Plasma Science and Fusion Center

Overview

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, nonneutral 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.

Similarly, MIT's Francis Bitter Magnet Laboratory (FBML) is internationally recognized for its advances in several areas of science and engineering involving high magnetic fields, including research in nuclear magnetic resonance (NMR), electron paramagnetic resonance (EPR), and magnetic resonance imaging (MRI). The lab also is also active in NMR and MRI magnet development and in nanoscience condensed matter physics. Effective July 1, 2013, at the direction of the vice president for research, the Francis Bitter Magnet Laboratory was reorganized as a research division of the Plasma Science and Fusion Center. The research direction of FBML continues to be set and guided by professor Robert G. Griffin in his capacity as the division's director. Organizationally, however, FBML is no longer an independent laboratory reporting to the vice president for research; rather, it is a subunit of PSFC, which is directed by professor Miklos Porkolab. Administratively, it is now a PSFC research division, joining the center's five other divisions.

Integration of FBML into PSFC was intended to allow for more thorough oversight and management by MIT of the risks associated with a range of fiscal and environmental compliance requirements from sponsors and government. It was also expected that the consolidation will lead to adoption of the center's strong administrative controls within FBML and enhance administrative efficiencies for both units.

There is a certain symmetry to this consolidation. From a historical perspective, PSFC was originally an outgrowth of research activities at the Francis Bitter National Magnet Laboratory (FBNML) in the late 1970s. In fact, the precursors to today's Alcator C-Mod experiment—the Alcator A and Alcator C experiments—were both located at FBNML.

We believe that the transition has been accomplished with minimal disruption to the FBML research programs and that some of the hoped-for benefits are beginning to be realized. Administrative actions to consolidate fiscal management of grants, management of personnel transactions and payroll processing, and oversight related to safety and facilities have taken place with little or no disruption of operations at either PSFC or FBML.

The center's research and development programs, including FBML, are supported principally by the Department of Energy's Office of Fusion Energy Sciences (DOE-OFES) and the National Institutes of Health (NIH). There are approximately 230 personnel associated with PSFC research activities, including 25 faculty and senior academic staff, 42 graduate students, and 6 undergraduates, with participating faculty and students from Aeronautics and Astronautics, Chemistry, Electrical Engineering and Computer Science (EECS), Mechanical Engineering, Nuclear Science and Engineering (NSE), and Physics; 74 research scientists, engineers, postdoctoral associates/fellows, and technical staff; 38 visiting scientists, engineers, and research affiliates; 2 visiting students; 22 technical support personnel; and 24 administrative and support staff.

Total PSFC funding for FY2014 (ending September 30, 2014) is expected to be $35.87 million, including $3.70 million from the consolidation of the Francis Bitter Magnet Laboratory into PSFC and $22.05 million in Alcator funding. This is a dramatic turnaround for Alcator given where the program stood a year ago. In April 2012, DOE unexpectedly announced that the program would be terminated in FY2013. In June 2013, the US Senate submitted an Energy and Water Appropriations Bill in which no funding was provided for Alcator C-Mod. In July 2013, however, the House's version of the bill was submitted and included $22 million in Alcator C-Mod funding. Following a 16-day government shutdown in the fall of 2013 and a subsequent bipartisan budget conference agreement, an omnibus bill was passed in January 2014 that restored $22 million in funding for the Alcator C-Mod experiment. This outcome reversed DOE's original intention of shutting down the Alcator experiment. At the same time, however, while it was understood that Alcator operations would continue through FY2016, there is no indication that DOE plans to fund Alcator beyond that fiscal year.

With the restoration of funds for FY2014, layoff notices to nearly three dozen staff were rescinded and machine operations resumed after having ceased for approximately 15 months. The resumption of experimental operations was officially recognized with an event in the Alcator control room on February 24, 2014, that included a visit by Senator Elizabeth Warren (D-MA) and Representative Katherine Clark (D-MA) (Figure 1).

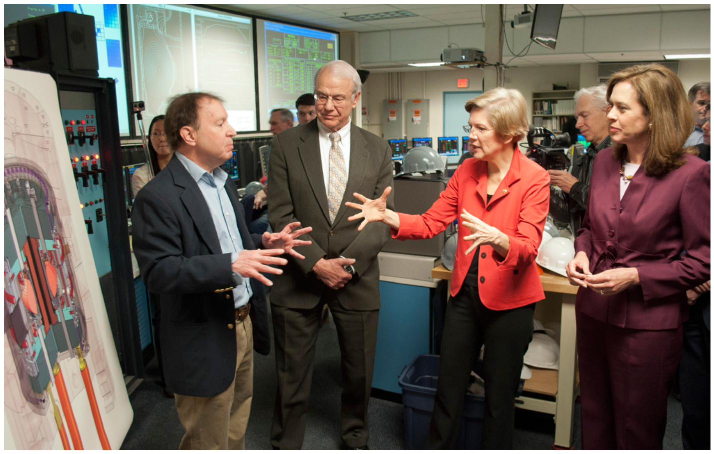


Figure 1. (From left) Associate Director Martin Greenwald and PSFC Director Miklos Porkolab discuss the potential of fusion energy with Sen. Elizabeth Warren and Rep. Katherine Clark in the Alcator C-mod control room.

Funding for four of the five other PSFC research divisions—Physics Research, High-Energy-Density Physics, Waves and Beams, and FBML—declined in FY2014 relative to FY2013. Physics Research funding dropped by 9.6% (from $4.37 million in FY2013 to $3.95 million in FY2014), HEDP funding decreased by 10.7% (from $2.81 million to $2.51 million), Waves and Beams funding decreased by 49.4% (from $3.46 million to $1.75 million), and FBML funding declined by 20.9% (from $4.68 million to $3.70 million). Fusion Technology and Engineering funding was $1.92 million, essentially the same as in FY2013.

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 (PI) and project head.

The C-Mod team at MIT consists of a full-time-equivalent staff of approximately 30 scientists and engineers, including five faculty and senior academic staff along with 10 graduate students and 16 technicians. Additionally, collaborators from around the world bring the total complement of scientific facility users to more than 150. The cooperative agreement with DOE-OFES, which funds the C-Mod project, was renewed in 2008 for a five-year period and then extended for a sixth year. A one-year renewal proposal has been approved for funding covering September 1, 2014, through August 31, 2015.

After DOE-OFES recommended that no funds be provided for C-Mod operations in FY2013, the facility was placed into cold shutdown status in October 2012. Subsequently, based on congressional directives to DOE, the status was upgraded to warm shutdown in June 2013. After final passage of FY2014 appropriations on January 17, 2014, funding was restored, and operations resumed on January 29. We plan a total of 12 research weeks in FY2014 (through September 30).

Areas of focus for the near-term C-Mod research campaign include core and pedestal energy, momentum and particle transport physics, plasma heating and sustainment, noninductive current drive, energetic particle studies, disruptions and their mitigation, divertor physics, and plasma-surface interactions. Particular emphasis will be placed on scrape off layer/divertor/plasma material interface physics, edge localized mode–free high confinement modes, and radio frequency (RF) tools for heating, current drive, and flow drive, with an eye to solving key questions in support of the International Thermonuclear Experimental Reactor (ITER). Also, beyond ITER, there will be a focus on issues that must be resolved on the path to the development of fusion energy, including the need for a successful fusion nuclear science facility and, ultimately, a demonstration power reactor.

Graduate student research and training on C-Mod continues in close cooperation with the academic departments at MIT.

Two members of the C-Mod team were recognized with prestigious awards in the last year. The 2013 Nuclear Fusion Journal Prize for best published paper went to Dennis Whyte and colleagues' "I-Mode: An H-Mode Energy Confinement Regime with L-Mode Particle Transport in Alcator C-Mod." This groundbreaking paper, presenting results from the Alcator C-Mod tokamak, provides an enhanced understanding of the formation of energy transport barriers and temperature pedestals in the boundary region of magnetic fusion devices. These pedestals are critical to the success of fusion devices because they establish a large pressure-gradient region in the outer perimeter of the fusion plasma. However, the formation of such pedestals is often accompanied by both an energy and a particle barrier. The particle barrier is unwanted in general because it makes control of the fuel and its purity much more difficult. The C-Mod research revealed a regime wherein an energy barrier in the pedestal could form without a particle barrier. This work, which could have a significant impact on future burning plasma devices such as ITER and fusion reactors, has stimulated significant research.

Anne White is the 2014 winner of the Katherine E. Weimer Award, established by the American Physical Society (APS) to recognize and encourage outstanding achievement in plasma science research by a woman physicist in the early years of her career. White was recognized for her "fundamental contributions to the understanding of turbulent transport in tokamaks through development and application of electron cyclotron emission diagnostics and insightful comparison of plasma fluctuations with gyrokinetic simulation predictions."

The presidential budget request for FY2015 includes funds to operate C-Mod for at least five research weeks. C-Mod would be restored to 12 weeks of operation, with funds for critical upgrades, under the appropriations bill passed by the House of Representatives; the Senate has not yet passed a version of the FY2015 appropriations bill. The presidential budget request also has language indicating DOE's intention to fund C-Mod operations through FY2016 but not beyond. The C-Mod team is currently working on proposals for a new, advanced divertor experiment (ADX) that would be constructed in the current C-Mod test cell; first operations would be scheduled in about six years. ADX is designed to investigate and answer key questions related to first-wall power handling in future nuclear facilities and to provide critical advances toward solving challenges on the path to steady-state operation of the tokamak concept.

Physics Reseach Division

Professor Miklos Porkolab is the head of PSFC's Physics Research Division. Its focus is on basic and applied plasma theory and simulations of magnetic confinement devices such as tokamaks and stellarators. The division 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 focuses on basic and applied plasma theory and simulations. It also supports Alcator C-Mod and other tokamak experiments worldwide, and in the past year the division performed some stellarator research. Nearly all of its funding is provided by DOE-OFES. The head of the theory program is PSFC assistant director Peter Catto. Catto was selected to spend Hilary term (January–March 2014) as a visiting research fellow at Oxford University's Merton College.

Dr. Darin Ernst serves as the MIT principal investigator at the multi-institutional DOE Science Discovery through Advanced Computing (SciDAC) Center for the Study of Plasma Microturbulence, has led several C-Mod experiments, and has led recent DIII-D experiments, including the first National Fusion Science Campaign experiment.

Some highlights of our recent progress in theory research on toroidal devices are presented below.

Current-driven electromagnetic modes in a tokamak: The induced electric field that typically drives the parallel current in a tokamak is a possible source of instability. In an inhomogeneous, finite pressure plasma, when this electron flow is comparable to the ion thermal speed, Alfven wave solutions of the kinetic equation were thought to become nearly purely growing kink modes. However, we have recently shown that these high-mode-number kinks identified in simulations and explained by simple analytic models are spurious, in spite of the remarkable agreement found in the parametric dependencies of frequencies and growth rates as well as radial mode structures for sheared magnetic fields. In this collaborative work performed by Drs. István Pusztai (MIT and Chalmers University of Technology), Michael Barnes (Oxford), and Peter Catto with Culham Centre for Fusion Energy colleagues Jack Connor and Jim Hastie, we developed a comprehensive theory model showing that these comparisons are made outside the simulation validity range, thereby resolving a controversy started in the 1970s.

Local and global neoclassical simulations of pedestal flow and bootstrap current: While at PSFC, Dr. Matt Landreman (now at the University of Maryland) developed the Pedestal and Edge Radially-global Fokker-Planck Evaluation of Collisional Transport (PERFECT) code to investigate neoclassical transport in the strong gradient or pedestal region at the edge of a tokamak. The steep density gradients were allowed to have scale lengths comparable to the magnetic drift departure from a constant pressure surface, with strong radial electric fields sufficient to electrostatically confine the ions. Weak ion temperature gradients (but arbitrary electron temperature gradients) were assumed to ensure small departures from a Maxwellian distribution. These assumptions are consistent with measured pedestal density and temperature profiles in many experiments. The parallel and poloidal pedestal flows were found to deviate strongly from the available theoretical expressions valid in the core, as expected. In the intermediate or plateau collisionality regime, comparisons with PERFECT showed remarkable agreement with our previously derived analytic expressions. Comparisons for the weakly collisional banana regime are encouraging but not yet complete, since very small collisionalities and large major to minor radius values are required.

Magnetohydrodynamics and Extended Magnetohydrodynamics Simulations

Principal research scientist Jesus Ramos participates in the SciDAC Center for Extended Magnetohydrodynamics (MHD) Modeling (CEMM). His fluid and kinetic model for weakly collisional plasmas is the basis of a new code, being developed in collaboration with Stephen Jardin and Brendan Lyons of the Princeton Plasma Physics Laboratory, that provides rigorous dynamical closure to the system of fluid equations used in the extended MHD code M3D-C1. Recent results obtained include the first self-consistent simulation of the dynamic formation of Ohmic and bootstrap currents during tokamak start-up and a successful benchmark over a broad collisionality range of neoclassical transport coefficients as derived from steady-state limits of time-dependent simulations. A separate analytical effort has yielded a novel alternative formulation of kinetic-MHD theory that fulfills naturally quasineutrality and parallel force balance conditions and affords a transparent proof of self-adjointness. Professor Jeffrey Freidberg (NSE) continues to collaborate with professors Antoine Cerfon and Leslie Greengard of the Courant Institute at New York University and will be teaching there during the fall 2014 semester. In addition, Freidberg's revision of his classic textbook *Ideal Magnetohyrodynamics* is now complete and the book is available.

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 scattering of RF waves used for heating and current drive by edge density fluctuations or blobs in magnetically confined fusion plasmas. These blobs modify the propagation properties of the RF waves by reflection, refraction, and diffraction. At the interface separating the blob from the background plasma, the boundary conditions that follow from Maxwell's equations need to be satisfied. These conditions require the simultaneous excitation of the two independent, cold plasma waves. For example, if an ordinary wave is coupled to the plasma from an external source, the blobs will not only scatter the ordinary wave but also couple some of the power to the extraordinary wave.

SciDAC Center for Simulation of Wave-Plasma Interactions and the International Collaboration on Scenario Control and Extension

PSFC participates in the SciDAC Center for Simulation of Wave-Plasma Interactions with senior research scientist Paul Bonoli, the lead principal investigator for the multi-institutional center. Also involved are Drs. John Wright and Ram from the PSFC theory group and Dr. Syun'ichi Shiraiwa from C-Mod. During the past year, Wright carried out extensive comparisons of wave solutions in the lower hybrid (LH) range of frequencies computed by an electromagnetic field solver and by a ray tracing approach; he found, counter to accepted practice, that thermal effects can influence the dispersion of LH waves in tokamaks, even at moderate temperatures (i.e., weak damping regimes). Bonoli also serves as the MIT principal investigator for the multi-institutional International Collaboration on Control and Extension for ITER and Advanced Scenarios to Long Pulse in EAST and KSTAR. Through this center, Bonoli, Wright, and Shiraiwa have collaborated with Dr. Cheng Yang and professor Boijang Ding of the Institute for Physical Sciences in Hefei, China, to carry out extensive ray tracing/full-wave/Fokker-Planck simulations of lower hybrid current drive in the EAST tokamak in Hefei.

Experimental Research

The 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." Headed by Dr. Jay Kesner of MIT and professor Michael Mauel and Dr. Darren Garnier of Columbia, LDX was originally inspired by magnetospheric studies and was conceived of 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 basic plasma physics research platform.

In 2012, LDX and Columbia's Collisionless Terrella Experiment (CTX) secured a three-year, $1.2 million grant from the National Science Foundation (NSF) and DOE-OFES to jointly develop basic plasma physics and test models of "space weather."

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.

One recent experiment involves the injection of lithium pellets into LDX using the Alcator C-mod pellet injector. As these pellets pass through the hot electron rings, the energy stored in these rings causes the pellets to explode, and the following three subsequent phases are observed: (1) the pellets vaporize, producing a burst of light; (2)

the Li gas ionizes, producing a tripling of plasma density; and (3) the density profile then relaxes to a stationary state (due to turbulent transport). The details relating to these phases are being studied as they are clearly relevant to processes that take place within the magnetosphere.

Plasma-Surface Interactions Science Center

The fifth and final year of research at the Plasma-Surface Interactions Science Center covered a broad set of research topics. There were several highlights, of which two are explained briefly here. The results have been published in or submitted to leading journals.

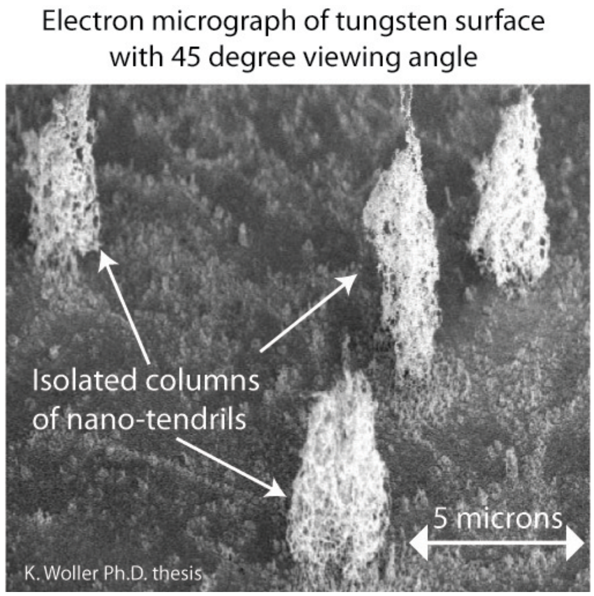


Figure 2. Electron micrograph showing isolated columns of nano-tendrils on a tungsten surface.

New in situ measurements provided critical insights into the formation of tungsten surface nanotendrils (Figure 2) caused by helium plasma exposure. This is a major issue for the viability of the leading material candidates for future fusion devices, including ITER. The MIT DIONISOS experiment measured the helium content of the tungsten in real time during plasma exposure just below and above the threshold conditions for tendril formation. These unique measurements clearly show that He density (or pressure) in the tungsten is not the cause of the tendril growth. This observation eliminates most leading models of the tendril growth mechanism. Further observations show very large isolated structures of tendrils and a high sensitivity to grain orientation at the surface. Taken together, these findings point to tungsten adatom mobility as the cause of the tendrils.

Needed depth marker techniques continue to be developed for providing in situ erosion and deposition diagnosis. Work from one year ago showed highly promising results with a novel lithium depth marker implanted by the MIT CLASS accelerator facility. This marker uses a high-Q nuclear reaction to probe the erosion/deposition of the bulk material without significant modification of the bulk’s properties. The newest measurements are even more encouraging because it has been shown that the Li atom markers are highly stable to thermal diffusion. In fact, no discernible lithium diffusion was measurable even for material temperatures up to 900 degrees Celsius. This is a somewhat surprising and positive result because the original expectation was that the lithium would become mobile at high temperatures. This result opens the door to exciting new applications for depth markers in high-temperature fusion environments.

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 has overseen the efforts of half a dozen undergraduate and graduate students. Unfortunately, these world-class experiments have been terminated due to the departure of Professor Egedal, the project's principal investigator, who did not receive tenure in the Department of Physics. One remaining graduate student completed his thesis work early in 2014 and defended his PhD thesis this summer, and with that the experiment was terminated due to a lack of funding and new leadership.

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.

In FY2014, the main activity has been 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) have been fabricated in Brazil to replace the current single 5 kW vacuum tube amplifier. MIT is providing the digital control system, which is responsible for generating swept frequency amplifier drive signals, amplifier gain control, and all protection and safety fault trips. This past 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. This summer a new grant proposal was written and submitted to DOE for another three years of continued operation of this program. The proposal is under evaluation by DOE.

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

Phase contrast imaging (PCI) experiments, led by Professor Porkolab under a DOE diagnostic grant, are being carried out on both Alcator C-Mod at MIT and the DIII-D tokamak at General Atomics in San Diego. The objective of these experiments is to measure coherent RF-driven waves and background turbulent density fluctuations due to various instabilities driven by temperature gradients in plasma. In Alcator C-mod, a series of experiments are measuring turbulence in ohmic plasmas, and the results are being compared with gyrokinetic codes by graduate student Paul Ennever. It is hoped that these studies will lead to a better understanding of electron transport due to microturbulence with relevance to reactor-type plasma regimes, such as in ITER, in which tellurium levels are greater than titanium levels. In a different set of experiments, mode-converted ion cyclotron waves have been measured during intense ion cyclotron resonance heating on Alcator C-Mod. Recently physics graduate student Naoto Tsujii has completed definitive measurements of this process, and the results were compared with predictions of 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). It was found that while the experimentally measured wave intensity agreed with theoretical predictions for small minority concentrations, significant discrepancies were discovered in the high minority concentration regime; these discrepancies were recently resolved as being due to the decreased sensitivity of the detector at the MHz frequencies used for detecting the waves by heterodyne techniques.

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 paper on the results of this work was recently published by Chris Rost and colleagues in *Physics of Plasmas*. The paper relates the evolution of microturbulence to evolving radial electric fields (typically 40–80 kV/m).

A new grant proposal for a significant upgrade of PCI on DIII-D has been funded for four years by the Department of Energy. Professor Porkolab and Dr. Rost (on site at DIII-D) will continue the leadership of this program. Under this grant, PCI measurement capabilities will be extended to longer wavelengths via an interferometer technique, in addition to the short wavelength measurements conducted with the PCI technique. This will allow for more complete spectral coverage and increased sensitivity to coherent electromagnetic instabilities, both valuable in validating computer models and theories of key importance to ITER. This work will constitute the thesis research of MIT physics graduate student Evan Davis, who has moved to San Diego to continue his work on the project. A significant technical aspect of the project is that adding two capabilities (interferometer and PCI) while using minimal port space will make this work applicable to next-step fusion devices.

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, they can be efficiently guided over long distances in borehole dimensions, and continuous megawatt sources are commercially available.

During FY2014, Dr. Woskov continued his collaboration with professor Herbert Einstein of the MIT Department of Civil and Environmental Engineering 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 on an expanded set of rock types, including granite, basalt, and limestone, continued to be carried out with a 10 kW, 28 GHz CPI gyrotron. Granite and basalt can be readily melted, and limestone is found to vaporize before a residue melts. The thermodynamic limit has been reached with the existing laboratory gyrotron in these experiments, with radiated power equaling input power to the rock samples. Further rock penetration will require a higher power gyrotron. To that end, contact has been made with the Air Force to use its 100 kW, 95 GHz gyrotron system at Kirkland Air Force Base, and discussions have started on using this system for further experiments. In addition, PSFC, the MIT Rock Mechanics Laboratory, and Impact Technologies submitted a proposal to DOE in response to a funding opportunity announcement to develop new deep drilling technologies for borehole storage of nuclear waste in basement rock. We have been informed that this new proposal will be funded.

3D Millimeter-Wave Radiometer System for Materials Research

A 3D millimeter-wave active radiometer system was developed for anisotropic materials studies, with MMWs used to measure temperature, emissivity, and position/flow of surfaces. This work extended the previous 2D MMW materials monitoring technology development efforts of PSFC (Dr. Woskov) and Alfred University (professor S.K. Sundaram). During FY2014, the state of New York funded PSFC through Alfred University to develop the 3D MMW monitoring system and deliver it to Alfred University's Materials and Science Department. Dr. Woskov completed the development work, delivered the system, and carried out initial experiments with Professor Sundaram. It was shown that the 3D MMW radiometer system was an effective tool for observations of anisotropic materials using a graphite cube with asymmetry imposed on one of the cube surfaces by linear grooving with groove dimensions much smaller than the observation wavelength. In addition, PSFC (Dr. Woskov) and Alfred University (Professor Sundaram) responded to an NSF funding opportunity announcement to use this technology in advanced materials research.

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).

During this academic year, several members of the division received awards for their accomplishments in high-energy-density physics and ICF. Former division PhD student Mario J.-E. Manuel, who graduated last year and is now at the University of Michigan, received the 2014 Marshall N. Rosenbluth Outstanding Doctoral Thesis Award from the American Physical Society for "thesis research of outstanding scientific quality and achievement in the area of plasma physics." For the second consecutive year, PhD student Alex Zylstra won the Outstanding Poster Award at the annual Stewardship Science Academic Programs Symposium on High Energy Density Physics. Finally, the group's founder and head, Dr. Petrasso (Figure 3), received the Edward Teller Medal from the American Nuclear Society's Fusion Energy Division for "pioneering research and leadership in the use of lasers, ion-particle beams or other high intensity drivers to produce unique high-density matter for scientific research and to conduct investigations of inertial fusion."

Figure 3. HEDP Division head Dr. Richard Petrasso was awarded the Edward Teller Medal by the American Nuclear Society in 2013.

Two other PhD students were selected to give invited talks on their research at the 2013 annual meeting of the APS Division of Plasma Physics. Michael Rosenberg was chosen for his work on magnetic reconnection in colliding laser-produced plasmas and Hans Rinderknecht for his work on kinetic effects in ICF plasmas.

The division's scientists and students made important advances in diagnostic instrumentation this year in ICF experiments conducted at NIF and at LLE's OMEGA laser facility. Particularly important are two temporal diagnostics for measuring the time history of nuclear burn. The new "dual particle temporal diagnostic" will measure differences in the times at which different nuclear reactions start (with a relative precision of 10 ps) to look for disagreements between simulations and experiments that could be related to possible kinetic effects. The "particle time-of-flight" diagnostic, which is being upgraded, has recently demonstrated its ability to measure the timing of both the shock and compression yields in implosions at NIF. Importantly, there have been many improvements over the past year in the division's Accelerator Laboratory for Diagnostic Development (Figure 4), which plays a critical role in the testing and calibration of diagnostics and provides important hands-on training for PhD students and undergraduates.

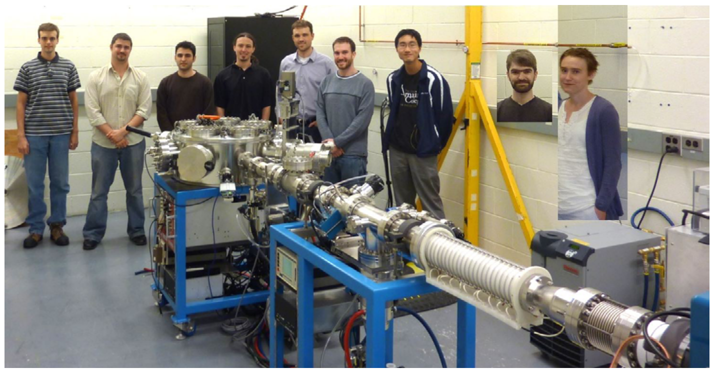


Figure 4. Members of the HEDP Division in the Division's Accelerator Laboratory for Diagnostic Development.

Recent research has focused on implosion dynamics, plasma properties, and self-generated electromagnetic fields. Experiments at the OMEGA laser facility using MIT-developed diagnostics have identified important differences in behavior between plasma regimes that can be described and simulated with standard hydrodynamic models and regimes wherein hydrodynamic modeling breaks down because of kinetic effects when the ion mean-free path exceeds the size of the plasma. It has also been shown that a nonhydrodynamic mix between fuel plasma and shell plasma at the fuel-shell interface can have a substantial impact on the fusion yields of imploding ICF fuel capsules. Other recent ICF-related experiments at OMEGA have focused on ion-electron equilibration and the stopping of charged particles in moderately to strongly coupled plasmas, and these studies have identified strong electric and magnetic fields that are generated during fuel capsule implosions and affect implosion dynamics. At NIF, where MIT is the only university playing a major role in the facility's programmatic research, division scientists and students have used MIT-developed diagnostics to help understand implosion dynamics and fusion yields, contributing to advancements in implosion quality that recently resulted in a record-breaking total fusion yield of 1,016 neutrons.

MIT also continued its role in plasma physics outreach, organizing all external OMEGA researchers for the sixth year in the annual OMEGA Laser 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 402 scientists, students, academics, and researchers from 43 universities, 77 centers and national laboratories, and more than 17 countries.

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 enhanced spectroscopy in the NMR research program. These applications require gyrotron vacuum electron devices operating at frequencies in the range of 90–500 GHz at power levels from watts to 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 applications. In 2013–2014, we successfully completed an experimental demonstration of tunable gyrotron operation in which megawatt-power-level output was obtained at 110 GHz with a magnetic field of 4.38 T and at 124.5 GHz with a magnetic field of 5.05 T. Such a tunable gyrotron would be useful in plasma heating experiments. We also demonstrated a gyrotron traveling-wave-tube amplifier at 250 GHz that uses a photonic band gap interaction circuit. The gyrotron amplifier achieved a peak small signal gain of 38 dB and 45 W output power at 247.7 GHz with an instantaneous 3 dB bandwidth of 0.4 GHz. This result represents the highest gain observed above 94 GHz and the highest output power achieved above 140 GHz by any conventional-voltage vacuum electron device–based amplifier. The gyrotron group is also using the gyrotron in three-microsecond pulsed operation to study breakdown in air and other gases, including production and investigation of arrays of breakdown filaments. We have successfully implemented two-color laser interferometry for making accurate density measurements of breakdown plasmas on a spatial scale of less than one millimeter.

We are also building 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 2013–2014, we completed the detailed design of a multimegawatt amplifier at 2.856 GHz that utilizes 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 obtained first-gain measurements of a 300-watt, 94 GHz traveling wave tube amplifier that uses an overmoded slow wave structure. If successful, this research will pave the way to high-power sources in the terahertz frequency region.

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 (HE11) into higher order modes, which can cause high losses and possibly damage the transmission line. In 2013–2014, we calculated the power lost due to mode conversion at the expansion units of the transmission line. Also, we derived a new method for estimating the mode content of the microwave power on the transmission line using the moments of the radiated fields.

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. In 2013–2014, we began testing a special copper photonic bandgap cavity in terms of breakdown rate at 17 GHz, at gradients exceeding 60 MV/m. Also, we successfully built a photonic bandgap accelerator cavity with sapphire rods that will be tested in the next phase of the research. Information on breakdown rates is critical in planning future high-energy accelerators.

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, design, development, and construction of magnet systems and supporting power and cryogenic systems. The division's major emphasis is on support of the US national fusion program and international collaboration, wherein PSFC provides leadership through the Magnets Enabling Technology program.

During the past year, division efforts were focused in three major areas: application of high-temperature superconducting (HTS) materials and systems to fusion magnet systems, research on HTS materials for power transmission and distribution, and research and development of very compact, high-field superconducting cyclotron accelerators for medical applications.

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 fusion-based demonstration power plant. Progress has been made in development of very-high-current cables and joints using yttrium barium copper oxide (YBCO) second-generation high-temperature superconductors. Experiments have been completed on HTS conductors carrying several thousand amps in magnetic fields as high as 20 T. Research by a PhD student has focused on the design of a reactor-scale toroidal field magnet system operating in a magnetic field of over 20 T, but with joints in the coil that are demountable to facilitate machine disassembly and maintenance.

We have also been performing research with YBCO HTS and MgB2 wires for power transmission and distribution applications. One of the projects has been supported under a phase 2 Small Business Technology Transfer grant funded by the US Air Force for high pulsed power delivery in airborne applications. Under the Low Carbon Energy University Alliance between Tsinghua University, the University of Cambridge, and MIT, we have delivered a YBCO cable and an MgB2 cable to Tsinghua University in Beijing, where a 22-m DC power distribution cable experiment is nearly complete. Cryostat integration and installation at Tsinghua was assisted by Dr. Philip Michael from

PSFC, on site at the test facility in Beijing. Experiments on the energized cable will begin this summer. A new project, begun in May and funded by the Office of Naval Research (ONR), will develop advanced concepts in superconducting generators and motors for ship propulsion systems. Initial studies are focused on all-superconducting machines in which both the magnetic field windings and the armature windings are made from HTS superconducting wires or tapes.

The third research focus area has involved highly compact superconducting cyclotrons for proton radiotherapy. We have published several papers and reports on our new concept for an all-superconducting cyclotron in which all iron is eliminated from the magnetic circuit, including the main iron poles and the iron yoke for return flux and shielding. We continue to pursue funded research opportunities in this area, including opportunities available through a new program established by the DOE Office of High Energy Physics.

Overall division funding has been relatively low but stable this fiscal year, supporting five research staff and one PhD student.

Francis Bitter Magnet Laboratory

Four principal investigators lead the research activities of the Francis Bitter Magnet Laboratory, now a division of PSFC: Robert Griffin (Chemistry), Yukikazu Iwasa (Mechanical Engineering), and Jagadeesh Moodera and Richard Temkin (Physics). The research activities of the first three investigators are discussed below. The activities of Dr. Temkin, who is associate director of PSFC and who also engages in research related to plasma science and fusion, were described above in the Waves and Beams Division section.

Robert G. Griffin, Professor of Chemistry

MIT-Harvard Center for Magnetic Resonance

The MIT-Harvard Center for Magnetic Resonance (CMR) is in its 39th year of operation as a facility providing scientists with access to high-field NMR equipment, including two 600, one 700, two 750, two 800, and one 900 MHz instrument along with 9 and 140 GHz pulsed EPR spectrometers. The collection of instruments is available to investigators at MIT, Harvard University, and other universities and companies. The arrival of the two 800 MHz instruments partially addresses the growing demand for high-field NMR spectrometer time.

In July 2014, professor Mei Hong will join the Department of Chemistry; her labs will be located in FBML, and she will be part of CMR. Her research is concerned with the structural biology of membrane proteins and cell walls.

In September 2013, the CMR grant was renewed for an additional five-year period through May 2019.

Structural Studies of Amyloid Peptides and Proteins

Amyloidosis is a group of disorders created by peptide or protein misfolding and characterized by the accumulation of insoluble fibrillar protein material in extracellular spaces. As the average age of the population increases, these disorders are becoming especially important. At present, about 25–30 different proteins are known to form disease-related amyloid aggregates—for example, beta-amyloid (Aβ) in Alzheimer's disease; the prion protein PrPc, which converts to PrPsc, leading to transmissible spongiform encephalopathy; the synuclein protein, which is responsible for Parkinson's disease; and beta-2-microglobulin (β2m), which is responsible for amyloidosis associated with kidney failure and dialysis. Currently, there are about 6 million Americans with Alzheimer's disease, and the annual cost of caring for these individuals is $172 billion. Thus, amyloidosis is a major health problem in the United States and other countries as well.

During the past few years, we have used magic angle spinning (MAS) NMR to determine the first complete structure of 11 residue fibrillar peptides derived from transthyretin. Specifically, using MAS NMR distance and torsion angle measurement techniques developed in our laboratory and methods to establish the interstrand and intersheet alignments of the peptides, we determined the complete atomic resolution structure of transthyretin. In combination with cryo-electron microscopy experiments, we were able to determine the structure of the fibril. In addition, during the past year the group completed a preliminary structure of the SH-3 domain of the protein phosphatidylinostol-3-kinase (PI3-SH3) and the spectral assignments of β2m, the protein associated with dialysis-related amyloidosis. Other experiments have been developed to determine the alignment of the fibrils, and in the case of both PI3-SH3 and β2m they are parallel in register. Dynamic nuclear polarization (DNP) has also been used successfully to establish other interstrand and intersheet contacts in PI3-SH3 and β2m. Recently we have recorded excellent spectra of Ab 1-42 that should provide the structure of fibrils of the Alzheimer's protein.

Membrane Proteins

We are continuing our studies directed at determining the structure and, more importantly, the functional mechanism of two different membrane proteins using state-of-the-art MAS NMR. All of the experiments utilize dipole recoupling, high-spinning-frequency 1H detection, and/or DNP. The proteins reside in lipid bilayers and therefore accurately represent the structure/function of the system.

The first system we are studying is the voltage-dependent anion channel (VDAC) composed of 283 AA; this is the most abundant protein in the mitochondrial outer membrane. VDAC is the primary pathway for metabolite transport between the mitochondrion and the cytoplasm. Studies are performed in 2D crystalline lipid bilayers, where VDAC is folded and stable over a wide pH range. We have shown that these preparations exhibit channel activity. At present, the optimal approach to producing a large population of "closed" channels is to lower the pH and lower the temperature to quench exchange between conformations. Using this approach, we are testing the hypothesis that the VDAC gate that controls metabolite flow involves either movement of the N terminus or a conformational change of the b barrel. Experiments are designed to determine the structure and to differentiate between these two mechanisms.

Another goal of our research is to determine the atomic resolution structure of the M218-60 construct of the M2 protein of influenza A and, therefore, the mechanism of H+ conduction and drug binding. M2 is vital to the life cycle of the flu virus, and it is important to understand how it conducts H+ and binds inhibitors. This will be accomplished by utilizing recently developed 1H-detected MAS techniques at high spinning frequencies (³60 kHz) as well as methods such as z-filtered transferred echo double resonance and RF-driven recoupling to measure intramolecular and intermolecular 1H-1H, 13C-15N, and 13C-13C distances. We recently demonstrated that M218-60 is a dimer of dimers rather than a tetramer, as reported previously. Subsequently, we have solved the structure of the S31N mutant, which is found in the majority of current flu strains and is resistant to the adamantidine and rimantidine inhibitors. The structure suggests a conduction mechanism that is different from that previously proposed along with a mechanism for drug resistance. We now need to refine the S31N structure and compare it to WT M2 with and without the bound drug and in its low pH conducting states.

Dynamic Nuclear Polarization

During the past year we discovered a major new polarization mechanism in insulating solids—namely the Overhauser effect (OE). Electron-1H hyperfine couplings, perhaps molecular vibrations that modulate the electron-nuclear coupling, mediate OE. We have studied OE enhancements as a function of B0 and in contrast to solid and cross effects.

In addition, we continued to operate our 700 MHz/460 GHz DNP spectrometer and obtained an enhancement of -55 on standard samples. With continued improvements, it is anticipated that enhancements will grow to approximately 140. The 140 and 250 GHz DNP spectrometers continue to operate reliably and routinely, allowing the group to pursue new methods and applications of DNP. Significant advances have been made in combining MAS with DNP and in developing new polarizing agents.

Third, we performed the first successfully pulsed DNP experiments using the NOVEL mechanism of frame-rotating spin locking. Finally, the 140 GHz spectrometer was rebuilt over the past year to increase its power output to 120 MW so that it can drive the 140 GHz gyroamplifier. Also, an NMR console has been added to the spectrometer so that pulsed DNP experiments can be performed. We hope that the gyroamplifier will be completed this year and that it can be used for further time domain DNP experiments.

As noted, the NIH P41 center grant supporting CMR is funded through 2019. In addition, the membrane protein grant was just renewed through September 2019. The renewal application for the DNP grant was submitted in July and will be reviewed in the fall. The level of productivity during the last four years has been excellent, so we are hopeful it will be renewed. The peptide protein grant has two more years of funding, and the renewal of that application will be submitted in July 2015. In total, we currently have three funded NIH R01 grants and a funded NIH P41 center grant.

Yukikazu Iwasa

During the period July 1, 2013, through June 30, 2014, the Magnet Technology Division, under Dr. Iwasa's leadership, was involved in three NIH-supported programs on NMR and MRI magnets and other magnet-related programs, each briefly summarized below.

NIH-Supported Programs

Insert Coil for 1.3 GHz NMR Magnet: Phase 3A

Since the theft in late 2011 of our original 600 MHz all-HTS insert, we have been working to complete coils 1 (innermost) and 2 (middle) of a three-coil, all-HTS 800 MHz insert. Coil 1 was successfully operated to its full self field of 8.65 T at 4.2 K. Coil 2 will be completed by the end of May 2015. This project is now supported by the National Institute of Biomedical Imaging and Bioengineering (NIBIB) and the National Institute of General Medical Sciences.

MgB2 0.5 T/800-mm Whole-Body MRI Magnet: Phase 1

The specific aim of this two-phase project, initiated in September 2009, is to complete, at the conclusion of phase 2, a whole-body MRI magnet. Using the MgB2, an HTS, we will demonstrate the feasibility of low-cost, liquid-helium-free magnets suitable for small hospitals, rural communities, and underdeveloped nations. The project is supported by NIBIB.

1.5 T Superconducting Solenoid Dipole for Slow Magic Angle NMR: Phase 1

Phase 1 of this project has two specific aims. The first is to build a superconducting magnet system comprising an axial-field solenoid and an x-y plane dipole whose combined magic angle field (MAF) is of NMR quality. The second is to demonstrate an innovative cryogenic system for a rotating low-temperature cryostat that houses this superconducting MAF magnet. In June 2014 we successfully tested the entire magnet system, which comprises a 0.8860 T solenoid, a 1.2247 T dipole, and an iron yoke. The dipole (125-mm inner diameter, 127.4-mm outer diameter, 495-mm overall length) was placed over the solenoid (106-mm inner diameter, 121.3-mm outer diameter, 151-mm overall length) and the iron yoke (150-mm inner diameter, 280-mm outer diameter, 500-mm overall length) surrounding the dipole. The entire magnet was also immersed in solid nitrogen at 4.2 K. In the remainder of this phase, the raw field homogeneity of 500 parts per million (ppm) over a 15-mm diameter spherical volume will be shimmed to 1 ppm with a combination of LTS shims and ferrotile shims. This project is supported by NIBIB.

Other Programs

Development and Application of a Partial-No-Insulation Winding Technique

The specific aims of this three-year research and development project, initiated by MIT and Japan Superconductor Technology Inc. (JASTEC) in April 2013, are to (1) further develop, through experiment and analysis, the partial-no-insulation (PNI) winding technique recently conceived at MIT with the goal of ensuring that JASTEC MRI magnets operate at enhanced stability; (2) design a JASTEC MRI magnet based on the PNI winding technique; and (3) build and test the magnet. Since June 2013, JASTEC magnet engineer Yasuaki Terao has been performing most of the work at FBML. The project is sponsored by JASTEC.

Development of an Insulation-Free Winding Technique

The specific aims of this three-year project are to develop (1) a lumped parameter equivalent circuit model for design and analysis of the steady-state field performance of 2G HTS insulation-free coils; (2) a distributed parameter equivalent circuit model for operational analysis of the dynamic performance of 2G HTS wind turbines; and (3) a computer code for design and analysis of 2G HTS insulation-free coils for wind power turbines above 10 MW.

During 2012–2014, Dr. Iwasa oversaw one graduate student, who is a PhD degree candidate in the Department of Mechanical Engineering, and three undergraduate students as part of the Undergraduate Research Opportunities Program (UROP).

Continued funding for Dr. Iwasa's research group at present levels is dependent on whether two major grants are renewed as well as his success on several new proposals. Even if renewed, there is the prospect of a gap in funding that could affect the size of his research group going forward. Dr. Iwasa expects word on these renewals later this year.

Jagadeesh Moodera

Dr. Moodera is a senior research scientist in the Department of Physics; his research labs are located in FBML. Dr. Moodera's research efforts focus on nanoscience condensed matter physics, with funding from ONR and NSF. Recently, he and professor Patrick Lee were awarded a prestigious John Templeton Foundation research grant. He is part of the large NSF-funded CIQM (Center for Integrated Quantum Materials) program, a collaboration involving MIT, Harvard, Howard University, and the Boston Museum of Science. This five-year award is renewable for an additional five years.

Dr. Moodera has collaborations with various universities in the United States, Canada, the United Kingdom, Germany, India, and Korea, as well as with national labs and IBM. Currently, he focuses on two-dimensional quantum coherent materials and interface-induced effects at the molecular level, emphasizing graphene, topological insulators, and organic semiconductors—some of the most significant topics in his field. His group investigates nanostructures for spin transport studies in these novel systems in addition to searching for exotic Majorana fermions.

In research on nanoscience condensed matter physics, in particular magnetism and superconductivity related to quantum coherent phenomena, Dr. Moodera's group continues to make significant contributions in both fundamental and applied sciences. The group's basic investigations emphasize spin transport in two-dimensional nanostructures (spintronics), including graphene, topological insulators, and organic molecular spintronics. Using its molecular beam epitaxy (MBE) system, the group seeks to contribute to the understanding of the spin properties of conventional materials and to unravel the spin properties of certain novel magnetic compounds that have a high potential for technological application. Adding to the state-of-the-art experimental facility, Dr. Moodera is installing a custom-designed extremely versatile cluster MBE system for studying molecules and quantum materials. In addition, he will acquire a low-temperature (300 mK) scanning tunneling microscope/atomic (conducting) force microscope system capable of operating in high magnetic fields. This extremely versatile and sensitive equipment (one of its kind in the Northeast) should lead to new discoveries and collaborations and should open up many technological possibilities.

The group's past research in the structure of quantum materials has been further developed by various companies such as IBM, Motorola, Seagate, TDK, and Fujitsu for application in digital storage. These companies have introduced into the market mini- and micro-disc drives with unprecedented capacity and read head sensors based on magnetic tunnel junctions. Another important area of application involves nonvolatile magnetic random access memory elements as well as reprogrammable logic circuits that will potentially have a significant and highly profitable impact on the memory technology being developed by major companies including IBM.

Dr. Moodera's group is continuing national and international collaborative research efforts with scientists and faculty from national laboratories and universities, including the Institute for Quantum Computing, the University of Waterloo, the Eindhoven University of Technology, and the University of Twente in the Netherlands; the University of Göttingen in Germany; Centre national de la recherche scientifique (CNRS), CEA Saclay, and the University of Paris in France; the Korea Institute of Science and Technology (KIST) and Ewha University in South Korea; Tohoku University in Japan; the University of California, Riverside; and the Saha Institute of Nuclear Physics in India. Dr. Moodera continues as a visiting professor at the Eindhoven University of Technology. In addition, he is an expert advisor for a spin-related national nanotechnology program in the Netherlands and at KIST that involves exchanges of scientists and graduate students. Collaborations are also in place with several faculty members from Physics and EECS; together, they have obtained an Initiative Research Grant from the MIT Center for Materials Science and Engineering to explore topological insulators.

Five postdoctoral scholars, graduate students, and undergraduates and four high school students have taken part in Dr. Moodera's research. The high school students have won several science competitions, and some of these students have joined the MIT undergraduate program. The current group consists of four postdocs and one undergraduate, and visiting scientists and students are expected to participate in the group's work.

In collaboration with professor Don Heiman of Northeastern University, Dr. Moodera is preparing a proposal for DOE as a co-PI in a study investigating novel oxides and quaternaries spin filters for spintronics. During the coming year, Dr. Moodera also plans to write a proposal to DOE to investigate molecular spintronics and a proposal to the Army Research Office to investigate spin injection into graphene via a quantum Hall state in a topological insulator.

Educational Outreach Programs

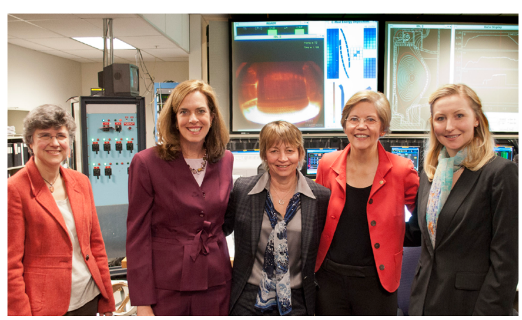
The Plasma Science and Fusion Center's educational outreach program is planned and organized under the direction of Paul Rivenberg, PSFC communications and outreach administrator. The program focuses on heightening the interest of K–12 students in scientific and technical subjects by bringing them together 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.

Richard Temkin oversees the PSFC seminar series, weekly plasma science talks aimed at the MIT community. Graduate students also hold their own weekly seminar series, where they take turns presenting their latest research in a relaxed environment. PSFC associate director Martin Greenwald has helped organize the center's annual Industrial Affiliates Program 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. For example, visits to PSFC were made by Congresswoman Nancy Pelosi (Figures 5 and 6), the House minority leader; Senator Mark Udall (D-CO), Senator John Walsh (D-MT), Senator Richard Blumenthal (D-CT), Senator Elizabeth Warren (D-MA), Representative Katherine Clark (D-MA), Representative Gary Peters (D-MI), and Representative Ann McLane (D-NH). We also hosted Jamie Williams, president of the Wilderness Society. All were guided around the Alcator C-Mod control room and experimental cell to learn more about the benefits of fusion energy. In early 2014, when Congress reversed an earlier proposal by the Department of Energy to shut down Alcator C-Mod, Senator Warren and Representative Clark were on hand to "restart" the machine (Figures 7 and 8).



Top left: *Figure 5. Director Miklos Porkolab welcomes Congresswoman Nancy Pelosi (D-CA) to the PSFC. Standing next to them (center) is Carl Parravano, Co-Director of MIT's Office of Government & Community Relations.* ***Top Right:*** *Figure 6. Alcator Division Head Earl Marmar with Congresswoman Nancy Pelosi (D-CA) in the Alcator C-Mod Experiment control room.* ***Lower Left:*** *Figure 7. From left, Senator Elizabeth Warren, NSE Assist. Prof. Anne White, and Rep. Katherine Clark at the formal restart event for the Alcator C-Mod Experiment.* ***Lower Right:*** *Figure 8. (From left) PSFC Principal Research Scientist Amanda Hubbard, Congresswoman Katherine Clark, MIT Vice President for Research Maria Zuber, Senator Elizabeth Warren, and NSE Assist. Prof. Anne White in the Alcator C-Mod control room.*

Paul Thomas, known for decades as "Mr. Magnet," has retired, creating a challenge for PSFC's outreach days. For the first time since we began Middle School Outreach Day, Thomas was not present to conclude the program with his hands-on plasma and magnetism activities. However, graduate student (now postdoc) Ted Golfinopoulos stepped in to educate the group, using some of Mr. Magnet's demonstrations. His success led PSFC director Miklos Porkolab to propose that he spend some of his postdoc time on outreach activities. Although the extent of his contribution has not yet been established, his participation will be helpful as the program deals with the reduced number of C-Mod students available for outreach activities.

PSFC continued its educational collaboration with the MIT Energy Club, bringing a variety of interactive plasma demonstrations to MIT Energy Night in October. This event, held on Family Weekend, was attended by hundreds of MIT students and their families, 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 APS Division of Plasma Physics meeting. This year's Plasma Sciences Expo in Denver was cancelled when exhibitors from national laboratories around the country reported that funding cuts would make it impossible for them to participate. The more stable funding currently in place should make the expo planned for New Orleans in 2014 possible.

PSFC also continues to be involved with educational efforts sponsored by the Coalition for Plasma Science (CPS), an organization formed by members of universities and national laboratories to promote understanding of the field of plasma science. Dr. 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 Paul 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 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 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. The group has created a three-year fusion communications plan and is exploring funding possibilities.

Honors and Awards

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

Professor Miklos Porkolab received the 2013 Hannes Alfvén Prize at a ceremony held in Espoo (Helsinki), Finland, on July 1. The honor, awarded annually by the European Physical Society during its Conference on Plasma Physics, recognizes outstanding work in the field of plasma science and fusion research.

HEDP division head Richard D. Petrasso received the 2013 Edward Teller Medal for HEDP's work in inertial confinement fusion and high-energy-density physics.

Assistant professor Anne White (NSE) received the Junior Bose Teaching Award for Excellence in Teaching, given annually to an outstanding contributor to education from among the junior faculty of MIT's School of Engineering. She also won the 2014 Katherine E. Weimer Award, which will be presented during the APS Division of Plasma Physics meeting in October 2014.

Professor Dennis Whyte received the 2013 Nuclear Fusion Journal Prize for outstanding paper for "I-Mode: An H-Mode Energy Confinement Regime with L-Mode Particle Transport in Alcator C-Mod."

Fusion Technology and Engineering Division head Joseph Minervini received the 2013 Award for Continuing and Sustained Contributions in the Field of Applied Superconductivity, presented by the Council on Superconductivity of the Institute of Electrical and Electronics Engineers (IEEE). He also coauthored a paper ("Investigation of REBCO Twisted Stacked-Tape Cable Conductor Performance"), with PSFC research scientist Makoto Takayasu, that was named by *Superconductivity News Forum* as a "Winning Preprint in Materials and Conductors."

JieXi Zhang, a graduate student in physics working in the PSFC Waves and Beams Division, won the 2013 best student paper award at the North American Particle Accelerator Conference in Pasadena, CA.

Darren Ernst received the 2014 Advanced Leadership Computing Challenge Award for the paper "Gyrokinetic Simulations of the Effect of Electron Heating on Particle and Electron Thermal Energy Transport in Magnetic Fusion Plasmas."

Graduate student Mario Manuel received the 2014 Marshall N. Rosenbluth Outstanding Doctoral Thesis Award, which will be presented during the APS Division of Plasma Physics meeting in October. The award was established to recognize exceptional young scientists who have performed original doctoral thesis research of outstanding scientific quality and achievement in the area of plasma physics.

Elizabeth Kowalski, a graduate student in Electrical Engineering and Computer Science, won the best student paper award at the 2014 International Vacuum Electronics Conference in Monterey, CA. The award includes an engraved plaque and a check for $500.

Graduate student Mark Chilenski received the Nuclear Science and Engineering Teaching Assistant Award.

Graduate student Jiayin Ling was awarded the IEEE Council on Superconductivity Graduate Study Fellowship at the 2013 International Conference on Magnet Technology.

PSFC fiscal officer Lee Keating received a 2014 Infinite Mile Award from the Offices of the Provost, the Vice President for Research, and the Dean for Graduate Education.

Appointments

Dr. Thibault Lecrevisse and Dr. Robert Lillianfeld were appointed as postdoctoral associates in the Francis Bitter Magnet Laboratory.

In the Alcator Project Division, Dr. Nathan Howard and Dr. Christian Theiler were appointed as postdoctoral fellows; Dr. Zach Hartwig, Dr. Seung Gyou Baek, Dr. Harold Barnard, and Dr. Theodore Golfinopoulos were named postdoctoral associates.

Promotions

In the High-Energy-Density Physics Division, Dr. Maria Gatu Johnson was promoted to research scientist and Dr. Johan Frenje was promoted to principal research scientist.

Dr. John Rice was promoted to senior research scientist in the Alcator Project Division.

Dr. Sudheer Jawla was promoted to research scientist in the Waves and Beams Division.

Graduate Degrees

- Nuclear Science and Engineering: Geoffrey Olynyk, PhD; Justin Ball, MS; Daniel Brunner, PhD; Roman Ochoukov, PhD; Seung Gyou Baek, PhD; Harold Barnard, PhD; Zachary Hartwig, PhD; Randy Churchill, PhD; and Jude Safo, MS
- Physics: Jennifer Sierchio, MS
- Electrical Engineering and Computer Science: David Tax, PhD, and Theodore Golfinopoulos, PhD
- Aeronautics and Astronautics: Michael Garrett, PhD
- Chemistry: Evgeny Markhasin, PhD

Miklos Porkolab
Director
Professor of Physics