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 five major areas:

1. The science of magnetically confined plasmas in the development of fusion energy, in particular the Alcator C-Mod tokamak project
2. The basic physics of plasmas, including magnetic reconnection experiments on the Versatile Toroidal Facility (VTF), plasma-surface interactions, development of novel high-temperature plasma diagnostics, and theoretical plasma physics and fusion science research
3. The physics of high-energy-density plasmas, including the center's activity on inertial confinement laser-plasma fusion interactions
4. The physics of waves and beams (gyrotron and high-gradient accelerator research, beam theory development, non-neutral plasmas, and coherent wave generation)
5. 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), as well as non-fusion-related technology development, mostly in the superconducting magnet area

Administratively, each of these areas constitutes a separate research division. In order of research area above, PSFC's research divisions are the Alcator Project, Physics Research, High-Energy-Density Physics (HEDP), Waves and Beams, and Fusion Technology and Engineering.

PSFC research and development programs are supported principally by the Department of Energy's Office of Fusion Energy Sciences (DOE-OFES). There are approximately 216 personnel associated with PSFC research activities, including 25 faculty and senior academic staff, 45 graduate students, and five undergraduates, with participating faculty and students from Aeronautics and Astronautics, Electrical Engineering and Computer Science, Nuclear Science and Engineering (NSE), and Physics; 69 research scientists, engineers, postdoctoral associates/fellows, and technical staff; 30 visiting scientists, engineers, and research affiliates; one visiting student; 18 technical support personnel; and 23 administrative and support staff.

Total PSFC funding for FY2013 is expected to be $24.2 million, down precipitously (by 34%) from the FY2012 funding of $37.7million. The magnitude of this drop is attributed to DOE's planned termination of the Alcator C-Mod program by the end of FY2013. The fate of this program has played out over the last two government budget cycles. For the second consecutive year, it appears likely that the government will start the fiscal year without a budget in place. Similar to last year, the House of Representatives submitted a budget proposal containing explicit language to fund the Alcator C-Mod experiment in FY2014, while the Senate's version of the budget would prevent funding Alcator in FY2014. Having failed to reach a budget agreement last year, Congress enacted a continuing resolution to fund the government through FY2013 at FY2012 levels. In the absence of an FY2013 budget to provide guidance, however, DOE acted to carry out the administration's plan to shut down Alcator in FY2013, ordering a "cold shutdown" of the experiment and the cessation of operations after September 30, 2013.

In June 2013, the House Appropriations Subcommittee on Energy and Water Development instructed DOE to rescind its cold shutdown notice. Consistent with these orders, Alcator is presently under a "warm shutdown" notice from DOE through the end of FY2013. The likely prospect of a continuing resolution in FY2014, however, would mean the absence of Alcator C-Mod funding in that fiscal year. At that point, we would return to the cold shutdown plan and expect to cease operations indefinitely.

In May 2013, 35 Alcator staff received layoff notice letters. The layoff notice periods range from eight weeks to a year, depending on the employee's position and years of service. Additional layoff notices are scheduled to be issued as shutdown tasks progress. To partially offset the complete termination of this activity, DOE has provided $4 million in funding (minus a modest service charge for subcontracts) for collaborations in FY2014 with the DIII-D (General Atomics, San Diego) and NSTX (Princeton Plasma Physics Laboratory) tokamaks to support physics staff and provide continuing graduate student support. Unfortunately, only a very modest number of engineers and technicians would be supported. In addition, $1.5 million was obtained for collaborations with foreign tokamaks, in particular EAST (China) and KSTAR (Korea), which would support additional research staff.

FY2013 funding for three of the four other PSFC research divisions, Physics Research, Waves and Beams, and Fusion Technology and Engineering, also declined in FY2013 relative to FY2012, but with a lesser impact on PSFC total funding. Physics Research funding dropped by 24.7% (from $4.74 million in FY2012 to $3.58 million in FY2013), Waves and Beams funding decreased by 11.9% (from $1.85 million to $1.63 million), and Fusion Technology and Engineering funding declined by 19.6% (from $2.72 million to $2.19 million). HEDP held its own in FY2013 at $2.30 million, essentially no change from FY2012.

Alcator Project and Magnetic Confinement Fusion Division

The Alcator C-Mod tokamak is an internationally renowned magnetic confinement fusion experimental facility and one of three major US national tokamak facilities. Dr. Earl Marmar, senior research scientist in the MIT Department of Physics and the Plasma Science and Fusion Center, is the principal investigator and project head.

The C-Mod team at MIT consists of a full-time-equivalent staff of approximately 50 scientists and engineers, including 10 faculty and senior academic staff along with 20 graduate students and 20 technicians. Additionally, collaborators from around the world bring the total complement of scientific facility users to more than 200. The cooperative agreement with DOE-OFES, which funds the C-Mod project, was renewed in 2008 for a five-year period. (Figure 1).

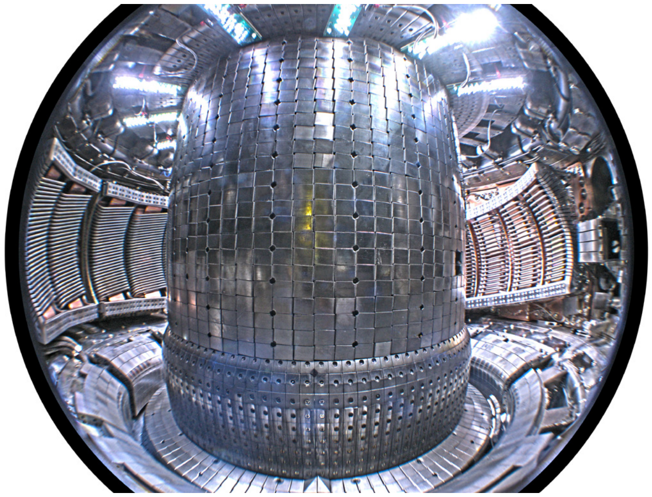

Figure 1. The interior of the Alcator C-Mod tokamak showing many of the "in vessel" structures.

C-Mod research continued through October 2012, with experiments in high-performance, high-magnetic-field plasma confinement. A total of 19 research weeks were completed during the 2012 federal fiscal year. Many of the experiments were in direct support of urgent International Thermonuclear Experimental Reactor (ITER) research needs.

Significant research progress across all topical areas was made in the last 12 months, and a few highlights are described here. In the ion cyclotron heating area, a unique, magnetic field-aligned antenna showed dramatic reductions in deleterious effects due to contamination of the plasma from wall impurities, and detailed modeling to understand the results is ongoing. The antenna also showed significant advantages with respect to power handling and tolerance to changes in edge plasma conditions, which are also the subject of theoretical investigations. The world's first intershot surface analysis system capable of interrogating changes in the surfaces of large areas of the plasma-facing wall has been implemented on C-Mod. The system uses a 1 MeV deuteron accelerator beam that is steered to different wall locations using variable magnetic fields. The resulting nuclear reactions are used to monitor changes in surface constituents, including deuterium, boron, molybdenum, and other elements. Effects of wall-conditioning techniques and high-power tokamak plasma interactions with the wall are being studied.

A novel edge plasma diagnostic (the "Mirror Langmuir Probe") has been used to explore edge plasma profiles and turbulence with unprecedented detail. Studies with this system of edge plasma transport barriers have proven that the mode structure of fluctuations that preferentially drive cross-field particle transport in certain enhanced energy confinement modes is that of a drift Alfvén wave. Recent results from experiments focusing on the onset, growth, and decay of relativistic electrons (REs) indicate that energy loss mechanisms other than collisional damping may play a dominant role in the dynamics of the RE population. Understanding the physics of RE growth and mitigation is motivated by the theoretical prediction that disruptions of full-current ITER discharges could generate as much as 10 MA of REs (with energy up to 20 MeV) through an avalanche growth process. The C-Mod results, which are being compared with results from other facilities (coordinated through the International Tokamak Physics Activity), show that the particle density required to suppress the runaway avalanche is significantly lower, by nearly an order of magnitude, than that expected from theoretical considerations, and the physics behind these results needs to be understood for extrapolation to ITER.

Another area of great importance for future steady-state tokamak reactors is the study of current drive with lower hybrid waves, a unique experimental program on C-Mod within the US program. Analysis of data from recent lower hybrid current drive (LHCD) experiments has revealed that theoretically predicted parametric decay instabilities may be the root cause of the previously unexplained loss in current drive efficiency in C-Mod at high density. It is believed that parametric decay instabilities are significant mainly in the so-called multipass regime, where the injected wave is reflected at the plasma edge one or more times before being absorbed. The key to developing steady-state non-inductive plasma regimes sustained in part by LHCD is to operate at temperatures required for single-pass absorption, typically 5 keV or more, with an optimized launch antenna position. An upgrade of the LHCD system in C-Mod has been proposed to test this theoretical prediction.

Funding guidance for continued operation of the Alcator C-Mod is currently uncertain. The presidential budget request for FY2014 has no funds for the facility. C-Mod would be restored under the appropriations bill passed by the House of Representatives; the full Senate has not yet passed a version of the appropriations bill, but the Senate appropriations subcommittee has supported the presidential request with respect to C-Mod. As noted, the facility is in a warm shutdown mode while awaiting congressional action, ready to operate starting in October 2014 if funds are available.

Physics Research Division

The Physics Research Division, headed by professor Miklos Porkolab, focuses on basic and applied plasma theory and simulations of magnetic confinement devices such as tokamaks and stellarators. It also develops novel plasma physics diagnostics, investigates general plasma mechanisms such as reconnection, and studies materials. In addition, it trains students for careers at universities, in industry, and at laboratories while striving to improve theoretical and experimental understanding of plasma physics and fusion science.

Fusion Theory and Simulations

The division's theory effort, primarily funded by DOE-OFES, focuses on basic and applied plasma theory and simulations. It also supports Alcator C-Mod and other tokamak experiments worldwide, as well as some stellarator research. The theory program head is PSFC assistant director Peter Catto. Two DOE Oak Ridge Institute for Science and Education (ORISE) postdoctoral fellows just began their new positions. Dr. Michael Barnes has become an assistant professor of physics at the University of Texas at Austin and Dr. Matt Landreman has become a physics postdoctoral fellow at the University of Maryland. In addition, NSE assistant professor Felix Parra will be leaving soon to take up an attractive new position as a professor in the Department of Physics at Oxford University. Professor Parra's first PhD student, Dr. Jungpyo Lee, finished during the spring semester and will become a postdoctoral fellow at New York University's Courant Institute in the fall. Also, Professor Parra has a master's student, Justin Ball, who will finish during the summer.

Some examples of recent progress in theory research at PSFC are listed below.

Professor Parra Diaz (NSE) and collaborator Dr. Ivan Calvo (CIEMAT/Euratom, Spain) derived turbulent tokamak equations describing rotation and momentum transport and extended them to stellarators. ORISE postdoctoral fellow Michael Barnes developed a new code based on these equations and, with Professor Diaz and Dr. Lee, used it to explain puzzling observations of rotation reversal when plasma parameters were changed. Another ORISE postdoctoral fellow, Matt Landreman, developed a new kinetic code, PERFECT, that retains the full collision operator in toroidal geometry. For stellarators, the code retains toroidal and poloidal spatial variation, while for tokamaks poloidal variation and strong radial density and temperature variation are allowed. Strong radial variation occurs in the pedestal region at the outer edge of the core plasma during high-confinement operation. Dr. Landreman's code provides insight into C-Mod observations in this poorly understood region known to play a key role in performance.

Dr. Darin Ernst serves as the MIT principal investigator within the multi-institutional DOE Science Discovery through Advanced Computing (SciDAC) Center for the Study of Plasma Microturbulence. Turbulence simulations conducted for his invited talk at the 2012 meeting of the American Physical Society (APS) revealed that the nonlinear critical density gradient for onset of trapped electron mode (TEM) turbulence increases strongly with collisionality. The upshift is associated with long-lived zonal flow states, whose lifetime increases with collisions. The resulting strong temperature dependence allows radio frequency heating to control TEM turbulence.

Magnetohydrodynamics and Extended MHD Simulations

Principal research scientist Jesus Ramos participates in the SciDAC Center for Extended MHD Modeling (CEMM). Stephen Jardin and graduate student Brendan Lyons of the Princeton Plasma Physics Laboratory are implementing his fluid and kinetic model for a weakly collisional tokamak in a new code that has recently begun simulating dynamic electromagnetic evolution. Collaborations with professors Eduardo Ahedo and Ignacio Parra of the Polytechnic University of Madrid have yielded new analytic results on two-fluid supersonic resistive instabilities used in verification runs of the CEMM codes and have led to the initiation of a new study of magnetic reconnection. Professor Jeffrey Freidberg (NSE) continues to collaborate with professor Antoine Cerfon, Dr. Andras Pataki, and professor Leslie Greengard of the Courant Institute at New York University on the development of a new fast, high-order, accurate numerical solver for the Grad-Shafranov equation. In addition, Freidberg's revision of his classic textbook *Ideal Magnetohyrodynamics* is nearing completion.

Heating, Current Drive, Advanced Tokamaks, and Nonlinear Dynamics

Dr. Abhay Ram, PSFC principal research scientist, and professor Kyriakos Hizanidis of the National Technical University in Athens, Greece, have been studying the scattering of radio frequency (RF) waves by edge density fluctuations in magnetically confined fusion plasmas. They have developed a full-wave scattering model used to determine the effect of cylindrical and spherical density blobs on the spectrum of RF waves propagating into the plasma core. The model, presented at an APS invited talk, is valid for arbitrary amplitude of density fluctuations and includes diffractive and refractive scattering and coupling between waves.

Center for Simulation of Wave-Plasma Interactions and Center for Simulation of Wave Interactions with MHD Fusion Simulation Project

PSFC participates in the SciDAC Center for Simulation of Wave-Plasma Interactions (CSWPI) and Center for Simulation of Wave Interactions with MHD with senior research scientist Paul Bonoli, the lead principal investigator for the multi-institutional CSWPI. Also involved are Drs. John Wright and Ram, professor Ronald Parker, Professor Diaz, and graduate student/postdoc Jungpyo Lee. Dr. Lee's thesis showed that it is necessary to include the lower hybrid wave-induced torque on plasma to understand early toroidal rotation behavior during lower hybrid wave injection; in addition, it is necessary to account for transport effects to understand long-term rotation behavior. Dr. Wright investigated diffraction and phase effects by comparing hard x-ray spectra produced in lower hybrid current drive experiments with simulations using ray tracing and full-wave solutions.

Experimental Research

Levitated Dipole Experiment

The Levitated Dipole Experiment (LDX) at MIT, a joint collaborative project with Columbia University, is a unique superconducting study that explores the confinement of plasmas in a "laboratory magnetosphere." (Figure 2) Headed by Dr. Jay Kesner (MIT) and professor Michael Mauel (Columbia), LDX was originally inspired by magnetospheric studies and was conceived as an alternate fusion concept experiment. However, DOE has narrowed its research focus in favor of projects that directly support the international ITER effort, and LDX is now funded as a platform for basic plasma physics research.

Figure 2. A "laboratory magnetosphere" using a half-ton levitated superconducting ring.

In 2012, LDX and Columbia's Collisionless Terrella Experiment (CTX) secured a three-year, $1.2 million grant from the National Science Foundation and DOE-OFES to jointly develop and test "space weather" models. Local weather forecasts do not typically include information about what is happening beyond the earth's ionosphere, and being able to predict space weather is of crucial importance. An understanding of geomagnetic storms caused by massive plumes of plasma ejected from the sun could be used to plan satellite operations, predict radio outages, and protect the electrical transmission grid.

Experiments are being performed at MIT's superconducting LDX facility and Columbia's smaller CTX facility. LDX and CTX permit the exploration of high-temperature ionized gas (plasma) trapped by strong magnets resembling the magnetic field of the earth. The strong magnets in these experiments have confined plasma at very high pressure and with intense energetic electron belts similar to the earth's radiation belts. With plasma diagnostics spanning global to small spatial scales and user-controlled experiments, these devices measure and study important phenomena in space weather such as fast particle excitation and rapid electromagnetic events associated with magnetic storms.

Plasma-Surface Interactions Science Center

The Plasma-Surface Interactions Science Center, headed by professor Dennis Whyte (NSE), seeks to provide a fundamental understanding of the complex plasma-surface interface. A critically important interaction to understand is how the plasma erodes the surface atoms through sputtering. A particular challenge is to understand erosion of the surface in the presence of a high-intensity plasma such as that found in fusion and plasma thrusters. A novel, high-resolution technique has been developed at the center for the measurement of erosion and deposition in solid material surfaces. This effort was led by postdoctoral associate Regina Sullivan. The technique uses a combination of nuclear reaction analysis and Rutherford backscattering spectrometry to determine the change in depth of a previously implanted marker layer consisting of 7Li. A scoping study showed that 7Li is an ideal marker candidate. Net erosion or deposition is measured by a nuclear reaction analysis of modified alpha energy passing through the bulk material. The reaction's high cross section provides for the fast time resolution needed to measure erosion from high flux plasmas, and a highly penetrating proton beam allows provides for a large range of erosion/deposition measurements. Additionally, the implantation of low-Z Li leads to relatively low vacancy concentrations in the solid material due to implantation.

The technique thus provides greater assurance that the measured erosion rate is indicative of the solid material because of both the low vacancy production and the fact that no films or deposits are involved. Validation was performed by comparing the measured and predicted amount of erosion based on previously measured sputtering yields; the two were found to agree within the uncertainty of the experiment. The depth resolution of the technique is approximately 50 nm at a net erosion depth of about 1 μm. The benefits of the technique are the short time scales (minutes) needed to obtain results, the ability to use the marker layer in any solid material, greater assurance that the measured erosion is indicative of the unperturbed solid material, and the continuous monitoring of the surface composition for contaminants and/or identification of deposited species using Rutherford backscattering spectrometry in conjunction with nuclear reaction analysis.

Magnetic Reconnection Experiments on the Versatile Toroidal Facility

Reconnection is the process by which stress in the field of a magnetized plasma is reduced by a topological rearrangement of its magnetic-field lines. The process is often accompanied by an explosive release of magnetic energy and is implicated in a range of astrophysical phenomena. In the earth's magnetotail, reconnection energizes electrons up to hundreds of kiloelectron volts, and solar-flare events can channel up to 50% of the magnetic energy into the electrons, resulting in superthermal populations in the megaelectron volt range. Magnetic reconnection has been studied in the Versatile Toroidal Facility under the leadership of professor Jan Egedal, who leads the effort of half a dozen undergraduate and graduate students. Depending on the topology and geometry of the magnetic field, a rich collection of magnetic reconnection scenarios is possible in 3D, including configurations with magnetic nulls. Such configurations are observed by spacecraft in the earth's magnetosphere and are likely important to the dynamics of magnetic storms driving the aurora borealis. In recent VTF experiments, we have formed a so-called flux rope along the background toroidal magnetic field. Additional magnetic field coils drive asymmetric reconnection and produce a pair of 3D null points along the flux rope. The rich plasma dynamics are being characterized through the recording of optical emissions from the plasma and through an array of plasma diagnostics available in the facility.

On the theoretical side, the experimental VTF results have led to the development of a new fluid model applicable to reconnection. As a breakthrough in reconnection research, this work demonstrates that the new physics included in the model is responsible for the elongated current layers routinely observed in kinetic simulations of reconnection but never seen before in fluid simulations. In a study published in *Physical Review Letters*, we documented that the dynamics of the reconnection region reside in four separate regimes depending on the properties of the underlying electron dynamics. The regime of our new fluid model occupies the range of parameters most relevant to reconnection as it occurs in nature.

Unfortunately, these experiments will be terminated in the coming year due to the departure of Professor Egedal, the principal investigator of this project, who did not receive tenure in the Physics Department. One remaining graduate student will complete his thesis work by the end of this calendar year, and with that the experiment will be shut down due to lack of funding.

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 a collaboration among PSFC, professor Ambrogio Fasoli of the Center for Plasma Physics Research (Lausanne, Switzerland), and a new group headed by professor Ricardo Galvao of the Instituto de

Física (University of Sao Paulo, Brazil). 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 result in Alfvén waves being unstable.

The main activity in 2013 was to continue a hardware upgrade with eight new amplifiers and a digital control system. Eight 4 kW class D solid-state amplifiers (one for each antenna) are being fabricated in Brazil to replace the current single 5 kW vacuum tube amplifier. One amplifier has been completed and is undergoing acceptance testing. MIT is providing the digital control system, which is responsible for generating the swept frequency amplifier drive signals, amplifier gain control, and all protection and safety fault trips. This year, the digital control system design was finalized and all hardware was procured from National Instruments. The digital control system work also included testing parts of the control software and the fabrication of custom signal conditioning electronics to provide the necessary signal levels and optical isolation to the amplifiers. This system has been shipped to JET. In the next year, the upgrade will be implemented at JET with plans for a plasma campaign with the new system in 2014.

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

PSFC research scientist Chris Rost (at the DIII-D tokamak in San Diego), postdoc Alessandro Marinoni, and graduate students on DIII-D and C-Mod (under the leadership of Professor Porkolab) have upgraded 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, transverse electromagnetic, and electron temperature gradient modes) should play a fundamental role in determining particle and energy transport, one of the frontiers of fusion research. These experiments are providing important new information on short-wavelength turbulence related to energy and particle transport. Ongoing comparisons with state-of-the-art gyrokinetic codes, in particular GYRO, have provided critical insight into the physics of electron transport, which is key to understanding energy transport in ITER scale burning plasma experiments in the presence of intense alpha particle heating of electrons. The group has continued its leadership role in the study of the linear ohmic confinement regime, which is important in the start-up phase of the ITER plasma, via novel experimental techniques to validate the state-of-the-art GYRO gyrokinetic computer code. Detailed PCI measurements have been compared with plasma turbulence as predicted by full nonlinear GYRO simulations. The current, more stringent tests show that some discrepancies between experiment and theory remain. In particular, this work has shown the importance of the partial depletion of deuterium density by oxygen-like impurity species.

In another series of experiments in Alcator C-Mod, mode-converted ion cyclotron waves have been measured during intense ion-cyclotron resistance heating. Recently, physics graduate student Naoto Tsujii defended his thesis on studying mode-converted ion cyclotron waves in Alcator C-Mod, and a comparison with the state-of-the-art full-wave codes AORSA (developed by scientists at the Oak Ridge National Laboratory) and TORIC (developed at the Max Planck Institute in Garching, Germany) was carried out. It was found that while the experimentally measured wave intensity agreed with theoretical predictions for small-minority concentrations, there were significant discrepancies in the high-minority-concentration regime, indicating the need to extend the full-wave codes to include nonlinear physics in the mode conversion process. This work has been published in the APS journal *Physics of Plasmas*. PCI is particularly suited to studying the edge plasma in high-confinement (H-mode) regimes, where its high spatial resolution and bandwidth match the turbulence in the very narrow edge region. Recent work in DIII-D has explored short-scale turbulence in H-mode regimes that is undetected by other diagnostics and may be important in understanding the transition into these regimes.

A new proposal for a significant upgrade of PCI on DIII-D has been funded for four years by the Department of Energy. The measurement capabilities of the PCI will be extended to longer wavelengths, allowing for more complete spectral coverage and increased sensitivity to coherent electromagnetic instabilities, both important in validating computer models and theories of key importance to ITER. Also, there is a significant technical component in adding these capabilities using the minimal port space that will be available on next-step fusion devices as well as making multiple measurements using a single laser probe beam. Professor Porkolab and Dr. Rost (on site at DIII-D) will continue the leadership of this program. Graduate student Evan Davis has moved to San Diego to continue his thesis work on this project while C-Mod is under the threat of shutdown.

Spinoff Research

Applications of Fusion Technology to Engineered Geothermal Systems

Engineered geothermal systems (EGSs) are geothermal power plants that can be built in any hot, dry rock location irrespective of the presence of natural hydrothermal fluids. Because crustal heat is ubiquitous throughout the earth, EGSs offer the potential for a large sustainable source of baseline energy. However, advances are required in drilling technology and reservoir heat exchanger formation in hard crystalline rock. Millimeter-wave (MMW) gyrotrons and related technologies developed for fusion energy research could contribute to the establishment of EGSs. Directed MMW energy can be used to advance rock penetration capabilities, borehole casing, and fracking. MMWs are ideally suited because they can penetrate through small particulate extraction plumes, can be efficiently guided long distances in borehole dimensions, and because continuous megawatt sources are commercially available.

During FY2013, Dr. Woskov collaborated with professor Herbert Einstein (Civil and Environmental Engineering) at the MIT Rock Mechanics Laboratory, and Impact Technologies LLC (through a contract from the DOE Golden Field Office in Colorado) on a phase 1 effort to better develop the basis for the use of MMW-directed energy for EGSs. Laboratory experiments carried out with a 10 kW, 28 GHz CPI gyrotron at MIT have shown that granite rock can be fractured and melted with power intensities of about 1 kW/cm^2 and minute exposure times. Observed melted rock MMW emissivity and estimated thermodynamics suggest that penetrating hot, hard crystalline rock formations may be economic with the MMW sources developed through fusion research. Among the tasks accomplished this past year was upgrading the MIT gyrotron system with a first-of-its-kind reflected power isolator that has made possible long rock sample exposures without tripping the gyrotron beam off. Fabrication has also been started on test equipment for MMW measurements of supercritical fluids that would be encountered in high-pressure deep drilling environments. PSFC and the MIT Rock Mechanics Laboratory have also partnered with the Petroleum Development Laboratory at the University of Alaska, Fairbanks (professors Abhijit Dandekar and Shirish Patil), and Impact Technologies to submit a proposal to DOE in response to a funding opportunity announcement to research mining hydrates using fusion spinoff MMW technology.

Thermal Analysis of Nuclear Reactor Materials

The development of next-generation very-high-temperature nuclear reactors (VHTRs) 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 FY2013, Dr. Woskov completed experiments funded by the DOE Nuclear Energy University Program on the development and use of novel MMW thermal analysis tools to address needs related to VHTR materials. It was shown that MMW radiometry can be an effective tool for observations of hot anisotropic materials, particularly low-emissivity materials such as graphite. A pair of 137 GHz radiometers with collinear views polarized orthogonal to each other was used to demonstrate the effectiveness of resolving asymmetry imposed on a graphite surface by linear grooving with groove dimensions much smaller than the observation wavelength (2.19 mm). SGL Group NBG17 nuclear graphite was found to have an emissivity of approximately 5% at 137 GHz and 525° C that did not change when the electric field of view was parallel to the grooves. When the electric field of view was perpendicular to the grooves, the emissivity increased by more than a factor of two for groove depths more than 10% of the wavelength. The measured (~5%) emissivity for the smooth surface itself was larger by more than a factor of two than would be expected by frequency scaling from the DC measured resistivity. The measurements suggest that stress-induced fracturing, which tends to grow linearly in the direction of least stress, could be dynamically monitored in a nuclear reactor environment to identify stress direction and strength. PSFC (Dr. Woskov), Alfred University (professor S.K. Sundaram), and the Environmental Molecular Sciences Laboratory (Dr. S. Thevuthasan) responded to a DOE Nuclear Energy Enabling Technology funding opportunity announcement this year to continue research and development of MMW technology and measurements for present and future nuclear reactors.

High-Energy-Density Physics Division

The High-Energy-Density Physics Division, led by Dr. Richard Petrasso, carries out pioneering and critical experiments in the areas of inertial confinement fusion (ICF) physics, high-energy-density physics, and laboratory astrophysics at the University of Rochester's Laboratory for Laser Energetics (LLE) and the Lawrence Livermore National Laboratory's National Ignition Facility (NIF). The division designs and implements experiments and performs theoretical calculations to study and explore the nonlinear dynamics and properties of plasmas in inertial fusion, in astrophysics, and under extreme conditions of density (~1,000 g/cc, or 50 times the density of gold), pressure (~1,000 billion atmospheres, or five times the pressure at the center of the sun), and field strength (~1 megagauss, corresponding to 2.5 million times the earth's magnetic field).

The division's scientists and students used HEDP-developed charged-particle and neutron diagnostics, including spectrometers, burn-history recorders, and charged-particle-based imaging techniques to make other advances in laboratory astrophysics, basic plasma physics, and ICF physics. In laboratory astrophysics, nuclear reactions important for stellar nucleosynthesis (e.g., ^{3}He-^{3}He) were studied, and experimental and theoretical insights into the nature of colliding plasma jets were obtained. In the area of basic plasma physics, methods were developed for studying the slowing of ions in plasmas for purposes of discriminating between competing theories. Many aspects of ICF physics along with their implications for achieving ignition were studied, including implosion asymmetries, mixing fuel capsule material into fuel plasma, shock behaviors, fuel areal densities, and the effects of non-hydrodynamic kinetic phenomena. All of this work was performed with the division's collaborators from LLE, NIF, the Los Alamos National Laboratory, General Atomics, and the Sandia National Laboratory. The NIF team, of which we are an integral part, recently achieved an all-time record D-D neutron yield of 2×10^{15}. This result bodes well for progress toward ignition.

Since MIT is the only university playing a major role in NIF research, NIF director Dr. Edward Moses made a point of posing for a photograph with the MIT division head, four students who are very active in NIF research and diagnostic development, and former HEDP PhD student Dan Casey (who wrote the first thesis based on NIF research and is now working at the facility). These students were involved in work on the most important single NIF diagnostic, the Magnetic Recoil Spectrometer, developed in an effort led by MIT scientists with our collaborators at LLE and the Lawrence Livermore National Laboratory. (Figure 3)

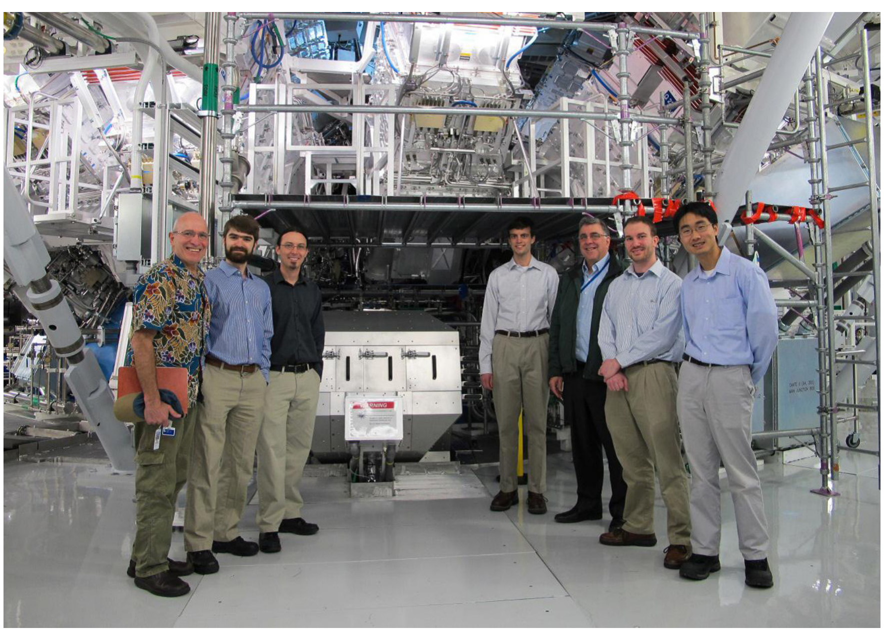

Figure 3. MIT and Lawrence Livermore National Laboratory staff in front of the NIF target chamber and the Magnetic Recoil Spectrometer. Left to right: Richard Petrasso, Hans Rinderknecht, Dan Casey, Alex Zylstra, Ed Moses, Mike Rosenberg, and HEDP student Hong Sio.

MIT also continued its role in plasma physics outreach, organizing all external OMEGA Laser Facility researchers for the fifth year in the now-annual OMEGA Laser Facility Users' Group workshop. This workshop brought together scientists and students from all over the world to discuss current research and to help LLE enhance its facility and procedures for outside scientists. The OMEGA Laser Users Group, the largest and most active in the high-energy-density physics community, now includes well over 300 members from 34 universities and national laboratories.

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 of the division's research programs.

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 vacuum electron devices operating at frequencies in the range of 90–500 GHz at power levels up to several megawatts. The gyrotron group, headed by Dr. Michael Shapiro, is conducting research aimed at increasing the efficiency of a 1.5 MW, 110 GHz gyrotron with an internal mode converter and a depressed collector. A second goal of this research is to demonstrate step tuning in the frequency of the gyrotron, to allow greater flexibility in its applications. The gyrotron, a form of electron cyclotron maser, is used for heating large-scale plasmas in the fusion energy research program. In 2012–2013, we rebuilt our gyrotron using a newly designed cavity and internal mode converter in preparation for testing the gyrotron at two frequencies, 110 and 124 GHz. The gyrotron group is also using the gyrotron in 3-microsecond pulsed operation to study breakdown in air and other gases, including the production and investigation of arrays of breakdown filaments. In addition, we implemented new diagnostics of the breakdown region to measure electron density, including measurement of the line width of the hydrogen Hα line and two-color laser interferometry.

The division is also pursuing high-power microwave sources based on slow-wave structures that support electromagnetic waves with phase velocity slower than the speed of light, in contrast to fast-wave gyrotron sources. In 2012–2013, we completed the design of a multimegawatt amplifier at S band (near 2.5 GHz) that will utilize a metamaterial structure. A metamaterial structure consists of a periodic array of sub-wavelength components, such as split rings, that yield changes to the permittivity and permeability of the medium. We have also assembled a 300-watt W band (94 GHz) traveling wave tube amplifier using an overmoded slow wave structure, which we will test on a newly completed test stand.

We are continuing research on low-loss microwave (170 GHz) transmission lines in collaboration with the US ITER project headquartered at the Oak Ridge National Laboratory. One of the major concerns with the transmission lines is conversion of the operating waveguide mode (HE_{11}) into higher order modes, which can cause high losses and possibly damage the lines. Over the past year, we have shown theoretically that miter bend mirrors that can be tilted or curved can eliminate most of the power converted into these higher order modes.

Research on high-gradient accelerators is focused on high-frequency linear accelerators that may greatly reduce the size and cost of future accelerators. The accelerator research group operates 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. The group also participates in a high-gradient collaboration headed by the Stanford Linear Accelerator Center that includes major labs in the United States as well as the European Organization for Nuclear Research (CERN) and Institute of Particle and Nuclear Studies (KEK) labs. In 2012–2013, we completed theoretical research on wakefields in novel accelerator structures that have photonic bandgap components to suppress higher order modes. We also upgraded the accelerator laboratory for testing novel, high-gradient metallic and dielectric structures at 17 GHz.

Fusion Technology and Engineering Division

The Fusion Technology and Engineering 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 has broad experience in all aspects of engineering research and in the design, development, and construction of magnet systems and supporting power and cryogenic systems. The division's major emphasis is on supporting the US national fusion program and on international collaborations, wherein PSFC provides leadership through the Magnets Enabling Technology program.

During the past year, division efforts were focused in three major areas: research and development of very compact, high-field superconducting cyclotron accelerators for detection of strategic nuclear materials; application of high-temperature superconducting materials and systems to fusion magnet systems; and analyses related to the design of the ITER central solenoid magnet.

Our work on high-field superconducting cyclotrons continued through a small grant from the Los Alamos National Laboratory using National Nuclear Security Administration (NNSA) funding. We completed a conceptual design of a compact superconducting cyclotron to demonstrate the feasibility of full particle beam acceleration, including injection, acceleration, and extraction. The cyclotron would be able to provide proton and deuteron beams up to a final energy of 20 MeV (10 MeV for deuterons) and with 100 µA of maximum current (protons) extracted. Other requirements include low beam losses and compactness (i.e., small volume and/or weight in order to make the device highly transportable). An innovative feature of the cyclotron analyzed in this work was that it was based on the concept of an ironless or nearly iron-free cyclotron accelerator. In this concept, the design incorporates multiple sets of magnetic field coils to generate the field profile required in a cyclotron, avoiding or minimizing the ferromagnetic pole pieces typically used in these machines. On the basis of this work, we filed a new patent application for the technology.

Under the fusion magnets base program, we have continued our research efforts on developing magnet technology for devices beyond ITER and toward the era of a DEMO fusion-based demonstration power plant. Progress has been made in development of very-high-current cables and joints using y**ttrium barium copper oxide** second-generation high-temperature superconductors. An apparatus was built and used to measure critical current in high-temperature superconductor tapes as a function of magnetic field and temperatures in the 4K–80K range. This work formed the basis of a student's master's thesis.

Work for the US ITER project office at the Oak Ridge National Laboratory was initiated for two types of analyses. In the first task, an analysis of various methods for detection of quench in the central solenoid was begun. This required extensive computation of a complex inductive matrix for all of the central solenoid coil windings as well as the six other poloidal field coils, including eddy currents in conducting structures. The goal was to determine the signal-to-noise ratio for different types of inductive voltage compensation schemes that could be practically implemented while meeting the signal-to-noise specification required for safe operation of the magnet system. A second task was to perform a failure modes and effects criticality analysis of the ITER central solenoid.

The total amount of division funding from all sources was substantially reduced during the past year, leading to the loss of our remaining technician, the division secretary, and several staff members, leaving us with six research staff and one graduate student. The budget outlook for the upcoming academic year is also not highly encouraging.

Educational Outreach Programs

The Plasma Science and Fusion Center's educational outreach program is planned and organized under the direction of Paul Rivenberg, PSFC communications and outreach administrator. 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 is aimed at encouraging young people to consider science and engineering careers, and feedback has always been extremely positive. Tours of our facilities are also available for the general public.

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.

Dr. Temkin, the center's associate director, oversees the PSFC seminar series, weekly plasma science talks aimed at the MIT community. Graduate students also hold their own weekly seminar series, taking turns presenting their latest research in a relaxed environment. PSFC's associate director, Dr. Martin Greenwald, has helped organize the center's annual Independent Activities Period open house seminars as well as special visits from dignitaries, including US and Massachusetts lawmakers.

PSFC received significant attention from lawmakers this year, facilitated by MIT alumnus Reiner Beeuwkes '67. These included visits by Representative Joseph Kennedy III (D-MA), (Figure 4) Representative John Tierney (D-MA), Senator Tom Udall (D-NM), state senator Katherine Clark (D-Melrose), Senator Jeanne Shaheen (D-NH), and Senator Mary Landrieu (D-LA) (Figure 5) motivated by the proposed cuts to the domestic fusion program in the 2013 presidential budget, which put the Alcator C-Mod at risk of being terminated. All of the visitors were guided around the Alcator C-Mod control room and experimental cell to learn more about the benefits of fusion energy.

Figure 4. Congressmen Joseph Kennedy III (center) touring PSFC's Alcator C-Mod control room, accompanied by PSFC director Miklos Porkolab (left).

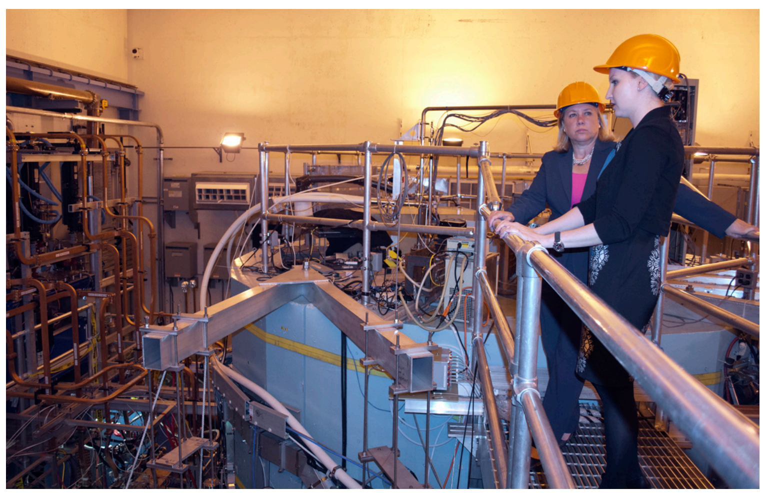

Figure 5. Senator Mary Landrieu (D-LA) learns about fusion from assistant professor Anne White (NSE; foreground) atop the Alcator C-Mod tokamak.

Paul Thomas, who retired his in-school Mr. Magnet Program, has not retired his vision of bringing science into elementary school classrooms. He has designed demos that can be handled and transported easily by PSFC personnel. Originally motivated by a desire to bring demonstrations to his niece's school, Thomas built three tabletop experiments for grades K–4 focused on measuring voltage, building circuits, and testing electromagnets; these experiments have become the foundation of PSFC's Portable Elementary Physics Program. PSFC employees or alumni interested in bringing science into K–4 classrooms are welcomed to sign out the equipment (or pieces of it). Thomas provides training that addresses safety issues involved with bringing MIT equipment into a school.

The Plasma Science and Fusion Center has continued its educational collaboration with the MIT Energy Club, bringing a variety of interactive plasma demonstrations to MIT Energy Night in October and the energy conference in March. These events were attended by hundreds of MIT students and business entrepreneurs, who learned about the latest directions in plasma and fusion research.

PSFC continues to collaborate with other national laboratories on educational events. The annual Teacher's Day (to educate middle school and high school teachers about plasmas) and Plasma Sciences Expo (to which teachers can bring their students) are traditions at each year's American Physical Society Division of Plasma Physics meeting. This year Paul Rivenberg coordinated educational activities for the Rhode Island meeting in October. He also organized PSFC's participation in the American Association for the Advancement of Science Family Days at Hynes Auditorium (over President's Day weekend), two days of hands-on presentations staffed by PSFC graduate students and staff.

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 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. Temkin and Rivenberg are members of the CPS steering committee. Rivenberg works with CPS on new initiatives and is editor of the coalition's *Plasma Page*, which summarizes CPS news and accomplishments of interest to members and the media. He also heads a subcommittee that created and maintains a website designed to help teachers bring the topic of plasma into their classrooms. In addition, he works with the coalition's technical materials subcommittee to develop materials that introduce the public to different aspects of plasma science.

Rivenberg is also a member of the Fusion Communications Group, a collaborative group of communications professionals from fusion laboratories around the United States that meets to discuss ways to best inform the general public about the benefits of fusion energy research.

Honors and Awards

During the past year, a number of PSFC staff and students were recognized for their achievements.

Awards

Research scientist Johan Frenje was honored as an APS fellow in October 2012 in recognition of his "pioneering development of unique neutron diagnostic methods and their utilization in inertial confinement fusion research, particularly in assessing implosion performance in fundamental and applied nuclear-science experiments."

Richard J. Temkin received the 2013 Institute of Electrical and Electronics Engineers (IEEE) Plasma Science and Application Award "for fundamental contributions to the field of high power gyrotrons and their application."

Darin Ernst, John Wright, and system analyst Ted Baker were presented the 2013 Infinite Mile Award by the Office of the Provost and the Office of the Vice President for Research. The team was cited for their tireless contributions to the design, acquisition, assembly, and maintenance of PSFC's 600 core Loki computing cluster.

Dennis Whyte received a Ruth and Joel Spira Award for Excellence in Teaching.

HEDP PhD student Mario J.E. Manuel was awarded NASA's prestigious Einstein Post-Doctoral Fellowship on the basis of his important thesis work and publications on the Rayleigh-Taylor instability. This is the first time someone from the high-energy-density physics/ICF community has received this distinction. Dr. Manuel is continuing his research at the University of Michigan.

Student Alex Zylstra won the Outstanding Poster award in the high-energy-density physics category at the annual NNSA Stewardship Science Academic Programs Symposium for his presentation about NIF research.

Graduate student Elizabeth Kowalski won an IEEE Nuclear and Plasma Sciences Society Best Student Paper Award at the 2013 Pulsed Power and Plasma Science Conference in San Francisco.

Joe Minervini received the 2013 IEEE Council on Superconductivity Award for Continuing and Sustained Contributions in the Field of Applied Superconductivity.

Miklos Porkolab received the 2013 Hannes Alfvén Prize and Medal from the European Physical Society, its highest award for plasma physics. Porkolab was recognized at the society's 2013 annual meeting on plasma physics in Espoo/Helsinki, Finland, "for his seminal contributions to the physics of plasma waves and his key role in the development of fusion energy." (Figure 6)

Figure 6. Professor Miklos Porkolab receiving the 2013 Hannes Alfvén Prize and Medal at the European Physical Society's annual meeting in Espoo, Finland, flanked by four young European scientists.

Appointments

In the Physics Research Division, Dr. Istvan Pusztai was appointed as a postdoctoral fellow, and Dr. Naoto Tsujii, Dr. Arturo Dominguez, and Dr. Jungpyo Lee were appointed as postdoctoral associates.

Dr. Kevin Cedrone was appointed as a postdoctoral associate in the Fusion Technology and Engineering Division.

Promotions

Atma Kanojia was promoted to lower hybrid engineering team leader in the Alcator Project Division and Dr. Gregory Wallace was promoted to research scientist.

Graduate Degrees

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

- Nuclear Science and Engineering: Tyler C. Sordelet, MS; Mario Manuel, PhD; Nareg Sinenian, PhD; Cale Kasten, MS; Jungpyo Lee, PhD; and Franco Mangiarotti, MS
- Physics: Arturo Dominguez, PhD; Naoto Tsujii, PhD; Yunxing Ma, PhD; Cornwall Lau, PhD; and Peng Xu, PhD
- Electrical Engineering and Computer Science: Emilio Nanni, PhD

Miklos Porkolab
Director
Professor of Physics