Garnier, the FPA Board notes the contributions and leadership he has provided for the design, fabrication, and operation of the LDX (a joint Columbia–MIT project located at PSFC) and his contributions to the diagnostics and control systems for that experiment.

Recipients of the 2010 Infinite Mile Award were Robert Granetz, principal research scientist; Brian Labombard, principal research scientist; and Richard Murray, RF instrumentation engineer.

For the second year in a row, PSFC received from provost Rafael Reif the Environment, Health and Safety Award of Excellence.

Appointments

Alcator Division: Mr. Graham Wright was appointed research scientist, Mr. Lee Berkowitz was appointed information technology and network manager, Dr. Gregory Wallace was appointed postdoctoral associate, and Dr. Regina Sullivan was appointed postdoctoral associate.

Waves and Beams Division: Dr. Alan Cook was appointed postdoctoral associate.

Graduate Degrees

During the past year, three departments awarded degrees to students with theses in plasma fusion and related areas:

- Electrical Engineering and Computer Science: Mr. Jason Sears, PhD
- Nuclear Science and Engineering: Mr. Leonardo Patacchini, PhD; Mr. Noah Smick, PhD; Ms. Jennifer Ellsworth, PhD; Mr. Mark Norsworthy, SM
- Physics: Mr. Kenneth D. Marr, PhD; Mr. Grigory Kagan, PhD; Mr. Brock Bose, PhD; Mr. Jim Dorris, PhD; Mr. Noam Katz, PhD

Miklos Porkolab
Director
Professor of Physics

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