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. Additionally, its Francis Bitter Magnet Laboratory (FBML) is internationally recognized for its advances in magnetic resonance imaging (MRI) and nuclear magnetic resonance (NMR) spectroscopy, in NMR and MRI magnet development, and in nanoscience condensed matter physics. Collectively, PSFC's research activities fall into six major areas:

1. The science of magnetically confined plasmas in the development of fusion energy, in particular the Alcator-C-Mod tokamak project
2. General plasma science, including plasma-surface interactions, the development of novel high-temperature plasma diagnostics, and theoretical plasma physics
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)
6. Research in magnetic resonance, including NMR, electron paramagnetic resonance (EPR), and MRI; NMR and MRI magnet development; and nanoscience condensed matter physics (quantum coherent behavior and spin transport)

Administratively, each of these areas constitutes a separate research division. In order of research area above, PSFC's six research divisions are as follows: Magnetic Fusion Energy/Alcator Project, Physics Research, High-Energy-Density Physics (HEDP), Waves and Beams, Fusion Technology and Engineering, and the Francis Bitter Magnet Laboratory.

The center's research and development programs are principally supported by the Department of Energy's Office of Fusion Energy Sciences (DOE-OFES) and the National Institutes of Health (NIH). There are approximately 250 personnel associated with PSFC research activities, including 26 faculty and senior academic staff, 42 graduate students, and 5 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; 83 research scientists, engineers, postdoctoral associates/fellows, and technical staff; 45 visiting scientists, engineers, and research affiliates; 2 visiting students; 24 technical support personnel; and 22 administrative and support staff.

Total PSFC funding for FY2015 (ending September 30, 2015) is expected to be $36.4 million. Sixty-one percent of this total ($22.2 million) is devoted to magnetic fusion energy (MFE) research. Of the $22.2 million dedicated to MFE research, 69% is attributable to the Alcator C-Mod tokamak experiment, at an estimated FY2015 funding level of $15.4 million. As noted in earlier reports, DOE planned to end the Alcator program in FY2013, a decision that was made with no review of the program or any technical justification. As a result of specific funding appropriation directions from Congress, DOE subsequently extended the project through FY2016. This extension has been welcome news to PSFC and will allow for a more orderly program shutdown than would have occurred otherwise. It also gives the center's leadership time to plan for the loss of Alcator funds and actively pursue other funding sources, including DOE-funded domestic collaborations with the Princeton Plasma Physics Laboratory (PPPL) and General Atomics (San Diego) as well as collaborations with Germany, China, and Korea on fusion research. To this end, PSFC has a new five-year cooperative agreement with DOE to continue the center's magnetic fusion energy research beyond the shutdown of the Alcator C-Mod tokamak in FY2016. At least initially, the shutdown of Alcator C-Mod will mean a transition to a smaller PSFC, but one with a somewhat more diverse range of research activities. Our best early estimate of DOE-OFES funding in FY2017 for MFE research post-Alcator is approximately $12 million. This amounts to a net reduction of about $10 million in MFE funding relative to FY2015 and approximately a 27% reduction in PSFC's total research funding relative to that fiscal year.

FY2015 funding for the five other PSFC research divisions—Physics Research ($4.1 million), HEDP ($2.6 million), Waves and Beams ($2.4 million), Fusion Technology and Engineering ($1.9 million), and FBML ($3.1 million)—is expected to be $14.1 million, or about 39% of the center's total ($36.4 million). Going forward, we expect the combined funding for these five divisions to remain relatively constant in FY2016 and beyond.

The Francis Bitter Magnet Laboratory, formerly a separate allocation unit reporting to the vice president for research, became a research division of the Plasma Science and Fusion Center in FY2014. This reorganization was undertaken at the direction of the vice president for research to strengthen the laboratory's administrative support and services as well as to improve administrative controls, bolster PSFC's research volume given the expected termination of the Alcator project, and encourage scientific collaborations between these formerly separate units.

Two years into this reorganization, the integration of these two units is essentially complete. FBML principal investigators (PIs) have adopted PSFC administrative procedures and have been interacting with PSFC's director and staff on matters of administrative and fiscal support. FBML proposals are now prepared by the PSFC fiscal office, matters of safety are handled by the PSFC environment, health, and safety (EHS) office in conjunction with the MIT EHS Office, and the PSFC facilities manager oversees repairs and maintenance within FBML's Building NW14 while working closely with MIT's Facilities Department to advocate for timely facilities support for the laboratory. We believe that the consolidation of FBML and PSFC has led to a greater level of service among the laboratory's PIs as well as a greater level of compliance by FBML with the Institute's environmental and safety requirements.

On January 1, 2015, Professor Dennis Whyte (Nuclear Science and Engineering) became the new director of PSFC, replacing Professor Miklos Porkolab (Physics). Professor Porkolab stepped down one month shy of 20 years as director. He has been a tireless advocate for fusion energy research at the center and provided solid leadership both at PSFC and within the US national fusion program during a period of constrained national budgets and fierce competition for federal research support. A reception held in his honor was attended by three other current or former PSFC directors along with MIT's vice president for research (Figure 1).

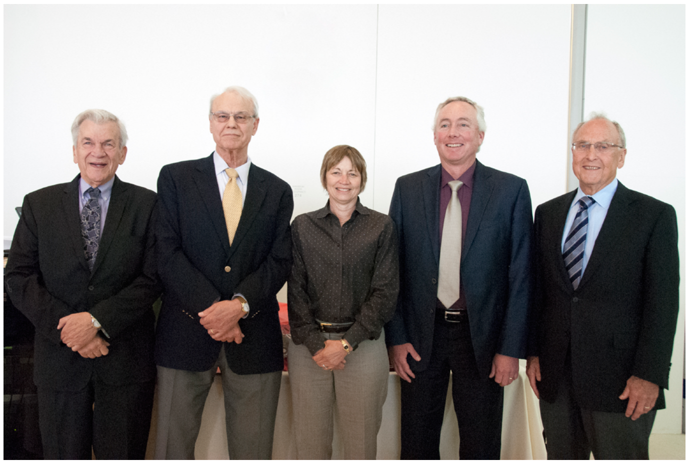

Figure 1. Professor Miklos Porkolab (second from left) stepped down as PSFC director this year. A reception celebrating his 20 years in this position was attended by two former PSFC directors, Ron Davidson (far left) and Ron Parker (far right), as well as current PSFC director Dennis Whyte (second from right) and MIT Vice President for Research Maria Zuber (center).

Alcator Project and Magnetic Fusion Energy Division

The Alcator C-Mod tokamak (Figure 2) 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.

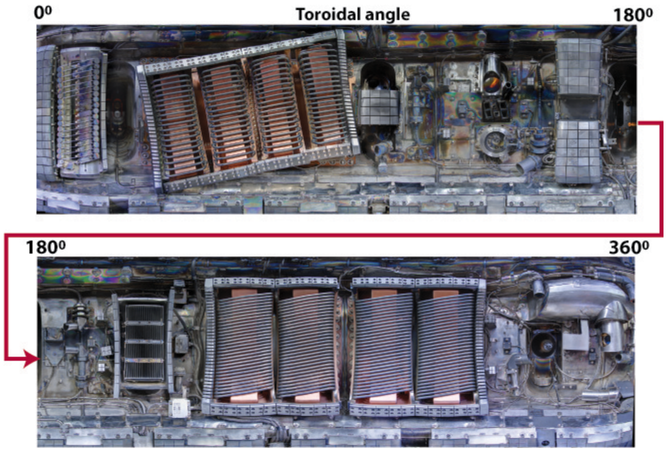

Figure 2. Composite picture of the outer wall of the Alcator C-Mod vessel. This nearly 360-degree view is made up of multiple photos taken from inside the torus looking outward, unfolding the toroidal shape into a linear geometry. Features visible in the image include radio frequency and microwave antennas used to launch waves that heat the plasma and drive toroidal plasma currents, measurement equipment used to diagnose plasma temperature and density, and some of the vacuum vessel ports that allow access from the outside.

The C-Mod team at MIT consists of a full-time-equivalent staff of approximately 30 scientists and engineers, including seven faculty and senior academic staff along with five postdoctoral fellows, 12 graduate students, and 15 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 two additional years. A final one-year extension proposal covering September 1, 2015, through August 31, 2016, is currently under review at DOE.

Research operations during FY2014 totaled 11.37 weeks, and we are currently in the middle of our FY2015 campaign, planned to total 12 research weeks. The current guidance from DOE is for a final research campaign of six weeks in FY2016, subject to change based on FY2016 appropriations. Following this campaign, the facility will be placed into cold shutdown, with no further operations planned.

The team is transitioning to primarily a collaborative mode of experimental research, with emphasis on participation in the DIII-D and NSTX-U facility experiments at General Atomics and the Princeton Plasma Physics Laboratory respectively. A new five-year cooperative agreement proposal to support these collaborations has received highly favorable peer reviews and has been recommended for funding by DOE-OFES. Negotiations are ongoing with the DOE Chicago finance office to implement the first year's funding, expected to start September 1, 2015. Additional grants are currently in place to support preservation of Alcator C-Mod data and participation in the International Tokamak Physics Activity; international collaborations, primarily focused on the EAST (China) and KSTAR (South Korea) superconducting tokamak facilities; and further development of the MDSplus data system software package, currently in use at more than 30 fusion research sites around the world.

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, 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 demonstration power plant. Because the FY2015 and FY2016 campaigns will be the last for the foreseeable future of an advanced divertor tokamak capable of operating at up to an 8 tesla toroidal magnetic field, anywhere in the world, there will be a particular emphasis placed on research opportunities that take advantage of this unique high-field capability.

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

MFE experimental scientists, in collaboration with a national team, are currently considering a new, advanced radio-wave-sustained divertor experiment (ADX) for possible construction in the current C-Mod test cell; first operations would take place in approximately six years. ADX is designed to investigate and answer key questions related to first-wall power handling in future nuclear fusion facilities and to provide critical advances toward solving challenges on the path to steady-state operation of the tokamak concept. Funding to support the conceptual design is proposed as part of the new five-year cooperative agreement.

Anne White, Cecil and Ida Green Associate Professor in Nuclear Engineering

Professor Anne White was promoted to the rank of associate professor with tenure. She currently leads the PSFC Magnetic Confinement Core Transport Group, coordinating collaborations with experiments such as NSTX-U and DIII-D while also serving as organizer for core transport experiments at the Alcator C-Mod tokamak.

Professor White's research focuses on the study of turbulent transport in fusion plasmas, with the goal of controlling the transport and improving performance of tokamaks. The turbulence in tokamak plasmas can exist at two distinct length scales: ion scales, where turbulent eddies have sizes comparable to the ion gyro radius, or electron scales, where the eddies are comparable in size to the much smaller electron gyro radius (60 times smaller in a Deuterium plasma). Over the past year, her group has focused on studies of electron heat transport and on the relative importance of ion scale versus electron scale turbulence. Theory predicts that electron scale turbulence can lead to substantial loss of electron heat in certain conditions wherein long wavelength turbulence is strongly suppressed by background sheared plasma flows (relevant near the edge of the plasma in H-modes or in spherical tokamaks such as NSTX-U and MAST). However, the role of electron scale turbulence in cases where ion-scale turbulence is not suppressed remains an open question.

Professor White's group is engaged in experimental research at three major tokamaks (NSTX-U, Alcator C-Mod, ASDEX Upgrade). At those sites, the team leads experiments, develops diagnostics, and leads validation projects using advanced turbulence simulation codes developed by theory collaborators.

At the NSTX-U tokamak at Princeton Plasma Physics Laboratory, Professor White's graduate student Juan Ruiz Ruiz (Department of Aeronautics and Astronautics) is using a high-k scattering diagnostic to measure electron scale density fluctuations directly and compare the turbulence with theory and simulation. The data show that the measured turbulence responds strongly to changes in background plasma density gradients, consistent with predictions for electron scale turbulence. Juan presented his results at three major fusion conferences, including the European Physical Society's June 2015 conference in Lisbon.

At C-Mod, Professor White's graduate student Alex Creely (NSE) has been measuring propagation of electron temperature heat pulses. Using heat pulse propagation measurements, we are able to indirectly identity the effects of electron scale turbulence by quantifying a plasma property known as "profile stiffness." The level of profile stiffness can be predicted by simulations. We have found that simulations with only ion-scale turbulence fail to match the experimental results. In contrast, simulations that include the effects of electron scale turbulence can match the experimental measurements. Alex presented his results this year at two major fusion conferences. Such simulations of electron scale turbulence are extremely computationally extensive and difficult to complete, so Professor White's group collaborates with researchers from PSFC, General Atomics, and the University of California, San Diego, who are responsible for developing the codes and running these challenging simulations.

At ASDEX Upgrade at the Max Planck Institute for Plasma Physics in Garching, Germany, Professor White and her group are installing new instruments to measure electron temperature fluctuations and correlations between density and temperature fluctuations. These instruments will vastly improve the capability to constrain models for electron heat transport because of the new, detailed measurements of ion-scale turbulence that will be possible.

Physics Research Division

The head of the Physics Research Division is Professor Miklos Porkolab. The division's focus is basic and applied plasma theory, simulations, and experiments in magnetized plasmas with an emphasis on fusion confinement devices. Students are trained for careers at universities, in industry, and at laboratories requiring a theoretical and experimental understanding of plasmas and fusion science.

Fusion Theory and Simulations

The division's basic and applied plasma theory and simulation efforts primarily support Alcator C-Mod and other tokamak experiments worldwide. The primary funding source is DOE-OFES. The head of the theory program is PSFC Assistant Director Peter Catto. Senior Research Scientist Paul Bonoli is the PI for the multi-institutional Science Discovery through Advanced Computing (SciDAC) Center for Simulations of Wave-Plasma Interactions (CSWPI), as well as for the International Collaboration on Control and Extension of ITER and Advanced Scenarios to Long Pulse in EAST and KSTAR. The radio frequency heating and current drive effort led by Dr. Bonoli has just hired Dr. Jungpyo Lee to further expand its work. PSFC Principal Research Scientists Jesus Ramos and Abhay Ram lead the group's efforts in the SciDAC Center for Extended MHD Modeling and NSTX research at PPPL, respectively. Research Scientist John Wright is involved in CSWPI and our main grant, while Research Scientist Darin Ernst is the PI for the SciDAC Center for the Study of Plasma Microturbulence. Although retired, Professor Jeffrey Freidberg (NSE) remains active. He will be teaching at New York University's Courant Institute during the fall 2015 semester. NSE is in the process of hiring a plasma theorist who will further enhance the PSFC theory effort. Some highlights of our recent progress are summarized below.

Ongoing Projects

PSFC participates in CSWPI with Dr. Bonoli. the center's lead PI. Also involved are Drs. Wright and Ram and Dr. Syun'ichi Shiraiwa from the Alcator Division. During the past year, Drs. Wright and Shiraiwa collaborated on a novel full wave solver for radio frequency heating in plasmas that combines the advantages of Fourier mode basis in the confining region of a tokamak plasma with the flexibility of a finite element approach in more complex edge geometry. As noted above, Dr. Bonoli also serves as the PI of the International Collaboration on Control and Extension of ITER and Advanced Scenarios to Long Pulse in EAST and KSTAR. Through this project, 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. In 2014, Dr. Bonoli carried out full wave lower hybrid field simulations for EAST using an electromagnetic field solver developed at the CSWPI. These are the largest simulations performed to date with this code, involving 32,256 computing cores at the National Energy Research Supercomputing Center. Dr. Wright is also a member of the Metadata, Ontology and Provenance project at MIT, the efforts of which are relevant to the data stewardship requirements of the US Congress.

In 2014–2015, at the request of the Department of Energy, Dr. Bonoli chaired a planning workshop for DOE on Integrated Simulations for Magnetic Fusion Energy Sciences, one of four planning workshops conducted by DOE to develop a 10-year fusion plan as requested by the US Congress.

Heating, Current Drive, and Nonlinear Dynamics

A theoretical model for scattering of radio frequency waves by blobs and filaments has been developed by Dr. Ram and Professor Kyriakos Hizandis (National Technical University, Athens). The results from this model have initiated two independent studies. The first is an experimental program on TORPEX (a toroidal device in Switzerland) to measure the spectra of the scattered radio frequency waves and compare them with the theory. The second is an extensive computational program in Greece to simulate the scattering process—initially to benchmark code against theory and then to extend it to experimentally relevant regimes that are beyond the scope of the theory.

Magnetohydrodynamics and Extended Magnetohydrodynamics Simulations

The collaboration of Dr. Ramos with Drs. Stephen Jardin (PPPL) and Brendan Lyons (General Atomics) on fluid and kinetic theory of weakly collisional plasmas has achieved a significant milestone, with the first simulation of the evolution of a fluid temperature equation tightly coupled to a dynamic kinetic equation for the distribution function that provides the self-consistent specification of the heat flux along the magnetic field. Such tight coupling, which involves advancing the fluid and kinetic equations simultaneously on the same fast time scale, is numerically challenging but necessary to properly simulate the rapid temperature equilibration along the magnetic field. A first-principle, dynamical simulation of this important physical effect has thus been carried out, without recourse to a phenomenologically greatly enhanced parallel thermal diffusivity.

Fusion Reactor Design

Professor Freidberg presented a very-well-received poster at the annual meeting of the American Physical Society (APS) Division of Plasma Physics with the somewhat eye-catching title “Who Will Save the Tokamak—Harry Potter, Arnold Schwarzenegger, Shaquille O'Neal, or Donald Trump?" The material has been converted into a tutorial paper ("Designing a Tokamak Fusion Reactor—Where Does Plasma Physics Fit In?") that will be published in *Physics of Plasmas.*

SciDAC Center for the Simulation of Plasma Microturbulence

Dr. Ernst has led three recent DIII-D experiments in collaboration with Drs. Keith Burrell (General Atomics), Terry Rhodes (University of California, Los Angeles), Walter Guttenfelder (PPPL), and Andris Dimits (LLNL) and the DIII-D group. Consistent with C-Mod work, they show, by using several megawatts of microwave electron heating to mimic fusion heating, that density gradient–driven turbulence associated with magnetically trapped electrons dominates the tokamak inner core as burning plasma conditions are approached. Gyrokinetic turbulence simulations closely reproduced the measured spectrum of density fluctuations, with and without strong electron heating, while matching all radial transport fluxes. Coherent trapped electron instabilities were directly observed for the first time, suggesting that fusion self-heating will degrade core confinement by exciting this type of turbulence, which can be avoided by driving off-axis current. In support of this work, Dr. Ernst received a 2014 DOE ASCR (Advanced Scientific Computing Research) Advanced Leadership Computing Challenge Award. This research was featured by APS in a press release carried by 30 news organizations.

Electromagnetic Zonal Flow Residuals

Zonal flow is sheared flow generated by turbulence. In a tokamak, it is a time-varying axisymmetric ExB drift with a fine scale radial structure and weak poloidal variation. In the electrostatic limit, important analytic checks of turbulence codes have been developed to show that the zonal flow damps to a level with a nonzero residual in a collisionless plasma due to finite orbit (or polarization) effects associated with magnetic drifts. However, these turbulence or gyrokinetic codes are typically fully electromagnetic. In work with Drs. Istvan Pusztai (Chalmers) and Felix Parra (Oxford), Dr. Catto has generalized the collisionless axisymmetric zonal flow residual calculation to allow the first electromagnetic tests of the zonal flow residual in gyrokinetic codes.

Impurity Behavior in Tokamak Pedestals

The pedestal is the region with strong density and/or temperature gradients that separates the core and edge of a tokamak. Graduate student Silvia Espinosa (NSE) and Dr. Catto are developing a theoretical description that, for the first time, explains how it is possible to generate strong poloidal variation of impurity density and temperature. Even in its present simple form, it is able to explain the experimentally observed six-fold increase in density from the low to high magnetic field side of C-Mod while also explaining the simultaneously observed temperature decrease.

Gravitationally Confined Axisymmetric 3D Rotating Magnetized Hot Plasma Equilibria

Dr. Catto and Professor Sergei Krasheninnikov (University of California, San Diego) have developed the first analytic equilibrium solutions for axisymmetric three-dimensional magnetized rotating hot plasma confined by a gravitational field. The solutions can exhibit strong equatorial plane localization of plasma density and current, resulting in disk equilibria. Recent numerical work with Dr. Istvan Pusztai indicates that a toroidal magnetic field may be necessary to find equilibria in the presence of gravity for the cases of most interest. These equilibria will be useful to set up global simulations to investigate magnetorotational stability in accretion disks examining mechanisms by which mass accretion occurs at a black hole as momentum is transported outward.

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 of Columbia University, LDX was originally inspired by magnetospheric studies and was conceived of as an alternate approach to controlled fusion. However, the focus of fusion research has narrowed 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 University'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 dipole plasma confinement.

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 can measure important phenomena in space weather such as plasma turbulence, 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 lithium gas ionizes, producing a tripling of plasma density; and (3) the density profile then relaxes to a stationary state (due to turbulent transport). The data analysis showed that, in the high-density (and high-density-gradient) state, the phase velocity of the wave spectrum reverses direction, corroborating a theoretical prediction. Details relating to this research are being analyzed, and publications are being prepared.

Plasma-Surface Interactions

New in-situ measurements continue to provide critical insights into the formation of tungsten surface nanotendrils 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 showed that He density (or pressure) in the tungsten is not the cause of the tendril growth. Further observations showed very large isolated structures of tendrils. A series of carefully designed experiments have subsequently shown that the local electric field produced by the plasma sheath and/or sample biasing is not responsible for the tendril growth. Taken together, this unique set of in situ measurements has provided critical insight into the controlling physics of nanotendril growth. PhD student Kevin Woller performed these experiments and presented the results at the Symposium on Fusion Engineering in June 2015, winning the best student paper award.

Needed depth marker techniques continue to be developed for providing in situ erosion and deposition diagnosis, with a particular focus on their use in plasma thrusters. Initial erosion measurements in magnetized-cusp plasma thrusters, in collaboration with Professor Manuel Martinez-Sanchez of Aeronautics and Astronautics, show that there is significant altering of the ceramic erosion caused by high-Z metal (tungsten) deposition. The suppression of erosion rates through this deposition is presently under study. In general, these successful results with depth markers open the door to exciting new research on plasma thrusters and fusion experiments at high temperatures. This research is led by Professor Whyte and Research Scientist Graham Wright.

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 group headed by Professor Ricardo Galvao of the Instituto de Física (University of São 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 few 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 FY2015, six new amplifiers were built to power six of the antennas, one of which was delivered to JET; also, a digital control system delivered by MIT last year was programmed and debugged. The original aim of building eight amplifiers was delayed due to budget constraints but is still part of the future plan. The new 4 kW class D solid state amplifiers (one for each antenna) have replaced the previous single 5 kW vacuum tube amplifier. In the next year, this upgraded Alfvén wave diagnostic system with six amplifiers will be commissioned at JET, and plasma measurements will begin. It is expected to be one of the key diagnostics during the next JET operation, currently planned for 2017. The grant for this project was renewed by DOE for another three years.

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

Experiments using the phase contrast imaging (PCI) Alcator C-Mod (MIT) and DIII-D (General Atomics) diagnostics are being performed under the leadership of Professor

Porkolab. These experiments, funded under a DOE diagnostic grant, measure incoherent turbulence, responsible for heat transport and critical to the overall performance of fusion-grade plasmas; propagation of externally generated RF waves, key to understanding heating of high-performance plasmas; and unstable coherent modes, responsible for degradation of energy confinement, stability, and RF heating of plasmas.

In Alcator C-Mod, a series of experiments were carried out by graduate student Paul Ennever, under the direction of Professor Porkolab, with the goal of understanding thermal transport driven by turbulence in the core tokamak plasma under the reactor-relevant conditions of roughly equal electron and ion temperatures and no external torque drive. Bulk plasma transport parameters and detailed turbulence measurements from PCI have been compared with predictions from the nonlinear gyrokinetic simulation code GYRO (developed at General Atomics). Motivated by gyrokinetic simulation code predictions, in recent experiments nitrogen was injected into the plasma to dilute the main ion species (deuterium) concentration and thereby reduce the instability that drives thermal ion transport. The nitrogen injection caused reductions in the measured thermal transport, as predicted by the codes. In experiments performed in 2015, it was observed that the measured core turbulence was also reduced by nitrogen injection in C-Mod. These plasma conditions served as a novel test of the codes' ability to predict the turbulence in plasmas with significant impurity content. The predictions matched the experimental results over a range of parameters, but discrepancies between experiment and code predictions were identified in some regimes, particularly electron thermal transport, and these issues are important to resolve in future work. A paper on this research has been accepted for publication.

Studies using PCI on the DIII-D tokamak continued with an emphasis on high-performance regimes. PCI has played an important role in the search on DIII-D for the robust, steady-state high-confinement regime referred to as I-mode. Experiments, led by postdoctoral associate Alessandro Marinoni, focused on transport analysis, PCI turbulence measurements, and gyrokinetic simulations with the GS2 code. The transient I-mode plasma achieved was found to exhibit changes in turbulence, indicating a shift to a high-confinement edge without the specific signature seen in steady-state I-modes on Alcator C-Mod and the ASDEX Upgrade. Gyrokinetic simulations suggest that both plasma flow and current in the edge are involved in reducing transport in I-mode. A paper summarizing these results has been accepted for publication, and plans for future experiments and modeling are being developed.

Significant effort has been spent during the past year on PCI diagnostic upgrades. On C-Mod, the primary detector has been upgraded to improve the frequency response and eliminate a serious deficiency with respect to the amplitudes of externally driven RF waves, a focus of the C-Mod PCI group for more than a decade. At DIII-D, the PCI group has been performing a significant upgrade, primarily directed by graduate student Evan Davis. The upgrade will combine a traditional interferometer density measurement with the PCI measurement, sharing a single laser and most of their optics. This will serve as a prototype for diagnostics that will need to optimize limited space on future fusion-grade devices; in addition, it will significantly expand PCI measurement capabilities by extending the coverage of turbulence measurements to lower wave numbers and will permit measurement of large-scale coherent instabilities through correlation with other diagnostics.

New Proposals for the Wendelstein 7-X Stellarator

Two new proposals, both involving collaborations on the recently completed Wendelstein 7-X stellarator in Germany, were prepared during this fiscal year and were successful in obtaining funding from DOE-OFES. Funding of the projects will start in FY2016. Professor Porkolab is the PI for the first project ("Phase Contrast Imaging for Wendelstein 7-X"), funded at $670,000 over three years. The second project ("Gas-Puff-Imaging for Diagnosis of Boundary and SOL Physics in W7-X") is under the direction of Dr. Jim Terry; funding is $504,000 over three years.

Spinoff Research

Engineered Geothermal Systems and Deep Nuclear Waste Storage

Development of low-cost access to deep hard rock formations would enable engineered geothermal systems for continuous climate-safe energy production and would also provide an option to remove and confine nuclear waste as far as possible from the biosphere. Under the leadership of Dr. Woskov, high-power millimeter-wave (MMW) gyrotron sources and related technologies developed for heating and control of magnetic confinement fusion plasmas are being explored to determine whether boring into deep hard rock with directed energy is economically possible. MMWs can succeed (where infrared beams from laser sources have not) in enabling directed energy penetration into hard rock formations because of fundamental physics and technology advantages. The longer wavelength MMWs are not scattered as easily by small particulate extraction plumes, and we have found that they are more efficiently absorbed by melted rock. Technologically, gyrotrons are more than twice as efficient as lasers and can be more efficiently guided at megawatt power levels over long distances. During FY2015, Dr. Woskov and Professor Herbert Einstein of the MIT Department of Civil and Environmental Engineering and Impact Technologies LLC concluded a phase 1 contract from the DOE Golden Field Office in Colorado to better develop the basis of MMW directed energy for engineered geothermal systems. Laboratory experiments on various rock types, including granite, basalt, and limestone, were carried out with a 10 kW, 28 GHz Communications & Power Industries gyrotron at MIT. It was found that the harder crystalline rocks melted more easily than the sedimentary rocks due to lower melt viscosity. With a small leak hole for melt flow, beam size holes (approximately 50-mm diameter) were made in 30-mm-thick basalt and granite (Figure 3). The basic features of the MMW directed energy penetration system, demonstrated on a small laboratory scale, included guided propagation, reflected power isolation, collinear gas flow, and collinear real-time monitoring.

Also in FY2015, the same team started a new Small Business Technology Transfer contract funded by the DOE Office of Nuclear Energy to study application of this technology to deep borehole nuclear waste storage. Sealing a small borehole with rock and steel casing melt was shown in the laboratory. A kick-off meeting was held at Sandia National Laboratory, which also is working on thermal methods for deep borehole storage of nuclear waste. Concurrently, an agreement has been reached with the Air Force Research Laboratory at Kirtland Air Force Base to allow MIT to use the 100 kW, 95 GHz gyrotron system for experiments at the High Energy Research Technology Facility. Planning meetings have been held for modifying the HERTF gyrotron system for the

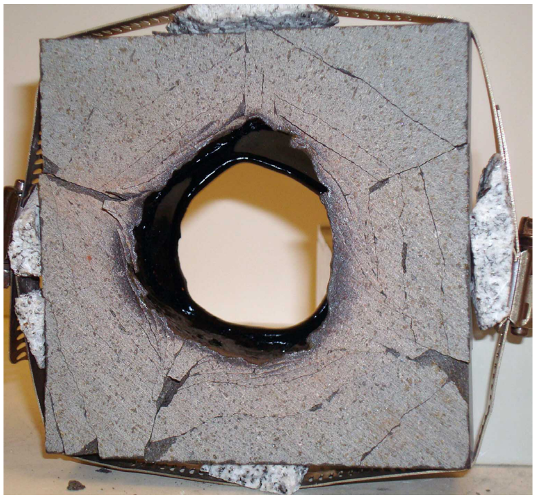

Figure 3. A 50-mm-diameter hole in basalt rock 30 mm thick made by exposure to a 4 kW, 28 GHz gyrotron beam at MIT. The steel strap around the perimeter restrains the rock from breaking apart due to thermal shock.

proposed rock experiments that will take place in FY2016. Access to this higher power gyrotron system is expected to advance the experimental studies to more significant rock melts, vaporizations, and penetrations.

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 Laboratory for Laser Energetics (LLE) and the Lawrence Livermore National Laboratory's (LLNL) 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).

This was an outstanding academic year for the division's graduate students. Three of them received PhD degrees (with thesis titles in parentheses): Michael Rosenberg ("Ion Kinetic Effects in Shock-Driven Inertial Confinement Fusion Implosions at OMEGA and the NIF"), Hans Rinderknecht ("Studies of Non-Hydrodynamic Processes in ICF Implosions on OMEGA and the National Ignition Facility"), and Alex Zylstra ("Using Fusion-Product Spectroscopy to Study Inertial Fusion Implosions, Stopping Power, and Astrophysical Nucleosynthesis at OMEGA and the NIF"). In addition to their theses, the three students published 25 first-author papers, including five in *Physical Review Letters* and one in *Nature Communications*. Dr. Rosenberg has moved on to a fellowship at LLE. Drs. Rinderknecht and Zylstra each received offers of two of the most prestigious national laboratory fellowships. Dr. Rinderknecht was offered the Truman Fellowship at Sandia National Laboratory but accepted the Lawrence Fellowship at LLNL. Dr. Zylstra was offered a Lawrence Fellowship at LLNL but accepted the Reines Fellowship at the Los Alamos National Laboratory. In addition, Dr. Zylstra was selected to give an invited talk on his research, titled "Studying In-Flight Areal-Density (ρR) Asymmetries and Shock Dynamics in Ignition-Scale NIF Implosions," at the 2014 annual meeting of the

APS Division of Plasma Physics. The three new PhDs join former division student Dr. Daniel Casey as the only four university students to use data from the important NIF research program in their theses (Figure 4). Three new physics PhD students are arriving this fall to replace the three new PhDs.

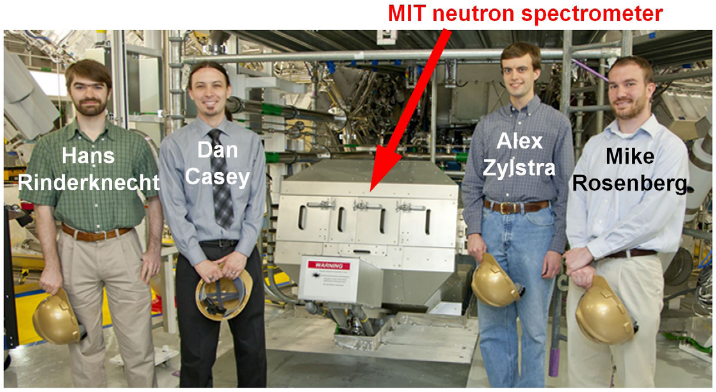

Figure 4. Four HEDP graduate students (current or former) in front of the MIT-designed neutron spectrometer at LLNL's National Ignition Facility.

The division's scientists and students made important advances in diagnostic instrumentation this year in experiments at NIF and at LLE's OMEGA laser facility. A great deal of the development and calibration of these instruments occurs at the division's unique Accelerator Laboratory for Diagnostic Development, which provides important hands-on training for PhD students and undergraduates (Figure 5). MIT has provided seven essential diagnostic instruments for NIF, including four implemented during the past year (two types of compact spectrometers for low-energy protons, a "bang-time" detector, and a burn-region imager); three others are still under development (time-resolved neutron spectrometry, a neutron temporal diagnostic, and proton radiography). MIT has developed at least 12 diagnostic instruments for the OMEGA facility, including three this year (a multi-burn-history diagnostic and two types of proton spectrometers).

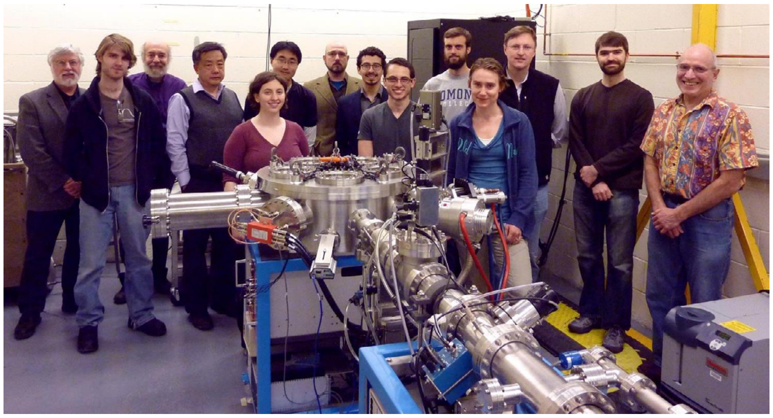

Figure 5. HEDP staff in the division's Accelerator Laboratory for Diagnostic Development.

Some of these diagnostics have been used for programmatic ICF research at NIF, where MIT is the only university playing a major role. However, other experiments at OMEGA and NIF have explored a wide range of topics this year in implosion dynamics, plasma properties, nuclear physics, laboratory astrophysics, and electromagnetic fields. Some highlights include kinetic effects in ICF plasmas, the stopping of ions in plasmas, magnetic reconnection, nuclear reactions important to stellar and big-bang nucleosynthesis, shock dynamics in ICF implosions, and laboratory modeling of the Crab Nebula jet.

MIT also continued its role in plasma physics outreach by leading the OMEGA Laser Users Group (OLUG). This group, the largest and most active in the high-energy-density physics community, now includes 428 scientists, students, academics, and researchers from 55 universities, 35 centers and national laboratories, and 21 countries on four continents. Through OLUG, MIT organized all external OMEGA researchers for the group's seventh annual workshop, which brought together scientists and students from all over the world to discuss current high-energy-density physics and ICF research and to help LLE enhance its facility and procedures for outside scientists.

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. Research on gyrotrons is aimed at increasing the efficiency of a 1.5 MW, 110 GHz gyrotron with an internal mode converter and a depressed collector. In 2014–2015, we performed the first tests of a novel internal mode converter that couples gyrotron output power directly into a corrugated waveguide. This concept was pioneered by scientists at Calabazas Creek Research a small business firm. Additional tests are planned for next year. The 1.5 MW gyrotron is also being used to study breakdown in air and other gases, including the production and investigation of arrays of breakdown filaments. We have successfully implemented two-color laser interferometry for making accurate density measurements of the breakdown plasmas on a spatial scale of less than one millimeter. Also during the past year, we demonstrated the amplification of very short pulses, down to a pulse length of 200 ps, in a gyrotron traveling wave tube amplifier that uses a photonic band gap interaction circuit. This result represents the shortest pulses amplified coherently at such a high frequency in a vacuum electron device.

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 2014–2015, we completed the first operation, at a frequency of 2.856 GHz, of a high-power backward wave oscillator with 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. Output power levels above 5 MW were obtained in microsecond pulsed operations with a 500 kV, 80 A electron beam. This is the first high-power microwave source to use a metamaterial structure. In addition, we completed testing of a 94 GHz traveling wave tube amplifier with an overmoded slow wave structure. Operating at a voltage of 30.6 kV with 250 mA of collector current, the wave tube was zero-drive stable and achieved a 21±2 dB linear device gain with 27-watt peak output power. This research should pave the way to higher 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 mode of the corrugated, metallic waveguide (HE_{11}) into higher order modes, which can cause high losses and possibly damage the transmission line. In 2014–2015, we completed a study of mode conversion at the expansion units of the transmission line and published the results. We are currently making preparations for a test of the properties of the motorized polarizers that will be used on the transmission line.

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 2014–2015, we completed testing of a special copper photonic bandgap cavity in terms of breakdown rate at 17 GHz, at gradients exceeding 90 MV/m. This is the first high-gradient, long-pulse test of an accelerator structure at a frequency above 11 GHz. Also, we successfully built a 17 GHz photonic bandgap accelerator cavity with sapphire rods and completed the first high-power microwave tests of the structure. 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 DOE-OFES Magnets Enabling Technology program.

During the past year, division efforts were focused in several research areas: application of high-temperature superconducting (HTS) materials and systems to fusion magnet systems, research on HTS magnets for electric superconducting generators, and research and development of very compact, high-field superconducting magnets for cyclotron accelerators and beam magnets 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 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.

A new multiyear project funded by the Office of Naval Research (ONR) will develop advanced concepts in superconducting generators and motors for ship propulsion systems. Studies are focused on all-superconducting machines with both magnetic field windings and armature windings made from HTS superconducting wires or tapes. Many different winding, cryogenic, and magnetic configurations have been investigated along with consideration of different types of superconducting wires and tapes.

The third research focus area has involved highly compact superconducting cyclotrons for proton radiotherapy. During the past year, an MIT-owned patent was issued that incorporates a new concept for an all-superconducting cyclotron wherein all iron is eliminated from the magnetic circuit, including the main iron poles and the iron yoke for return flux and shielding. This work has been successful in that we have received multiyear funding from the DOE Office of High Energy Physics, under its new Accelerator Stewardship Program, to develop advanced accelerator technologies for hadron radiotherapy. We are carrying out this program with ProNova Solutions Inc., a company focused on building and operating medical centers for proton beam radiotherapy.

Related research on superconducting magnets has been funded under a program sponsored by Ion Beam Applications to develop a new type of ion beam bending magnet, also for proton beam radiotherapy. This work could result in lowering the cost of delivery of this type of cancer treatment.

During the past year, we have also completed a conceptual design study of a superconducting magnetic energy storage system for use as an uninterruptible power source for critical loads such as data centers, medical facilities, and financial institutions. This program has been funded under a grant from the Walloon Regional Government of Belgium.

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

Francis Bitter Magnet Laboratory

Five principal investigators lead the research activities of the Francis Bitter Magnet Laboratory: Professors Robert Griffin and Mei Hong (Chemistry), Dr. Yukikazu Iwasa (PSFC), and Drs. Jagadeesh Moodera and Richard Temkin (Physics). The research activities of the first four 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 40th year of operation as a facility providing scientists with access to high-field NMR equipment, including two 600, one 700, two 750, three 800, and one 900 MHz instrument (Figure 6) 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. In July 2014, Professor Hong joined the Department of Chemistry, and her labs are now 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).

Figure 6. The 900 MHz NMR spectrometer system at PSFC's Francis Bitter Magnet Laboratory.

Structural Studies of the Toxic Species of Amyloid Beta in Alzheimer's Disease

The presence of amyloid plaques composed of amyloid beta (Aβ) fibrils is a hallmark of Alzheimer's disease (AD). The Aβ peptide is present as several length variants with two common alloforms consisting of 40 and 42 amino acids, denoted Aβ1-40 and Aβ1-42, respectively. While numerous reports have structurally characterized Aβ1-40 fibrils, very little is known about the structure of amyloid fibrils of Aβ1-42, which are considered the more toxic alloform involved in AD. During the past year, we have prepared isotopically 13C/15N labeled AβM01-42 fibrils in vitro from recombinant protein and examined their 13C-13C and 13C-15N magic angle spinning (MAS) NMR spectra. In contrast to several other studies of Aβ fibrils, we observed spectra with excellent resolution and a single set of chemical shifts, suggesting the presence of a single fibril morphology. We reported the initial structural characterization of AβM01-42 fibrils using 13C and 15N shift assignments of 38 of the 43 residues, including the backbone and sidechains, obtained through a series of cross polarization–based 2D and 3D 13C-13C, 13C-15N MAS NMR experiments for rigid residues along with J-based 2D through-bond correlation spectroscopy (TOBSY) experiments for dynamic residues. We found that approximately the first five residues are dynamic and most efficiently detected in a J-based TOBSY spectrum. In contrast, residues 16–42 are easily observed in cross polarization experiments and most likely form the amyloid core. Calculation of ψ and ϕ dihedral angles from chemical shift assignments indicates that four β strands are present in the fibril's secondary structure. Determining the complete atomic-level high-resolution structure of these fibrils may yield important clues to approaches to the design of drugs for treating and preventing AD.

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 N-terminus of the voltage-dependent anion channel (VDAC) is proposed to contain the mechanistically important gating helices that modulate channel opening and closing. In this study, we used MAS NMR to determine the location and structure of the N-terminus for functional channels in lipid bilayers by measuring long-range 13C-13C distances between residues in the N-terminus and other domains of the DMPC-bilayer-bound VDAC. Our structural studies show that the distance between A14 Cβ in the N-terminal helix and S193 Cβ is approximately 4–6 Å. Furthermore, VDAC phosphorylation by a mitochondrial kinase at residue S193 has been claimed to delay mitochondrial cell death by causing a conformational change that closes the channel, and a VDAC-Ser193Glu mutant has been reported to show very similar properties to phosphorylated VDAC in a cellular context. We expressed VDAC-S193E and reconstituted it into DMPC lipid bilayers. Two-dimensional 13C-13C correlation experiments showed chemical shift perturbations for residues located in the N-terminus, indicating possible structural perturbations to that region. However, electrophysiological data recorded on VDAC-S193E showed that the channel characteristics were identical to wild-type samples, indicating that phosphorylation of S193 does not directly affect channel gating. The combination of NMR and electrophysiological results allow us to discuss the validity of proposed gating models.

We also reported an MAS NMR structure of the M218-60 construct from influenza A carrying the drug resistance mutation S31N. The protein was dispersed in diphytanoyl-sn-glycero-3-phosphocholine (DiPhPC) lipid bilayers, and the spectra and an extensive set of constraints derived from them indicate that M218-60 consists of a dimer of dimers. The resulting structure sheds new light on the mechanisms of proton conduction and drug resistance. Structural constraints were obtained using a number of innovative dipole recoupling experiments that yielded well-resolved 13C-15N, 13C-13C, and 1H-15N 2D, 3D, and 4D MAS spectra, all of which showed a doubling of cross peaks for these membrane protein samples. Interhelical distances were measured unambiguously via mixed 15N/13C labeling. Several additional restraints were determined using extensively deuterated protein, MAS at $\omega r/2\pi=60$ kHz, $\omega 0H/2\pi=1000$ MHz, and 1H detection of methyl-methyl contacts via 4D spectra. A mechanistically important 15N-1H-15N distance of less than 3.5 Å was observed between His and Trp on the two different chains of the dimer. The experiments collectively yielded approximately 280 structural constraints, which led to a structure consisting of a compact tetramer composed of four transmembrane helices in which two opposing helices were displaced and rotated in the direction of the membrane normal relative to a fourfold symmetric arrangement yielding a twofold symmetric structure. Sidechain conformations of the important gating and pH sensing residues W41 and H37 were found to differ markedly from fourfold symmetry. The RMSD of the structure was 0.7 Å for backbone heavy atoms and 1.1 Å for all heavy atoms. This twofold symmetric structure is different from all of the previous structures of M2, many of which were determined in detergent and/or with shorter constructs that are not fully active. The structure has implications for the mechanism of H+ transport since the distance between His and Trp residues on different helices is found to be short. Constriction within the tetramer at residues H37 and W41 excludes passage of water, consistent with the idea that M2 conducts via H+ shuttling. The structure also exhibits twofold symmetry in the vicinity of the binding site of adamantyl inhibitors, and comparison of steric constraints with drug-bound structures may explain the mechanism of the drug resistance S31N mutation.

Dynamic Nuclear Polarization

We reported MAS DNP experiments at magnetic fields of 9.4 T, 14.1 T, and 18.8 T using the narrow line polarizing agents BDPA (1,3-bisdiphenylene-2-phenylallyl) dispersed in polystyrene and sulfonated BDPA and trityl OX063 in glassy glycerol/water matrices. The 1H DNP enhancement field profiles of the BDPA radicals exhibit a significant DNP Overhauser effect (OE) as well as a solid effect (SE) despite the fact that these samples are insulating solids. In contrast, trityl exhibits only an SE enhancement. The experimental data suggest that the appearance of the OE is due to rather strong electron-nuclear hyperfine couplings present in BDPA and SA-BDPA but absent in trityl and d21-BDPA. In addition, and in contrast to other DNP mechanisms such as the solid effect or cross effect, the data suggest that the OE in nonconducting solids scales favorably with magnetic field, increasing in magnitude from 5 T to 9.4 T, 14.1 T, and 18.8 T. Simulations using a model two-spin system consisting of an electron hyperfine coupled to a 1H reproduce the essential features of the field profiles and indicate that the OE in these samples originates from the zero and double quantum cross relaxation induced by fluctuating hyperfine interactions between the intramolecular delocalized unpaired electrons and their neighboring nuclei and that the size of these hyperfine couplings is crucial to the magnitude of the enhancements. Microwave field-dependent studies show that the OE saturates at considerably lower power levels than the solid effect in the same samples. Our results offer new insights into the mechanism of the Overhauser effect and also provide a new approach to performing DNP experiments in chemical, biophysical, and physical systems at high magnetic fields.

We also described the results of a pulsed DNP study at 0.35 T (9.7 GHz/14.7 MHz for electron/1H Larmor frequency) using a lab frame–rotating frame cross polarization experiment that employed electron spin locking fields matching the 1H nuclear Larmor frequency, the so-called NOVEL (nuclear orientation via electron spin locking) condition. We applied the method to a series of DNP samples including a single crystal of diphenyl nitroxide (DPNO) doped into benzophenone (BzP), BDPA doped into polystyrene (PS), and sulfonated BDPA (SA-BDPA) doped into glycerol/water glassy matrices. The optimal Hartman-Hahn matching condition is achieved when the nutation frequency of the electron matches the Larmor frequency of the proton, together with possible higher order matching conditions at lower efficiencies. The magnetization transfer from electron to protons occurs on a time scale of approximately 100 ns, consistent with the electron-proton couplings on the order of 1–10 MHz in these samples. In a sample of partially deuterated PS doped with BDPA, we obtained an enhancement of 323, which is a factor of approximately 3.2 higher than the protonated version of the same sample and accounts for 49% of the theoretical limit. For SA-BDPA doped in a glycerol/water glassy matrix at 80 K, the sample condition used in most applications of DNP in NMR, we also observed a significant enhancement. Our findings demonstrate that pulsed DNP via the NOVEL sequence is highly efficient and can potentially surpass continuous wave DNP mechanisms such as the solid effect and cross effect, which scale unfavorably with increasing magnetic field.

Mei Hong, Professor of Chemistry

Mei Hong moved from Iowa State University to MIT as a professor of chemistry in July 2014. Her laboratory occupies space on the second floor of FBML. Her wet chemistry laboratory, equipped with protein molecular biology and organic synthesis capabilities, became operational in October 2014. Also, a 400 MHz solid-state NMR spectrometer was installed in November and is up and running. Finally, a major dry lab space renovation, at a cost of $1 million, was completed in April 2015, and an 800 MHz solid-state NMR spectrometer came on line. The Hong group engages in solid-state NMR-based structural biology and biophysics research. The group’s current interests focus on disease-relevant membrane proteins and energy-relevant plant cell walls.

Structural and Mechanical Studies of the Influenza M2 Protein

Developing new antiviral drugs to curb seasonal and pandemic flu outbreaks is an important public health goal. The influenza M2 protein is one of a few essential proteins of the flu virus and is drug targetable. The protein forms a tetrameric proton channel during virus entry into host cells and mediates membrane scission during virus budding. Elucidating the molecular structure and dynamics of the influenza M2 protein is important for drug development as well as elucidating fundamental aspects of ion channel function and virus assembly and budding.

Our previous studies of the influenza M2 protein have elucidated where and how drugs inhibit this proton channel and how protons are transported across the lipid membrane at the molecular level. These studies largely relied on short transmembrane peptide constructs of the protein. In 2014–2015, we studied longer constructs of M2 that encompass both the transmembrane domain and the cytoplasmic domain to understand how the latter regulates proton conduction and how it causes high membrane curvature, which is necessary for membrane scission. Using ^{15}N NMR, we studied the proton-exchange equilibria of the proton-selective residue of the channel, a histidine in the transmembrane domain. We found that the proton-association constant of histidine increased in the presence of the cytoplasmic domain; in other words, protonation occurs at a higher pH relative to the short peptides. We attribute this finding to the many negatively charged residues in the cytoplasmic domain, since they can cause electrostatic repulsion among the four subunits of the tetramer to open the transmembrane pore and hence facilitate histidine protonation. This is supported by 2D correlation NMR spectra showing that the histidine conformation becomes more helical in the longer protein than in the shorter peptide. Separately, we introduced a novel NMR approach involving oriented bicelles, which are phospholipid bilayer discs containing both flat and curved domains, to characterize how the cytoplasmic domain induces membrane curvature. We showed that an amphipathic helix in the cytoplasmic domain is sufficient and necessary for generating high membrane curvature, as manifested in ^{31}P NMR spectra of the bicelles. Moreover, 2D correlation NMR experiments and relaxation time measurements indicate that the protein preferentially binds to the high-curvature region of the membrane, which mirrors the biological function of M2 to cluster at the neck of the budding virus and carry out membrane scission.

Structural Studies of Viral Fusion Proteins

Viral fusion proteins mediate the entry of enveloped viruses such as HIV and influenza into cells by undergoing large conformational changes that bend and merge the viral lipid envelope and the cell membrane. The exact mechanisms of protein conformational changes and membrane curvature induction are of both fundamental and biomedical significance. We have been studying the fusion protein of a parainfluenza virus, PIV5, that is responsible for infant respiratory diseases such as croup and bronchitis. In 2014–2015, we discovered, using ^{31}P and ^{13}C NMR and small-angle X-ray scattering, that the C-terminal transmembrane domain of the PIV5 fusion protein is capable of transforming lipid bilayers of certain compositions into cubic phases, which are characterized by negative Gaussian curvature, essential in hemifusion intermediates along the virus-cell fusion pathway. Moreover, the state of the transmembrane domain responsible for this negative Gaussian curvature is rich in the β-strand conformation rather than α-helix. These novel results revise the existing, helix-centric view of virus-cell fusion. We are now characterizing the high-resolution structure and oligomeric assembly of this β-strand conformation and studying the interaction between the C-terminal transmembrane domain and an N-terminal fusion peptide domain, both of which interact with the lipid membrane during viral fusion but through unknown mechanisms.

Plant Cell Wall Polysaccharides

Plant cell walls mainly consist of polysaccharides, including cellulose, hemicellulose, and pectins. Cell walls provide mechanical strength to plants while being capable of loosening to enable plant growth. Elucidating the plant cell wall structure at the molecular level is driven by the need to better understand fundamental aspects of plant biochemistry, as well as by the economic impetus to use plant biomass as an alternative energy source. We recently began a DOE-funded program to investigate intact, native cell walls using solid-state NMR spectroscopy. The insoluble and disordered nature of plant cell walls makes them recalcitrant to most high-resolution structural techniques, and solid-state NMR is the perfect method for investigating this class of biopolymers in their native state. In 2014–2015, we carried out the first-ever study of the wall polysaccharide structure and dynamics of *Brachypodium*, an internationally agreed-upon model organism for grasses. Using 2D 13C correlation NMR of 13C-labeled cell wall samples, we showed that cellulose forms direct molecular contact with the main matrix polysaccharide, glucuronoarabinoxylan (GAX), even though GAX contains branched sidechains. In a second study, we investigated whether lyophilization followed by rehydration of the cell wall changes the structure of polysaccharides relative to never-dried cell walls. We found that there is no detectable difference in the intermolecular contact or polysaccharide mobility in these two types of wall samples, and thus the results on rehydrated cell walls reflect the native-wall structure. This similarity implies that the network structure of cell-wall polysaccharides is chiefly maintained by the rigid cellulose microfibrils so that temporary dehydration does not cause irreversible distortion of the wall structure.

Future Project Funding

The NIH-funded influenza M2 project is funded through July 2016, and a renewal application will be submitted in July 2015. The viral fusion protein NIH grant is funded through August 2017, and a renewal application is planned for July 2016. Our plant cell wall study is funded until 2018 by an *Energy Frontier Research Center* grant from Pennsylvania State University.

Yukikazu Iwasa, Senior Research Scientist

During the period July 1, 2014, through June 30, 2015, 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

NMR Magnet Program: Phase 3A

Phase 3A of the 1.3 GHz LTS/HTS NMR magnet (1.3 G) program was completed on May 31, 2015. The next phase of the program, to be supported by the National Institute of General Medical Sciences, may begin as early as December 2015.

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. Phase 1 officially ended on August 31, 2014. A PhD thesis based on phase 1 is expected to be completed in January 2016.

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. Phase 1 will end on August 31, 2015.

Other Programs

In April 2013, MIT and Japan Superconductor Technology Inc. (JASTEC) initiated a three-year research and development project to (1) develop further, 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 had been performing most of the work at FBML. The project, sponsored by JASTEC, ended on March 31, 2015.

During 2012–2014, Dr. Iwasa oversaw one graduate student, a PhD candidate in the Department of Mechanical Engineering.

Dr. Iwasa's magnet technology group was unsuccessful in securing timely renewals of several key awards, and this has made it necessary to issue layoff notifications to three key personnel within the group. The intention is to rescind these notices as funds became available.

Jagadeesh Moodera, Senior Research Scientist

Dr. Moodera is a senior research scientist and group leader in the Department of Physics; his research labs are located in FBML. Dr. Moodera's research efforts focus on nanoscience condensed matter physics (e.g., quantum coherent transport in nanodevices, investigation of Majorana bound states, molecular spintronics), with funding from ONR, NSF, and (with Professor Patrick Lee of the Department of Physics) the John Templeton Foundation. He is part of the large NSF-funded Center for Integrated Quantum Materials program, a collaboration involving MIT, Harvard, Howard University, the Boston Museum of Science, and more.

Dr. Moodera has collaborations with various universities in the United States, Canada, the United Kingdom, Germany, and Italy, as well as with national laboratories and IBM. Currently, he focuses on two-dimensional quantum coherent transport and interface-induced magnetic and electronic effects at the molecular level, emphasizing graphene, topological insulators (TIs), and organic molecules—some of the most significant topics in physics. His group investigates nanostructures for spin transport in these novel systems in addition to searching for exotic Majorana fermions.

He continues mentoring graduate students, undergraduates, and high school students by providing research opportunities in his lab. Three visiting students from Spain, Germany, and Brazil, along with an undergraduate from Yale University, took part in his research during the past year.

Dr. Moodera's group and his collaborators published several articles in journals such as *Nature Materials*, *Science*, and *Physical Review Letters*. He was one of the editors of the *Applied Materials* special issue on topological insulators. In addition, he delivered many invited talks at universities, international conferences, and summer school sessions (e.g., in Israel, Norway, and Spain).

One of the group's notable research accomplishments involves the quantum anomalous Hall (QAH) effect. The discovery of the integer quantum Hall (QH) effect in 1980 led to the realization of a topological electronic state with dissipationless currents circulating in one direction along the edge of a two-dimensional electron layer under a strong magnetic field. With precise quantum values, QH serves as a resistance and voltage standard. While the QH effect requires a huge magnetic field to reach that state, the QAH effect shares similar physical phenomena, including dissipationless quantized Hall transport in ferromagnetic materials, but occurs in the absence of external magnetic fields. As such, the QAH effect is believed to have unique potential for applications in electronic devices with low power consumption. We have achieved the experimental observation of a perfect and robust QAH state in a complex TI system ((Bi,Sb)2Te3 compound film with V atom dopants) in zero field and unambiguously established the dissipationless edge transport. This realization of a nonvolatile QAH state in magnetic TIs is a major step toward dissipationless electronic applications without external fields.

In research on nanoscience condensed matter physics, and Dr. Moodera's group continues to make significant contributions in both fundamental and applied sciences. Using its state-of-the-art molecular beam epitaxy system, the group seeks to contribute to the understanding of the quantum state exhibited by TIs displaying properties such as fully spin polarized chiral dissipationless edge conduction 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 has installed and is operating a custom-designed extremely versatile cluster molecular beam epitaxy system for studying as yet unexplored molecules and quantum materials. In addition, a custom-designed low-temperature (280 mK) scanning tunneling microscope/atomic (conducting) force microscope system capable of operating in high magnetic fields will be installed soon. This versatile and sensitive equipment is expected to lead to new discoveries and collaborations and to 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 (Argonne National Laboratory, the Oak Ridge National Laboratory, and Brookhaven National Laboratory) and universities, including Pennsylvania State University; the University of California, Riverside; the University of Waterloo The Universities of Eindhoven Twente in the Netherlands; the University of Griefswald in Germany; the Saha Institute of Nuclear Physics in India; Scuola Normale Superiore in Italy; Centro de Fisica de Materiales in Spain; and the University of Cambridge in England. 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.

Four postdoctoral scholars, visiting scientists, graduates, 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 these students have joined the MIT undergraduate program. New postdocs and a visiting scientist are expected to participate in the coming year.

Educational Outreach

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 (Figure 7). Tours of our facilities are also available for the general public.

Figure 7. Postdoctoral Associate Hans Rinderknecht introduces a group of high school students participating in an MIT international summer education program to the experimental resources of the HEDP laboratory.

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. This year, more than 850 students visited PSFC.

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 deputy director Martin Greenwald has helped organize the center's annual Industrial

Affiliates Program open house seminars as well as special visits from alumni and 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 Representative Ted Deutch (D-FL); mayors Setti Warren (Newton, MA), Annise D. Parker (Houston, TX), Pedro E. Segarra (Hartford, CT), and Lisa A. Wong (Fitchburg, MA); Representative Dan Maffei (D-NY); Buffy Wicks and Justin Brennan from Hillary Clinton's staff; John Moreschi and David Bon from Representative Katherine Clark's (D-MA) staff; Representative Debbie Wasserman-Schultz (D-FL); Representative Seth Moulton (D-MA); and Representative Niki Tsongas (D-MA) (Figure 8). In addition, Beeuwkes hosted an event for 65 MIT alumni at which PSFC staff made presentations and performed demonstrations related to fusion research.

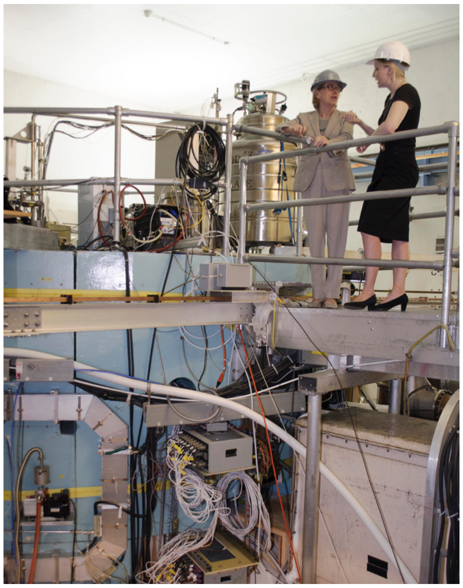

Figure 8. Professor Anne White (right) discusses the importance of fusion energy research with Massachusetts Congresswoman Niki Tsongas in the Alcator C-Mod experimental cell.

PSFC also hosted technology and industrial leaders. A group of Google executives visited, including John Woolard, vice president for energy; renewable energy technologist David Fork; and Ross Koningstein, general engineer and director emeritus. A leading industrialist from India, Sanjay Kirloskar, also visited the center, as did Professor Chris Warshaw, Sierra Club national board member. All were guided around the Alcator C-Mod control room and experimental cell to learn more about the benefits of fusion energy.

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. Paul Rivenberg continues to organize the Plasma Sciences Expo. This year 16 exhibitors representing laboratories and schools around the United States provided hands-on plasma and physics demonstrations for more than 2,000 students and teachers (Figure 9). The PSFC booth, staffed by Rivenberg, NSE administrator Valerie Censabella, and PSFC graduate students, introduced students to MIT's Alcator C-Mod fusion project with a video game that encourages participants to work cooperatively to confine a fusion plasma in a tokamak vacuum chamber.

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 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.

Anne White, the Cecil and Ida Green Career Development Associate Professor in the Department of Nuclear Science and Engineering, was granted tenure. She also received the 2014 Katherine E. Weimer Award from the American Physical Society, which recognizes outstanding achievement in plasma science research by a female physicist in the early years of her career, and the Fusion Power Associates Excellence in Fusion Engineering Award.

Martin Greenwald received the Fusion Power Associates Leadership Award, which recognizes outstanding leadership in accelerating the development of fusion.

Dennis Whyte, professor of nuclear science and engineering, was presented the International Atomic Energy Agency's 2013 Nuclear Fusion Award at the agency's Fusion Energy conference in St. Petersburg, Russia.

Donald Cook, deputy administrator for defense programs, recognized Research Scientist Maria Gatu Johnson and Principal Research Scientist Johan Frenje with National Nuclear Security Administration Defense Programs Awards of Excellence. The awards recognized their significant contribution to the Stockpile Stewardship Program in the area of supporting diagnostics. They also received an FY2014 Lawrence Livermore National Laboratory Director's Science and Technology Award as coauthors of "Measurement of the T + T Neutron Spectrum Using the National Ignition Facility."

HEDP graduate students Alex Zylstra and Hans Rinderknecht were awarded two of only three prestigious Lawrence Postdoctoral Fellowships given by Lawrence Livermore National Laboratory this year. Zylstra also received a Los Alamos National Laboratory Fredrick Reins Postdoctoral Fellowship, and Rinderknecht was awarded the Harry S. Truman Fellowship in National Security Science and Engineering from Sandia National Laboratory. In addition, Rinderknecht won a poster award at the 2015 NIF/Jupiter Laser Facility user group meeting for "Studies of Ion Thermal Decoupling and Species Separation in OMEGA Implosions: Implications for the NIF."

NSE graduate student Sergey Arsenyev, supervised by Waves and Beams Division Head Richard Temkin, received a Distinguished Performance Award for his work at the Los Alamos National Laboratory.

NSE graduate student Kevin Woller received a Best Student Paper Award from the Institute of Electrical and Electronics Engineers Nuclear and Plasma Sciences Society during the 2015 Symposium on Fusion Engineering in June.

Dr. Zach Hartwig became the first winner of the Del Favero Prize, awarded annually to a PhD graduate in nuclear science and engineering whose thesis is judged to have made the most innovative contribution to the field. He was cited for "his exceptional contributions to the conception, development, and implementation of accelerator-based in situ materials surveillance techniques for magnetic fusion devices, and for generating outstanding innovations in nuclear detection and modeling along the way."

PSFC's Lee Berkowitz and Ronald Rosati received Infinite Mile Awards from the Offices of the Provost, the Vice President for Research, and the Dean for Graduate Education.

Appointments

Dr. Daniel Brunner, Dr. John Walk, and Dr. Robert Mumgaard were appointed as postdoctoral associates in the Alcator Project Division.

In the High-Energy-Density Physics Division, Dr. Michael Rosenberg, Dr. Hans Rinderknecht, and Dr. Alex Zylstra were appointed as postdoctoral associates.

Dr. Jungpyo Lee was appointed as a research scientist in the Physics Research Division.

Karen Cote was appointed as EHS coordinator at PSFC headquarters.

Promotions

Edward Conroy was promoted to associate fiscal officer at PSFC headquarters.

Graduate Degrees

- Nuclear Science and Engineering: Chi Gao, PhD; John Walk, PhD; and Choongki Sung, PhD
- Physics: Hans Rindernecht, PhD; Alex Zylstra, PhD; Brian Munroe, PhD; Arturs Vrublevskis, PhD; Obioma Ohia, PhD; Michael Rosenberg, PhD; and Robert Mumgaard, PhD
- Electrical Engineering and Computer Science: Elizabeth Kowalski, PhD
- Engineering Systems Division: Angela Acocella, SM

Dennis Whyte
Director
Professor of Nuclear Science and Engineering