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 Division 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, the PSFC's research activities are organized into six research divisions:

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, development of novel high-temperature plasma diagnostics, and theoretical plasma physics
3. The physics of high-energy-density plasmas which includes the center's activity on inertial confinement laser-plasma fusion
4. The physics of waves and beams: gyrotron and high gradient accelerator research, beam theory development, non-neutral plasmas, and coherent wave generation
5. A broad program in fusion technology and engineering development that addresses problems in several areas: magnet systems, superconducting materials, system studies of fusion reactors, and superconducting magnets for non-fusion areas
6. Research in magnetic resonance, which includes nuclear magnetic resonance (NMR), electron paramagnetic resonance (EPR), and magnetic resonance imaging (MRI); NMR and MRI magnet development; and nanoscience condensed matter physics (quantum coherent behavior charge and spin transport)

PSFC research and development programs are principally supported by the Department of Energy's (DOE) Office of Fusion Energy Sciences and by the National Institutes of Health (NIH). There are approximately 240 personnel associated with PSFC research activities. These include 27 faculty and senior academic staff members; 45 graduate students and seven undergraduates, with participating faculty and students (in alphabetical order) from the Departments of Aeronautics and Astronautics, Chemistry, Electrical Engineering and Computer Science, Nuclear Science and Engineering, and Physics; 85 research scientists, engineers, postdoctoral associates/fellows and technical staff; 32 visiting scientists, engineers, and research affiliates; three visiting students; 20 technical support personnel; and 20 administrative and support staff.

Total PSFC funding for FY2016 (ending on September 30, 2016) is expected to be \$33.6 million, with 57% of this amount—\$19.1 million in FY2016—for magnetic fusion energy (MFE) research. Of the \$19.1 million for MFE research, 58% is associated with the Alcator C-Mod tokamak experiment, which was funded at $11.1 million in FY2016. As previously reported, DOE's funding of the Alcator C-Mod program is coming to an end after more than two decades of support. Magnetic Fusion Energy research will nevertheless continue to be the centerpiece of the PSFC's mission and research activities. DOE's Office of Fusion Energy Sciences is supporting a new five-year cooperative agreement that provides a foundation for a post-Alcator MFE program and which emphasizes collaborations with other US and international tokamak programs. At the same time, the new cooperative agreement is funded at a lower level than the previous one. As a result, we anticipate a drop of approximately $8.4 million in our DOE funding in FY2017 (from $19.1 million to about $10.7 million).

While the total funding picture for the PSFC in FY2017 is still taking shape, the aforementioned drop of $8.4 million in research funding represents about a 25% reduction in the PSFC's total research funding relative to the FY2016 level. PSFC's director, Dennis Whyte, and his senior technical managers have been working diligently over the past year to develop and attract new sources of support to offset this loss and to preserve as much as possible of the workforce knowledge and expertise of the last 25 years. We are also working closely with MIT's Office of Resource Development to give the PSFC and fusion energy research a higher profile within the Institute's broader development activities.

In October 2015, the Institute announced an ambitious five-year plan for action on climate change. Integral to the initiative is the creation of eight low-carbon energy centers across MIT focused on a number of promising energy-related technologies, one of these being fusion energy. PSFC participation in a low-carbon energy center could replace some of the funding eliminated by the end of the Alcator program. The exact timing for the start of such a center is uncertain, however, and is at least partially dependent on attracting corporate/industrial sponsors. Professor Whyte and his team are working closely with the MIT Energy Initiative team to secure funding for a fusion-focused low-carbon center.

Funding for three of the five other PSFC research divisions—High-Energy-Density Physics, Fusion Technology and Engineering, and the Francis Bitter Magnet Laboratory—declined in FY2016 relative to FY2015. Funding for High-Energy-Density Physics dropped by 4.9% in FY2016 to $2.4 million, down from $2.6 million. Fusion Technology and Engineering experienced a 30% decrease from $1.8 million in FY2015 to $1.2 million in FY2016. The Francis Bitter Magnet Laboratory declined to $3.3 million in FY2016, down $22.8% from $4.2 million. Meanwhile, funding for two of our research divisions increased. The Waves and Beams division increased by 3.7%, up from $2.4 million in FY2015 to $2.5 million in FY2016. Finally, the Physics Research division saw a 29.9% increase in support, growing from $3.9 million in FY2015 to $5.0 million in FY2016.

In January 2016, the PSFC welcomed Assistant Professor Nuno Loureiro of the Department of Nuclear Science and Engineering (NSE). Loureiro is an established world leader in the theory of magnetic reconnection and will greatly enhance the research and education of plasma theory at the PSFC. He will work within the PSFC plasma theory group.

In September 2015, Director Whyte was named head of MIT's Nuclear Science and Engineering Department. He retains his directorship of the PSFC. We believe Professor Whyte's leadership of these two separate organizations will create synergistic opportunities for greater collaboration and broader strategic initiatives.

Alcator Project and Magnetic Fusion Energy Division

First opened in 1991, The Alcator C-Mod tokamak is now in the middle of its final experimental campaign for the facility. It is an internationally renowned magnetic confinement fusion experiment, and one of three major US national tokamak facilities. Earl Marmar, senior research scientist in the Department of Physics, is principal investigator and project head.

Research operations for FY2015 (through Sep 30, 2015) totaled 12.48 weeks. We are currently in the middle of our FY2016 campaign, with a plan to complete up to 14 research weeks. Our official guidance from DOE is for a final research campaign in FY2016 of a minimum of five weeks, consistent with FY2016 appropriations. However, with carryover funds from FY2015, we will run the maximum number of weeks we can through September 30, 2016. In accordance with explicit guidance from the DOE's Office of Fusion Energy Sciences, there will be no further C-Mod operation past the end of fiscal year 2016. Following this campaign, the facility will be placed into cold shutdown.

The team is transitioning to a primarily collaborative mode of experimental research. A new five-year cooperative agreement proposal, beginning September 1, 2015, and expected to continue at least through August 31, 2020, is in place with the Department of Energy. Additional grants are currently in place to support the preservation of Alcator C-Mod data and participation in the International Tokamak Physics Activity; also to support international collaborations (primarily focused on the superconducting tokamak facilities EAST in China and KSTAR in South Korea) and to further develop the MDSplus data system software package currently in use at MIT and at more than 30 other fusion research sites around the world.

Areas of focus for the final research campaign on C-Mod are emphasizing the unique capabilities of the facility, including extensive operations at the highest available magnetic field (8 tesla on-axis), which is helping to inform pathways to develop the tokamak for fusion energy production with compact, cost-effective facilities. Research areas include core and pedestal energy, momentum and particle transport physics, plasma heating and sustainment, non-inductive current drive, disruptions and their mitigation, divertor physics and plasma-surface interactions. Particular emphasis will be placed on SOL/divertor/PMI physics, ELM-free high confinement modes, and advancing 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), while also looking beyond ITER at issues that must be resolved on the path to the development of fusion energy, including the need for a demonstration power plant.

Graduate student research and training on C-Mod continues in close cooperation with academic departments at MIT. Students who completed and successfully defended their

PhD theses in the last 12-month period include Paul Ennever from the Department of Physics and Chi Gao, Christian Haakonsen, and Robert Mumgaard from the Department of Nuclear Science and Engineering.

Three young MFE scientists at the PSFC received prestigious awards in the past 12 months. Nathan Howard, formerly a graduate student and now a research scientist in the C-Mod group, received the 2016 Department of Energy National Energy Research Scientific Computing Center (NERSC) award for high impact scientific achievement by an early career scientist. The citation reads: “For advancing our understanding of turbulent transport in fusion experiments such as ITER.” His groundbreaking gyrokinetic simulations and comparisons with Alcator C-Mod have shown that short wavelength turbulence and its cross-scale interactions play an important role in electron heat transport in many fusion plasma regimes, and offer a likely explanation for a long-standing discrepancy between predicted and experimentally observed electron heat losses in magnetically confined fusion plasmas. NSE graduate student Kevin Woller received the 2015 Best Student Paper Award at the 2015 Institute of Electrical and Electronics Engineers Nuclear and Plasma Sciences Society symposium on fusion engineering for his work on ion beam analysis of plasma facing materials, including analysis of samples exposed in the C-Mod divertor. Silvia Espinosa, another NSE graduate student working in the PSFC theory division, received the 2016 International Sherwood Fusion Theory Conference Award (for Excellent Graduate Student Presentation) for her research on a theoretical explanation for strong poloidal impurity asymmetry in tokamak pedestals, which includes detailed comparisons between her theory and the experimental results from Alcator C-Mod.

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

Professor Anne White currently leads the PSFC Magnetic Confinement Core Transport Group, coordinating collaborations with experiments in the US and abroad; 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. Over the past year, the group has been focused on studies of electron heat transport and on the relative importance of the ion scale versus the electron scale turbulence. Theory predicts that the electron scale turbulence can lead to substantial loss of electron heat in certain conditions where the long wavelength turbulence is strongly suppressed by background sheared plasma flows. However, the role of the electron-scale turbulence in cases where the ion-scale turbulence is not suppressed remains an open question. The group is expanding research to include diagnostic development that will enable new particle and momentum transport experiments, as well as investigations of “non-diffusive” transport in fusion plasmas. In addition, Professor White supervises several Undergraduate Research Opportunity Program projects involving studies of both core and edge turbulence on Alcator C-Mod and the development of small, table-top plasma devices such as “fusors”—electrostatic inertial confinement devices—for aid in classroom teaching at MIT.

Professor White's group is engaged in experimental research at four major tokamaks (Alcator C-Mod, ASDEX Upgrade, DIII-D, and NSTX-U). She is also involved in collaborations at the new stellarator in Germany, helping supervise a student on a boundary physics project led by James Terry, a scientist at the PSFC.

At the NSTX-U tokamak at Princeton Plasma Physics Laboratory (PPPL) Prof. White's graduate student Juan Ruiz Ruiz (NSE) is using a high-k scattering diagnostic to measure the 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 gradient, which is consistent with predictions for the electron scale turbulence. Juan presented his results this year at major fusion conferences, including the American Physical Society Division of Plasma Physics Meeting, and the US-EU Transport Task Force (US-EU TTF), where he gave a talk on his research from NSTX. Juan published this work in *Physics of Plasmas* in January 2016.

Also at NSTX-U, Professor White is working closely with PSFC scientist John Rice and student Norman Cao (NSE) to develop a new imaging x-ray crystal spectrometer that will allow new measurements of the plasma ion temperature profile and plasma rotation profile. These measurements are critical for advanced validation studies in new regimes of interest at NSTX-U.

At C-Mod, Professor White's graduate student Alexander Creely (NSE) has been measuring propagation of electron temperature "heat pulses." These allow for perturbative heat transport studies much like periodically heating and cooling the end of a metal rod allows for the measurement of the metal's thermal diffusivity. Here the tracking of heat pulses allows for measurements of the plasma thermal diffusivity. Using the heat pulse propagation measurements, we are able to indirectly identify the effects of the electron scale turbulence by quantifying a plasma property known as profile stiffness. The level of profile stiffness can be predicted by simulations, and simulations with only ion-scale turbulence fail to match the experimental results. In contrast, simulations that include the effects of the electron scale turbulence can match the experimental measurements. Alex presented his results this year at two major fusion conferences.
He has been selected to give an invited talk at the American Physical Society Division of Plasma Physics Meeting in November 2016 on results from core transport model validation and stiffness in high performance I-mode plasmas at C-Mod.

At the Max Planck Institute for Plasma Physics in Garching, Germany, Professor White continues to collaborate with her group (including her postdoc Simon Freethy and Alex Creely). The group is installing new instruments at the ASDEX tokamak for measurements of 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 detailed ion-scale turbulence measurements that will be possible. A notable publication of Simon's diagnostic development and transport physics work will appear in *Review of Scientific Instruments*.

At the DIII-D tokamak, Professor White's graduate student Pablo Rodriguez Fernandez is collaborating with General Atomics scientist Craig Petty on understanding propagation of "heat pulses" stimulated using Electron Cyclotron Heating or ECH. In contrast to steady state transport experiments, perturbative transport experiments tend to yield results that cannot be easily understood in terms of standard gradient-driven plasma turbulence models. To augment the DIII-D collaboration, Pablo is also working with PSFC scientist Nathan Howard to develop a new Laser Blow Off system for DIII-D.

Professor White is heavily engaged with the international fusion community via service and committee work. She is a member of the executive committees for the American Physical Society Division of Plasma Physics and the US-EU Transport Task Force, and is chair of the local organizing committee of the International Sherwood Fusion Theory Conference. Professor White also serves on the editorial board of the European journal *Plasma Physics and Controlled Fusion*, and serves as guest editor for two special issues of that journal.

The publication of a conceptual design for a pilot fusion power plant that is "affordable, robust, and compact" garnered significant worldwide interest. The design features a highly compact and modular fusion device design enabled by new high-temperature, high–magnetic field superconductors.

Physics Reseach Division

The head of the Physics Research Division is Professor Miklos Porkolab. The division focuses on 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 theoretical and experimental understanding of plasmas and fusion science.

Fusion Theory and Simulations

The Physics Research Division's efforts support Alcator C-Mod and other tokamak experiments worldwide. Funding is predominately from DOE's Office of Fusion Energy Sciences. The head of the theory program is Peter Catto. Senior Research Scientist Paul Bonoli is the lead Principal Investigator (PI) for the multi-institutional Science Discovery through Advanced Computing (SciDAC) Center for Simulations of Wave-Plasma Interactions (CSWPI) and PSFC PI for the International Collaboration on Scenario Control and Extension for ITER and Advanced Scenarios to Long Pulse in EAST and KSTAR. PSFC principal research scientists Jesus Ramos and Abhay Ram lead the group's efforts in the SciDAC Center for Extended magnetohydrodynamics (MHD) Modeling (CEMM) and NSTX-U research at Princeton Plasma Physics Laboratory, respectively. Research Scientists John Wright and Jungpyo Lee are involved in CSWPI and our main grant also partially supports Research Scientist Darin Ernst, who is the PSFC PI for the SciDAC Center for the Study of Plasma Microturbulence. In January the Department of Nuclear Science and Engineering hired Nuno Loureiro. Like retired professor Jeffrey Freidberg, Loureiro is a plasma theorist who further enhances the PSFC theory effort.

Professor Loureiro joined MIT in January 2016. His research expertise is in the theory and computation of nonlinear plasma dynamics, with applications to laboratory, space, and astrophysical plasmas. One of his leading interests is magnetic reconnection—the phenomenon that empowers solar flares, magnetospheric sub-storms, and several instabilities in magnetically confined fusion devices. Professor Loureiro's recent work on this topic focuses on the problem of reconnection onset and the theoretical interpretation of the data from a novel reconnection experiment hosted at Imperial College London.

Professor Loureiro has initiated a project to understand the behavior of energetic particles in high magnetic field fusion devices. He continues his development of the massively parallel computer code *Viriato*, designed to investigate turbulence in weakly collisional, strongly magnetized plasmas.

Parallel Computing Cluster

Thanks to the efforts of Paul Bonoli (and in response to a supplementary proposal developed by Darin Ernst, John Wright, Ted Baker, and Jungpyo Lee of the PSFC Theory Group), the US Department of Energy awarded $600,000 of supplemental funding for a state-of-the-art computing cluster to replace the 600 core Loki Computing cluster that has been in operation since 2007. This new cluster will allow the PSFC to continue its leadership role in computational plasma physics. The new funds helped us add approximately 90 dual 12-core 2.5 GHz Xeon E5-2680v3 nodes, totaling 2160 cores, providing a total of 51M NERSC Hopper-equivalent hours per year. The hardware purchased will become part of an innovative shared cluster experiment at MIT, which is co-located in the Massachusetts Green High-Performance Computing Center facility in Holyoke, Massachusetts.

Center for Simulation of Wave-Plasma Interactions

The PSFC participates in the Center for Simulations of Wave-Plasma Interactions with Paul Bonoli. Also involved are John Wright, Jungpyo Lee, Abhay Ram, and Shunichi Shiraiwa from the Alcator Division. During the past year, Wright and Shiraiwa produced the first ever simulations of ion cyclotron resonance heating that combine accurate core wave physics with a detailed description of the complicated edge geometry of a fusion device. These simulations were carried out with a novel full-wave solver 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 the edge.

This year, Bonoli, Wright, Lee, and Shiraiwa collaborated with C. Yang and B. Ding of the Institute for Physical Sciences in Hefei to carry out extensive ray tracing, full-wave, Fokker-Planck simulations of lower hybrid current drive in the EAST tokamak in Hefei. To facilitate these simulations Lee succeeded in achieving a factor of six speed-up in the full-wave solver at large scale, which has now made it practical to iterate the solver with a Fokker-Planck calculation.

Wright is also a member of the Metadata, Ontology and Provenance (MPO) project at MIT. The MPO project focuses on recording the structure of scientific workflows and connecting that provenance along with other metadata to the inputs and outputs of these workflows. The efforts of MPO are also relevant to the requirements of data stewardship from the US Congress. The MPO research contract ended this spring, but a new proposal to the National Science Foundation may continue aspects of the MPO project.

In AY2016, Bonoli also continued his duties chairing a planning workshop for the Department of Energy on integrated simulations for magnetic fusion energy sciences—one of four workshops conducted to develop a ten-year plan for fusion as requested by the US Congress.

Heating, Current Drive, and Nonlinear Dynamics

Theoretical, computational, and experimental studies on the scattering of radio frequency waves by fluctuations in fusion plasmas have become a multi-institutional effort since the development of the pioneering theoretical model by Ram and Professor Kyriakos Hizanidis (National Technical University, Athens). Computational codes within the framework of COMSOL have been benchmarked against the theory leading to confidence in the coding. These codes are being used to study the scattering of waves in experimentally relevant regimes beyond the scope of theory. Experimental observations on DIII-D (General Atomics, San Diego) are being examined carefully to quantify the effect of scattering on the power deposition profile. In Lausanne, Switzerland, a comprehensive effort on plasma devices TORPEX and TCV is under way to directly measure the effect of fluctuations on radio frequency waves and compare the results to theory and computations.

Magnetohydrodynamics and Extended Magnetohydrodynamics Simulations

Jesus Ramos leads the group's effort in CEMM. During a two-month leave from MIT, he had a visiting professor appointment as Santander Bank Chair of Excellence at Universidad Carlos III de Madrid.

Lee and Freidberg investigated the maximally achievable elongation in a tokamak against a vertical instability due to the MHD resistive wall mode in collaboration with Martin Greenwald at the PSFC and Professor Antoine Cerfon at New York University. New analytical and numerical methods were developed to compute the MHD instability efficiently and they were used to find a general scaling of the maximum elongation for many plasma parameters. This study was selected as a featured article in the *Journal of Plasma Physics* 2015 and some progress will be reported at the 2016 International Atomic Energy Agency's fusion energy conference.

At the 2016 meeting of the International Conference on Plasma Science, Freidberg (in collaboration with Antoine Cerfon of the Courant Institute) presented a paper titled "A Tokamak Pilot Plant at Walmart Prices," which demonstrated how the recent development of high-field superconductors can lead to a much more compact, and hence less expensive, fusion pilot plant reactor.

Center for the Simulation of Plasma Microturbulence

The physics and scaling of the nonlinear threshold must be understood to predict fusion performance. Nonlinear gyrokinetic simulations done by Darin Ernst show the nonlinear critical density gradient for trapped-electron mode turbulence increases strongly with collisionality and with the tilt of magnetic field lines. A first-principles predator-prey model was developed which reproduces the collisionality variation of both the critical density gradient and the period between bursts of flux. The model also applies to ion temperature gradient driven turbulence and does not rely on fitted coefficients. It predicts other key parameter variations, including a strong isotope effect.

Ernst continued analysis of his DIII-D National Fusion Facility experiment to measure the stiffness of electron temperature profiles in quiescent H-Mode plasmas. Ernst's work on the direct observation of discrete trapped electron modes in DIII-D quiescent H-Mode experiments with strong electron heating (described in last year's report) was featured in invited papers at the 2015 American Physical Society Division of Plasma Physics (APS DPP) meeting and at the upcoming 2016 EU-US TTF meeting in Switzerland.

Impurity Behavior in Tokamak Pedestals

For optimized operation, a narrow pedestal region with strong radial density and/or temperature gradients separates the core and edge of tokamak plasmas. Measurements in Alcator C-Mod often find strong poloidal variation in the impurity density, with significant poloidal variation of the radial electric field and impurity temperature. Graduate student Silvia Espinosa (NSE) and Peter Catto are developing a more general pedestal model by retaining impurity diamagnetic effects and the friction of impurities with background ions. These features allow stronger radial and poloidal variation in the impurity density and radial electric field. The extensions considered explain the impurity density and temperature, and electric field variations in C-Mod.

Gravitatitionally Confined Rotating Magnetized Hot Plasma Stability

Catto and Professors Istvan Pusztai (Chalmers University of Technology, Sweden) and Sergei Krasheninnikov (University of California, San Diego) developed the first analytic equilibrium solutions for axisymmetric, magnetized, rotating, gravitationally confined hot plasma. For Keplerian motion, the solutions can exhibit strong equatorial plane localization of the plasma density, resulting in disk equilibria. These equilibria were used by Catto and Krasheninnikov to investigate the magneto-rotational stability of accretion disks, where a black hole accretes mass as momentum is transported outward. The stability investigation highlights the important roles of density variation, compressibility, and departure from strict Keplerian motion.

Electromagnetic Zonal Flow Residuals

Sheared flow generated by and controlling turbulence is referred to as zonal flow. In the electrostatic limit checks of tokamak turbulence, codes show that the zonal flow damps to a level having a non-zero 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. It is now clear that for electromagnetic tests, poloidal variation must be retained. Work by Catto and Pusztai with Professor Felix Parra Diaz (University of Oxford) is attempting to generalize the zonal flow residual calculation to allow code tests for which the poloidal dependence of the perturbed perpendicular and parallel magnetic field responses is retained.

The Levitated Dipole Experiment

The Levitated Dipole Experiment (LDX) at MIT, in combination with the Collisionless Terrella Experiment (CTX) at Columbia University, forms a joint collaborative project with Columbia University. LDX is a unique superconducting experiment located in NW21 at MIT that explores the confinement of plasmas in a "laboratory magnetosphere". Headed by 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 for controlled fusion. As the focus of fusion research has narrowed in favor of projects that directly support the international ITER effort, LDX obtained funding as a basic plasma physics research facility through July 2015 by the National Science Foundation (NSF) and DOE's Office of Fusion Energy Sciences to jointly develop basic plasma physics and to test models of dipole plasma confinement. Since August 2015 LDX has had a no-cost extension which was recently extended through July 2017 and which has allowed data analysis to continue.

Experiments were performed on the superconducting LDX facility at MIT and on the smaller CTX facility at Columbia. LDX and CTX explored the behavior of high-temperature ionized gas (plasma), trapped by strong magnets resembling the magnetic field of the Earth. The magnetic fields were seen to confine plasma at very high pressure and with intense energetic electron belts similar to Earth's radiation belts. With plasma diagnostics spanning from global to small spatial scales and user-controlled experiments, these devices can measure important phenomena seen in space weather, such as plasma turbulence, fast particle excitation, and rapid electromagnetic events associated with magnetic storms.

The most recent experiments included 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 cause the pellets to explode. The following three subsequent phases have been 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 subsequently relaxes to a stationary state as the net radial plasma flow is observed to reverse direction (due to turbulent transport as previously reported). The data analysis shows that in the high-density (and high-density-gradient) state, the phase velocity of the wave spectrum reverses direction, corroborating a theoretical prediction.

Plasma-Surface Interactions

New 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 and fusion devices. Graham Wright, Research Scientist, and Dennis Whyte lead this research. Research examines novel combinations of implanted low-Z materials that can be used to non-destructively obtain erosion rates using combinations (or ratios) of nuclear reactions of high-energy protons and deuterons with the implanted isotopes. The use of fluorine implants appears particularly promising.

Significant progress has been made in understanding the development of tungsten nano-tendrils which self-form under helium plasma bombardment at high surface temperatures. Through a comprehensive set of exquisite plasma-surface measurements, PhD student Kevin Woller has definitively shown that these are caused by ad-atom migration at the surface and that the tendrils are a form of surface instability caused the ad-atom migration. In some conditions spectacular nano-tendril "columns" grow so large that they can be seen with the naked eye. This result is important in understanding the growth of these structures, which could have significant implications for nano-engineering of refractor metals. Journal articles for *Journal of Nuclear Materials* and *Nature* have been submitted or are in preparation.

Collaboration on Alfvén Wave Propagation and Instabilities

Professor Porkolab leads this project from MIT, with significant participation by 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 the Plasma Science and Fusion Center, 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. 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 which may make Alfvén waves unstable. DOE renewed the grant for this project for another three years. Consequently, a new post-doc was hired in 2016, who started working on site at JET since April 1, 2016. His name is Valentin Aslanyan and he is a recent PhD from the University of York, England.

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

Experiments using the Phase Contrast Imaging (PCI) diagnostics on the Alcator C-Mod tokamak at MIT and the DIII-D tokamak at General Atomics in San Diego are being performed under the leadership of Professor Porkolab and are funded under a DOE diagnostic grant. The experiments 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 the 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 were compared to 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 and 2016, it was observed that the measured core turbulence was also reduced by nitrogen injection in C-Mod. These plasma conditions also 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 in electron thermal transport (presently under further investigation). In February 2016, Ennever successfully defended his PhD thesis in the Physics Department and continued on as a postdoctoral researcher for the remaining operation of C-Mod. He published a paper on the physics of plasmas and a second paper is under review. He also gave an invited talk at the 2015 November APS DPP meeting in Savannah, Georgia on his thesis research work.

Studies using PCI on the DIII-D tokamak continued with an emphasis on high-performance regimes. The 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 tokamak in Garching, Germany. 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 published this fiscal year. Plans for future experiments and modeling are being developed. This past year additional results were obtained in trying to understand electron transport during Electron Cyclotron Heating (ECH) of ITER Baseline (BS) experimentation on DIII-D. It was found by PCI diagnostic that high-frequency turbulence increased when shutting off ECH and its impact on the well-known density pump-out during ECH was studied. Results of this work will be presented by Professor Porkolab at the International Atomic Energy Agency meeting in October 2016 in Kyoto, Japan. Finally, Chris Rost continued his work of understanding turbulent transport in the QH mode of operation when large amplitude ELMS are not present, but short wavelength turbulence is effective in controlling transport.

Significant effort has been spent during the past year on PCI diagnostic upgrades. At DIII-D, the PCI group performed an 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 be optimized for limited space on future fusion-grade devices, and will also significantly expand the measurement capabilities of PCI by extending the coverage of turbulence measurements to lower wave numbers while also permitting measurement of large-scale coherent instabilities by correlating with other diagnostics.

Detection of Helicon Waves and Parametric Decay Instabilities in DIII-D

A new proposal has been submitted to DIII-D for detecting helicon waves and related parametric instabilities in DIII-D. The proposal was part of the DIII-D National Program call for new initiatives. The proposal was selected for funding for a three-year period starting in August 2016. The total funding is for $840,000. As a result, Alessandro Marinoni was hired as permanent PSFC researcher and will be the key person carrying out this project under the direction of Professor Porkolab. Marinoni will reside on site at DIII-D in San Diego.

Phase Contrast Imaging for Wendelstein 7-X Stellarator

Funding of this project commenced in FY2016. Initial design work was carried out by PSFC staff scientist Eric Edlund. The principal investigator for the project is Professor Porkolab, with funding of $780,000 over three years. Excellent progress was made in the initial conceptual design, which was favorably reviewed by the W7-X engineering staff in Greifswald, Germany. It is anticipated that the diagnostic will be available for initial physics operations in summer of 2017. The project enjoys strong collaboration with W7-X scientist Olaf Grulke along with a German graduate student on site. Edlund expects to spend substantial time in Germany next year during the assembly and initial operation phase.

Gas-Puff Imaging for Diagnosis of Boundary and SOL Physics in Wendelstein 7-X

This project is under the direction of Jim Terry, with funding of $590,000 over a three-year period. The aim of the project is to provide a final design for a diagnostic system to measure turbulence and instabilities in plasma boundary and divertor regions, a so-called Gas-Puff Imaging diagnostic. Additionally, the project will provide design, installation, and operation of a camera-based system for ultra-fast imaging on W7-X during its 2017 experimental campaign. It is another example of the strong US–German collaboration effort on stellarator research. The work is being performed by the Jim Terry and PSFC research scientist S.G. Baek. In September, the project will also support an incoming NSE graduate student, Sean Ballinger, who has had experience with the ultra-fast camera as a summer student in 2015. Olaf Grulke is the project's W7-X scientific contact.

Engineered Geothermal Systems and Deep Nuclear Waste Storage

Low-cost access to deep basement rock formations would enable engineered geothermal systems for continuous climate-friendly energy production and would also provide an option for deep borehole nuclear waste storage. Under the leadership of Paul 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 and sealing holes with directed energy is technologically and economically feasible. MMWs can succeed (where infrared beams from laser sources have not) to enable full-bore directed energy penetration into hard rock formations due to technology advantages. The longer wavelength MMWs are not scattered as easily by small particulate extraction plumes and appear to be 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 FY2016, Woskov along with Professor Herbert Einstein (of MIT's Department of Civil and Environmental Engineering and Impact Technologies LLC) worked on a Small Business Technology Transfer contract, funded by DOE's Office of Nuclear Energy, to research application of this technology to deep borehole nuclear waste storage. The work is primarily focused on sealing holes in rock with melted rock. It was found that basalt melt flows more easily than granite melt. Holes in basalt and granite were sealed with basalt melt. Collaboration also continued with the Air Force Research Laboratory at Kirtland Air Force Base to use their 100 kW, 95 GHz gyrotron system for experiments at the High Energy Research Technology Facility (HERTF). Several onsite visits and planning meetings have been held to modify the HERTF gyrotron system for the proposed rock experiments that will take place toward the end of FY2016. Access to this higher power gyrotron system is expected to advance the experimental studies to more significant rock melts, vaporizations, and penetrations than was possible with the 10 kW MIT laboratory system.

High-Energy-Density Physics Division

The High-Energy-Density Physics (HEDP) Division, led by 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), the Lawrence Livermore National Laboratory's National Ignition Facility (NIF), and Sandia National Laboratory's Z machine. The Division designs and implements experiments and performs theoretical calculations to study and explore the non-linear dynamics and properties of plasmas in inertial fusion, in astrophysics, and under extreme conditions of density (~1000 g/cc, or 50 times the density of gold), pressure (~1000 billion atmospheres, or 5 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).

AY2016 was an outstanding academic year for the division's PhD students. Three recent students, Michael Rosenberg, Hans Rinderknecht, and Alex Zylstra, graduated in 2014 and 2015 and are working at the University of Rochester's Laboratory for Laser Energetics, the Lawrence Livermore National Laboratory, and the Los Alamos National Laboratory. Rosenberg was recently awarded the American Physical Society's 2016 Rosenbluth Outstanding Doctoral Thesis Award for his 2014 PhD thesis. During the past academic year, fifth-year student Hong Sio developed an important new diagnostic instrument for simultaneously measuring the time history of multiple nuclear reactions and of x-ray emissions in different energy bands during ICF experiments; second-year student Brandon Lahmann developed instrumentation for measuring the spectra of low-energy protons and neutrons from reactions in ICF plasmas; first-year students Neel Kabadi, Graeme Sutcliffe, and Christopher Wink have been developing other new nuclear diagnostics; and new PhD student Raspberry Simpson and recent postdoctoral researcher Cody Parker will join the division during the next two months.

The division's scientists have played major roles in a number of MIT experiments at national laboratories. Maria Gatu Johnson recently finished a series of experiments at the NIF (as part of the NIF's Discovery Science program) on stellar and Big-Bang nucleosynthesis (the formation of new nuclei through reactions of existing nuclei in stars and in the early evolution of the universe). Division scientists have also assumed leadership roles in national research programs. Johan Frenje is currently leading a national group of scientists studying the physics of plasmas during ICF fuel capsule implosions near the time of "stagnation," when the fuel approaches maximum compression. Understanding the physics is crucial for reaching "ignition" in the fuel and releasing the maximum fusion energy.

Important work done by the division's PhD students includes the impact of kinetic and multi-ion-species fluid processes on ICF plasmas. As a practical matter, almost all computer simulations used to model ICF physics use computer programs that assume pure hydrodynamic behavior for a plasma made up of only a single "average" type of ion. In actuality, most ICF plasmas consist of at least two kinds of ion (e.g., deuterium nuclei and tritium nuclei) and our experiments show that this hydrodynamic assumption is often inaccurate. Other research this past year includes the slowing down of ions traveling through plasmas; the nature of self-generated electric and magnetic fields in ICF experiments and in astrophysical shocks and jets (as modeled in scaled-laboratory experiments); and the behavior of nuclear reactions that are important for nucleosynthesis in astrophysics (the formation of different nuclei through reactions in the Big Bang and in stars). This work has resulted in 13 publications (nine with students as first authors) and several conference presentations (including 11 invited talks). Over the last ten years, MIT has produced the first four PhDs who have used NIF data as essential parts of their thesis work. In addition, the MIT team has supplied seven critical diagnostics to the NIF itself. The division's PhD students, past and present, developed some of these diagnostics and continue to use them to do essential science for their theses and for the field.

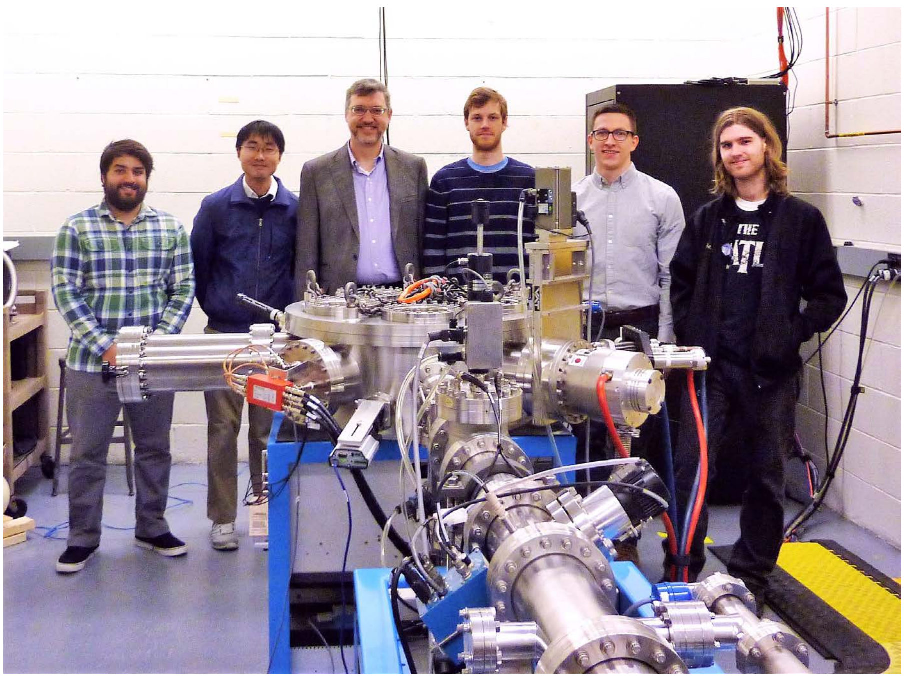

Figure 1: National Ignition Facility Director Mark Herrmann (3rd from left) and (left to right) PSFC graduate students Neel Kabadi, Hong Sio, Graeme Sutcliffe, Christopher Wink, and Brandon Lahmann with target chamber at the HEDP Division's accelerator facility for diagnostic development.

This year the High-Energy-Density Physics Division continued its role in plasma physics outreach by leading the OMEGA Lasers Users Group (OLUG), which is the largest and most active users group in the HEDP community and 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 eighth annual OLUG workshop, which brought together scientists and students from around the globe to discuss current HEDP and ICF research and to help LLE enhance its facility and procedures for outside scientists. After founding OLUG in 2009 and organizing and running it for eight years, Richard Petrasso retired in April and handed responsibility over to Roberto Mancini, professor of physics at the University of Nevada in Reno.

Waves and Beams Division

The Waves and Beams Division, headed by 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. During 2015–2016, we continued our collaboration with a small business, Calabazas Creek Research, on tests of a novel internal mode converter of a gyrotron that couples the output power directly into a corrugated waveguide. We also tested at low microwave power levels the transmission efficiency of a microwave window made of CVD diamond in a Brewster angle configuration prior to high power testing at General Atomics. The 1.5 MW gyrotron is being used to study breakdown in air and other gases, including the production and investigation of arrays of breakdown filaments. We have successfully implemented laser interferometry for making accurate density measurements of the breakdown plasmas on a spatial scale of less than one millimeter. Related experiments on vacuum breakdown are being developed in collaboration with the Stanford Linear Accelerator Center.

The division is also building high-power vacuum microwave devices that are based on slow-wave structures, including traveling wave tubes, backward wave oscillators, and klystrons, at frequencies reaching from the microwave to the THz region. These devices use electromagnetic waves with phase velocity slower than the speed of light (in contrast to fast-wave gyrotron sources). In 2015–2016, we obtained over 5 MW of output power at 2.4 GHz in a high-power backward wave oscillator that utilizes a metamaterial interaction structure. A metamaterial structure consists of a periodic array of sub-wavelength components, such as split rings, which yield changes to the permittivity and permeability of the medium. This is the first high-power microwave source to use a metamaterial structure. Surprisingly, the output power was not in the expected reverse Cherenkov mode but in a cyclotron-Cherenkov mode. In 2015–2016, we initiated a project for an oversized klystron at 94 GHz as part of a DARPA (Defense Advanced Research Projects Agency) program to innovate high-frequency microwave devices, extending to the terahertz frequency region.

The division is also continuing research on low-loss microwave (170 GHz) transmission lines in collaboration with the US ITER Project headquartered at 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 2015–2016, we tested a pair of motorized polarizers that will be used on the ITER transmission line and compared the results with theory.

Research on high-gradient accelerators is focused on high-frequency linear electron 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 2015–2016, we completed testing of a hybrid metal and dielectric photonic bandgap cavity for breakdown rate at 17 GHz, at gradients up to 19 MV/m. This is the first high-gradient, long-pulse test of a dielectric photonic bandgap accelerator structure. Information on breakdown rate is critical to planning future high-energy accelerators. We have also completed a successful collaboration with Los Alamos National Laboratory and Niowave on the design and test of a superconducting accelerator structure with a photonic bandgap cell for damping high-order modes.

Fusion Technology and Engineering Division

The Fusion Technology and Engineering Division, headed by 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 collaborations, wherein the PSFC provides leadership through the DOE Office of Fusion Energy Sciences Magnets Enabling Technology program.

During the past year, division efforts were focused in several research areas including the application of high temperature superconducting (HTS) materials and systems to fusion magnet systems, research on HTS magnets for all 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. Our efforts are now being directed at a very high field, highly compact tokamak called ARC, which would be capable of producing several hundred megawatts of electrical power delivered to the grid. Our laboratory scale research and development has been focused on staged development of high-current conductors using a rare-earth barium copper oxide (REBCO) HTS superconductor. A several-meter-long conductor sample is being produced to be tested this coming fall under relevant operating conditions at a new test facility beginning operation at the National Institute for Fusion Studies in Japan.

In January of this year, Nuclear Science and Engineering graduate student Franco Mangiarotti completed his PhD. His thesis 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. He has joined our staff as a postdoctoral research associate where he is playing an important role in organizing and carrying out the initial design of a compact tokamak based on the results being developed from our experimental program.

A second year of research was performed under a grant from the Office of Naval Research (ONR) for the development of advanced concepts in superconducting generators and motors for ship propulsion systems. Studies are focused on all-superconducting machines with both the magnetic field windings and the armature windings made from HTS superconducting wires or tapes. This year, studies were focused on evaluating AC (alternating current) losses in the superconducting windings and the development of different concepts for removing this dissipated power from the cryogenic environment.

A third area of research focuses on highly compact superconducting cyclotrons for proton radiotherapy. Work continued under the second of a three-year program funded by the DOE Office of High Energy Physics, under the 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 (PBRT). The focus of the program is to perform a conceptual design for an all-superconducting cyclotron where all iron is eliminated from the magnetic circuit, including the main iron poles and the iron yoke for return flux and shielding. Not only will such a system be much more compact and lightweight than existing systems, it could also be capable of producing a variable energy proton beam. This would have many advantages over existing systems.

We also continued to develop several new concepts for lightweight superconducting bending magnets to be used on PBRT rotating gantries. This work could result in lowering the cost of delivery of this type of cancer treatment. One of the projects is funded by Ion Beam Applications, a Belgian company. A second project is funded as part of an NIH Small Business Innovation Research program to Superconducting Systems Inc., a local company. This project is based on developing a concept for a toroidal bending magnet, also for a PBRT gantry. MIT received a patent for this technology last year.

Francis Bitter Magnet Laboratory Division

Five Principal Investigators lead the research activities of the Francis Bitter Magnet Laboratory (FBML) division of the PSFC. They are Professors Robert Griffin and Mei Hong (Chemistry), Yukikazu Iwasa (PSFC), and Jagadeesh Moodera and Richard Temkin (Physics). Research activities of the first four investigators are discussed below. The research activities of Richard Temkin, who is associate director of the PSFC, are described in the Waves and Beams Division section above.

Robert G. Griffin (Chemistry)

Research in the Griffin Group covers four different areas: (1) structure determination of amyloid fibrils; (2) structure and mechanism of membrane protein function; (3) development of high frequency dynamic nuclear polarization and electron paramagnetic resonance; and (4) development of new NMR methods for measurement of distance and torsion angles via dipolar recoupling. We discuss three of these here.

Amyloid Peptide and Protein Structure

Protein misfolding and aggregation, and the subsequent formation of amyloid fibrils is established as part of the pathology of over 40 human diseases, including Parkinson's disease, dialysis related amyloidosis (DRA), and Alzheimer's Disease (AD). Of these, AD is the most devastating of the neurodegenerative diseases, in terms of both case numbers and severity. In the US alone there are currently about 5.2 million AD patients, and, in addition to the enormous personal suffering, the cost associated with care for these individuals is $214 billion annually. By 2050 these numbers are projected to increase to 16 million patients and a cost of $1.2 trillion. There is therefore an urgent need for new therapeutic and diagnostic approaches for the treatment of AD and other amyloid diseases and for a fundamental understanding of the underlying chemical and structural biology.

A unique barrier to the development of treatments for these diseases originates from the fact that there are very few structures of amyloids known. In particular, fibrils and oligomers are sparingly soluble and do not diffract to high resolution, and, therefore, solution NMR and x-ray diffraction, the primary tools of structural biology, are not applicable to these systems. Thus, a critical barrier to progress in this field is the availability of a general approach to provide structures of amyloid fibrils and oligomers. The availability of structural information can be invaluable to determine the interactions between the relevant therapeutic/diagnostic and amyloid fibrils.

For these reasons, we have developed methods to determine the structure of fibrils and the first complete structure was of an 11-mer peptide, YTIAALLASPYS, and was published in 2006. More recently we described how this molecule is incorporated into amyloid fibrils with a combined cryoEM and magic angle spinning NMR study.

We have also been using these methods to examine proteins which form fibrils such as ß2m and ΔN6 associated with dialysis related amylosis (DRA). However the most recent and complete study involved the determination of the structure of Aβ1-42 which is the toxic species in Alzheimer's disease. We recorded 2D 13C-13C NMR spectra from Aβ1-42 fibrils and extracted over 500 distance constraints. These constraints are divided into four categories: (1) sequential, (2) medium range, and (3) long range, which determine the structure of the monomer. In addition, the fibrils consist of two molecules arranged back to back and (4) generate intermolecular constraints. The structure of Aβ1-42 is a dimer and shown in more detail in our recent publication.

In more detail the structure shows that the fibril core consists of a dimer of two Aβ42 molecules with each of the two monomers arranged in four β-strands in a S-shaped amyloid fold. The interior of the S-shape is arranged in a manner that generates two hydrophobic cores, containing L17, F19, F20, V24, A30, and I32 in one and I31, V36, V39, I41 in the second, and is stabilized at the end of the chain by a salt bridge from the C-terminal COO- of A42 and the –NH3+ on the sidechain of K28. In contrast, the outer surface of the monomers presents hydrophilic sidechains from K16, E22, D23, and S26 to the solvent. The interface between the monomers shows clear contacts between M35 of one molecule and L17 and Q15 of the second, so that two molecules of Aβ42 are arranged back-to-back as the primary structural unit of the AD fibril. Intermolecular 13C-15N constraints along the fibril axis demonstrate that the amyloid fibrils are parallel in register. Thus, two hydrophobic cores will be repeated along the fibril axis and propagate as continuous hydrophobic cores inside the fibril. The RMSD of the backbone structure (Q15-A42) is 0.77±0.14 Å and of all heavy atoms is 1.11±0.14 Å.

The structure provides a point of departure for the design of drugs and other therapeutic approaches to mitigate Aβ42 aggregation and to approach a cure for this devastating disease.

Structure and Function of Membrane Proteins

The solid state NMR techniques mentioned above and discussed more below are equally applicable to membrane proteins and we started work in this area in the 1980s and 1990s, focusing mostly on bacteriorhodopsin and its photocycle intermediates. Those experiments are continuing with structural studies of the structure of the M and L photocycle intermediates.

In addition, we have started to apply the approaches to other membrane proteins and recently completed work on the structure of the S31N mutant of the M218-60 construct from influenza-A. We recorded two types of magic angle spinning (MAS) spectra of M218-60 showing 13C-15N and 1H-15N dimensions which were used for assigning the spectra for the protein dispersed in lipid bilayers. A prominent feature of these spectra is that all of the cross peaks are doubled, indicating that the protein is present as a dimer of dimers rather than as a tetramer, as indicated in previous studies of this system.

In addition, we have performed a variety of dipolar recoupling experiments on M218-60 and measured over 270 distance constraints. These data permitted us to calculate the structures. The structures show the required twofold symmetry, especially in the neighborhood of the 4 x His and 4 x Trp box that is crucial in the proton conduction mechanism. They also show the possibility of the presence of H_2O in the channel and that it is excluded in the central portion. More interesting is the fact that we see in the 1H-15N spectra contacts between His on one chain of the tetramer with the Trp on a second and a ~3.5 Å contact between the His 15N and the Trp indole 15N that is bridged by an H+. This interchain conduction mechanism is new to this protein—it has not been seen in previous studies where it is always assumed that the protein is a tetramer.

Dipolar Recoupling and Distance and Torsion Angles Measurements

In the late 1980s and early 1990s we introduced the concept of dipolar recoupling to solid state NMR via the rotational resonance (R2) experiment to measure 13C-13C distances. Shortly thereafter we published the rotary resonance recoupling (R3) experiment to measure 13C-15N and other heteronuclear distances. These two papers and the REDOR experiment of Gullion and Schaefer nucleated a substantial worldwide research effort to develop methods to measure homo- and heteronuclear distances and torsion angles, and resulted in the publication of pulse sequences such as RFDR, FS-REDOR, DARR, DREAM SPR-5, etc.

The initial complete structure of a peptide was that of N-f-MLF-OH that was determined primarily with 13C-15N distance measurements and some torsion angle experiments. The data were highly accurate and resulted in an RMSD = 0.02Å which was below the level of thermal fluctuations. In addition, we have determined structural features in many membrane protein samples, for example in bacteriorhodopsin (bR), rhodopsin (Rho), and most recently in the complete structure of M218-60 as discussed above. These experiments are equally applicable to amyloid peptides and proteins with the initial publication in this area being our 1995 paper on Aß34-42 with Professor Peter Lansbury. This subsequently led to the structure of TTR105-115, and most recently the complete structure of Aß1-42 as discussed above.

Efforts in the development of dipolar recoupling are continuing with the development of proton assisted recoupling (PAR) and proton assisted insensitive nuclei (PAIN-CP). The 13C-13C MAS PAR spectrum obtained from U-13C/15N-AβM01-42 fibrils recorded at ω0H/2π=800MHz was essential in determining the structure. The resolution is excellent and the distance information obtained from it and similar spectra were essential to solving the structure of Aß1-42.

Our most recent efforts in dipolar recoupling are directed at developing 17O NMR into a practical tool for protein structure determination. The pulse sequences that we are developing consist of evolution under MQ MAS excitation to obtain an isotropic 17O dimension and recoupling to 13C/15 and or 1H. Recently we have recorded MAS spectra of 17O labeled peptide N-Ac-VL and 13C-17O correlation spectrum. Although we have yet to generate an isotropic 17O dimension in this spectrum, it is clear that it will span about 100 ppm and therefore considerably increase the resolution of peptide and protein spectra. Clearly signal-to–noise is going to be an issue in these experiments and we plan to incorporate DNP (dynamic nuclear polarization) into the scheme. We also need to develop methods to decrease the cost of producing 17O and to find ways to 13C/15N and 17O label proteins. Thus we see a number of exciting challenges on the scientific horizon.

Mei Hong (Chemistry)

The Hong group employs and develops solid-state NMR spectroscopy techniques to investigate structural biology and biophysical questions of contemporary interest. Current interest focuses on disease-relevant influenza and parainfluenza virus proteins, energy-relevant plant cell wall materials, and amyloid fibrils involved in neurodegenerative diseases and in catalysis.

Structure and Dynamics of Influenza M2P Proteins

The M2 protein of influenza viruses mediates virus entry into cells and budding from host cells by acting as a proton channel and by causing membrane scission, respectively. The proton channel activity of influenza A virus' M2 protein (AM2) can be inhibited by antiviral drugs, but M2 of influenza B and C viruses are not yet druggable. Structural biology of influenza M2 proteins are therefore important for developing new antiviral drugs and for enhancing our fundamental understanding of ion channel structure and function.

Since 2007, the Hong group has engaged in a high-impact project of elucidating the structure, dynamics, and mechanism of action of the influenza M2 protein. These studies have elucidated the drug-binding site and drug-bound structure of the transmembrane (TM) domain of AM2 as bound to phospholipid bilayers, and have revealed the structure and dynamics of the crucial proton-selective residue, a histidine in the TM domain. In 2015–2016, efforts in this project have broadened to include the influenza B virus M2 (BM2). Influenza B infections are prevalent in the spring months of each flu season, and BM2 is not yet druggable. Interestingly, BM2 is only a functional analog of AM2, with little amino-acid-sequence homology with AM2 except for the proton-selective histidine and the gating residue, a tryptophan. Using 2D magic-angle-spinning correlation NMR experiments, the Hong group showed that BM2's histidine protonation equilibria differ significantly from those of AM2 histidine, and the BM2 channel is less hydrated than AM2 unless it is at very low pH. These results indicate differences in the proton-conduction mechanism of BM2 as compared to AM2. These results suggest that the presence of a second titratable histidine in BM2, which is absent in the AM2 amino acid sequence, is responsible for the altered protonation equilibria of the proton-selective histidine. Future efforts will delineate the BM2 structure and dynamics in more complete atomic details.

Structure and Lipid Interactions 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 mechanism of protein conformational changes and membrane curvature induction are of both fundamental and biomedical significance. Most class I viral fusion proteins such as those found in influenza and HIV contain two hydrophobic domains, an N-terminal fusion peptide (FP) domain and a C-terminal TM domain, which interact with the lipid membrane to cause membrane curvature. In 2015–2016, the Hong group completed a study of a novel chimera of the FP and TM of the fusion protein of the parainfluenza virus, which is responsible for infant respiratory diseases such as croup and bronchitis. This protein has a large water-soluble ectodomain that prohibits structural biology of the membrane-bound FP and TM. By linking the fusion peptide and TM domain with a short polar linker, the Hong group is able to carry out the first structural study of the FP and TM in the membrane. This tethered state mimics the post-fusion state of the intact protein, where the two hydrophobic termini should reside in the same membrane due to the formation of an ectodomain helical hairpin. Interestingly, the Hong group found no inter-domain contacts between the FP and TM in this tethered chimera, suggesting that the long-held paradigm of the helical hairpin structure for the post-fusion state does not continue into the membrane to the FP and TM. Thus, the current viral fusion model may need to be modified to account for the final states of the protein.

Structures of Amyloid Proteins

In 2015–2016, the Hong group carried out two new and collaborative projects that address the structures of amyloid fibrils. Amyloid proteins are found in many neurodegenerative diseases but can also have other functions. These proteins typically assemble into intermolecular β-sheet structures with the cross-β motif, where the molecular chain axis runs perpendicular to the direction of fibril growth. The Hong group investigated two amyloid fibrils: 1) the Arctic mutant of Alzheimer's disease Aβ peptide, which is one of the Aβ mutants responsible for early-onset AD; and 2) a designed amphipathic peptide fibril that catalyzes ester hydrolysis reactions in the presence of zinc ions. Using solid-state NMR spectroscopy, the Hong group showed that the Arctic Aβ peptide is intrinsically polymorphic due to the mutation of a glutamate residue to a glycine. Moreover, comparisons of NMR chemical shifts, long-range contacts, and fibril hydration, suggest that one of the polymorphs has a similar three-dimensional fold as Aβ42. For the catalytic amyloid fibril, the Hong group determined the detailed geometry and structures of the histidine and water ligands that coordinate the zinc ion. This is arguably the first *de novo* solid-state NMR study of a zinc metalloprotein where no prior structural information is available from alternative high-resolution techniques such as x-ray crystallography and solution NMR.

Plant Cell Wall Polysaccharides

Plant cell walls mainly consist of polysaccharides, including cellulose, hemicellulose, and pectins. Cell walls provide mechanical strength to plants and at the same time are 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. In collaboration with plant biochemists at Pennsylvania State University, the Hong group investigated the structure of cellulose in plant cell walls. High-field high-resolution 2D spectra indicate that plant cell wall cellulose is structurally polymorphic, and none of the structures resembles the highly crystalline cellulose produced by bacteria, algae, and marine organisms. This structural polymorphism and difference are attributed to extensive interactions of cellulose microfibrils with matrix polysaccharides in plant cell walls.

The M2 project and viral fusion protein projects are funded by NIH, while the plant cell wall project is funded by an EFRC grant from Penn State.

Yukikazu Iwasa (Plasma Science and Fusion Center)

During July 1, 2015, through June 30, 2016, the Magnet Technology Division, under Yukikazau Iwasa's leadership, was involved in two NIH-supported programs on NMR and MRI magnets, each briefly summarized below.

Modified Phase 3B of a 3-phase Program 1.3 GHz LTS/HTS NMR Magnet

The next phase of this 1.3-GHz LTS/HTS NMR magnet (1.3G), modified Phase 3B supported by the National Institute of General Medical Sciences began on September 1, 2015; its end date is August, 31, 2018. This project seeks to design a very high magnetic field NMR magnet (~30 T) using high-temperature REBCO superconductors. This group's efforts have been better integrated into the HTS magnet work for fusion.

LHe-free Persistent-mode HTS Magnets for NMR and MRI Application

Supported by the National Institute of Biomedical Imaging and Bioengineering and begun on July 1, 2016, the project has two specific aims that enable REBCO-based double-pancake (DP) coils to operate LHe-free in persistent mode: 1) to build REBCO DP coils, each terminated with a superconducting joint; and 2) to design, build, and operate persistent-current switches viable to these REBCO DP coils operating in the range 4.2 K to 77 K.

From 2012 to 2016, Iwasa oversaw one PhD graduate student, Jiayin Ling, who completed his thesis on January 15, 2016, in the Department of Mechanical Engineering. Thesis title is "A Persistent-Mode MgB2 0.5-T/240 mm Solid-Nitrogen-Cooled Magnet for MRI."

Jagadeesh Moodera (Physics)

Jagadeesh Moodera is a senior research scientist and a group leader in the Department of Physics, with research labs located in the Francis Bitter Magnet Laboratory division. His research efforts focus on nanoscience condensed matter physics (quantum coherent transport in nanodevices, the investigation of Majorana fermions, molecular spintronics, etc.)Funding for the group's research comes from the Office of Naval Research and the National Science Foundation, as well as from research grants (obtained with Professor Patrick Lee of the Department of Physics) from the John Templeton Foundation. Moodera is part of the larger NSF-funded five-year CIQM (Center for Integrated Quantum Materials) program that is a collaboration among MIT, Harvard University, Howard University, the Boston Museum of Science, and other institutions.

Modera collaborates with various universities, (in the United States, Canada, the United Kingdom, Germany, and Italy), the Oak Ridge National Laboratory, Brookhaven National Laboratory, as well as with IBM (Yorktown Heights, NY). Currently, he is focusing on two-dimensional quantum coherent and dissipationless transport, interface-induced magnetic and electronic effects at the molecular level, with emphasis on topological insulators (TI)—one of the most significant topics in physics. His group investigates nanostructures for observing quantum coherent behavior of charge and spin transport in these novel systems. In addition, his team is searching for the exotic Majorana fermions and manipulating spins in organic molecules.

Moodera's group along with his collaborators published approximately 10 articles in journals such as *Nature Materials*, *Nature Communications*, *Nano Letters* and *Physical Review Letters*. He continues mentoring graduate students, undergraduates, and high school students by providing research opportunities in his lab. Several visiting students from Spain, Germany, Korea, and Brazil, along with an undergraduate from Yale University, took part in his research during the past year.

In a notable research accomplishment, Moodera's group showed proof of dissipationless chiral spin polarized edge current flow in a TI. 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 quantum anomalous Hall (QAH) effect shares a similar physical phenomenon as the QH effect, including the dissipationless quantized Hall transport in ferromagnetic materials, but it 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 have unambiguously established the dissipationless edge transport. The realization of a nonvolatile QAH state in magnetic TI is a major step towards dissipationless electronic applications without external fields. Showing the dissipationless spin polarized edge current flow in TI is expected to have a significant influence on the development of low-power spin-based storage and communication technology in the future. In particular it can have transformational influence when combined with graphene's excellent transport properties.

Moodera's group continues to make significant contributions to condensed matter physics, in particular as it relates to quantum coherent phenomena. Using the state-of-the-art molecular beam epitaxy (MBE) system, the group seeks to contribute to the understanding of the quantum state exhibited by TI displaying properties such as fully spin polarized chiral dissipationless edge conduction. In addition, Moodera has begun producing hitherto unknown interface combinations of materials using the newly installed and custom-designed (and extremely versatile) cluster MBE system. In order to investigate behavior of atoms and molecules on various interacting surfaces, a custom-designed low temperature (280 mK) scanning tunneling microscope/atomic (conducting) force microscope system capable of operating in high magnetic fields (in-plane with precise sample orientation capability) has been installed and is being brought into use.

The group's past research into 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 and reprogrammable logic circuits. These innovations will potentially have a significant and highly profitable impact on memory technology and are being developed by major companies.

Moodera continues as a visiting professor at Eindhoven Technical University. He is an expert advisor for a spin-related national nanotechnology program in the Netherlands, Ireland, and France. Moodera was invited by the French National Center for Scientific Researchto be part of an international review board to set scientific orientations and objectives on nanosciences at the frontiers of nanoelectronics.

Educational Outreach Programs

The Plasma Science and Fusion Center's educational outreach program is planned and organized under the direction of Paul Rivenberg, communications and outreach administrator of the PSFC. The program conveys the excitement of advances in plasma physics and fusion energy research to the MIT community, the national and international scientific communities, and the general public. A particular focus of the program is to heighten 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 the PSFC for hands-on demonstrations and tours. PSFC graduate student volunteers are key to the success of our tours. The hosting experience helps the graduate students develop their skills in communicating complex scientific ideas to those without an advanced science backgrounds. This year the PSFC hosted over 900 people on site.

The PSFC has continued to receive attention from lawmakers this year, facilitated by MIT alumnus Reiner Beeuwkes ’67. These included visits by State Senator Michael J. Barrett, (3rd Middlesex District, MA), Senator Cory Booker (D-NJ), Ken Kimmel (President of Union of Concerned Scientists), Matthew Beaton (Massachusetts Secretary of Energy and Environmental Affairs), Kathleen McGinty (candidate for the US Senate and former environmental advisor to President Bill Clinton), Congressman Peter Welch, (D-VT), State Senator Jamie Eldridge (Middlesex and Worcester District, MA) , and Catherine Cortez Masto (November 2016 candidate for the US Senate).

The PSFC also hosted technology and industry leaders, including Mitsubishi Electric, Bechtel, ExxonMobil, Two Sigma, and the Brazilian Atomic Energy Commission. All were guided around the Alcator C-Mod control room and experimental cell to learn more about fusion energy.

This year the PSFC participated in MIT’s 2016 Open House. The PSFC provided tours of the Alcator C-Mod tokamak. Graduate students Alex Tinguely and Alex Creely showed off the project to almost 200 visitors. At a central campus location, PSFC students and postdoctoral associates manned eight tables of demonstrations on fusion, plasmas, magnetism, and superconductivity, connecting with hundreds of families and individuals eager to learn about the latest plasma research. PSFC students showed visitors how to create a plasma in a glow discharge tube (and even in a pickle).

The PSFC also had the opportunity to team with the Department of Nuclear Science and Engineering to present a Science on Saturday event in December 2015. NSE professor Anne White introduced graduate students and researchers from her department and the PSFC, and PSFC postdoctoral associate Ted Golfinopoulos ,along with graduate students Alex Tinguely and Adam Kuang, introduced the crowd to plasmas and fusion research through a series of demonstrations that involved magnets and a glow discharge tube, culminating—like High School Outreach Day—with the plasma pickle demonstration. Attendees were able to spend one-on-one time with the presenters after the show, getting a deeper understanding of the science presented on stage.

The PSFC has 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 Day weekend, was attended by hundreds of MIT students and their families, who learned about the latest directions of plasma and fusion research.

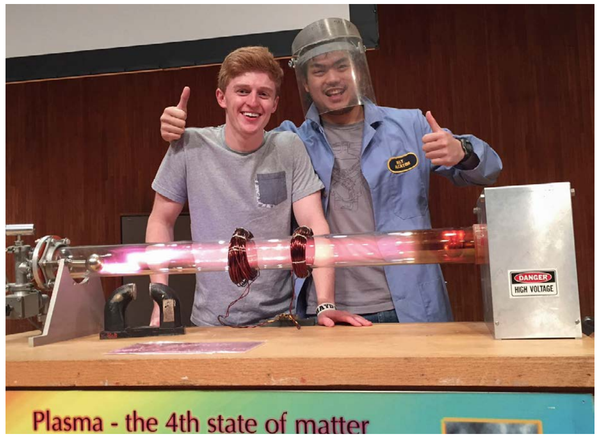

Figure 2: Graduate students Alex Tinguely (left) and Adam Kuang show off a plasma demo as part of the Science on Saturday event in December 2015

The PSFC continues to collaborate with other national laboratories on educational events. An annual Teacher's Day (to educate middle school and high school teachers about plasmas) and Plasma Sciences Expo (to which teachers can bring their students) is a tradition at each year's American Physical Society-Division of Plasma Physics (APS-DPP) meeting. This year Paul Rivenberg was the committee chair of the APS-DPP Education Committee. He continues to organize the Plasma Sciences Expo, at which 12 exhibitors representing laboratories and schools from around the US provided hands-on plasma and physics demonstrations to more than 2,500 students and teachers. The PSFC

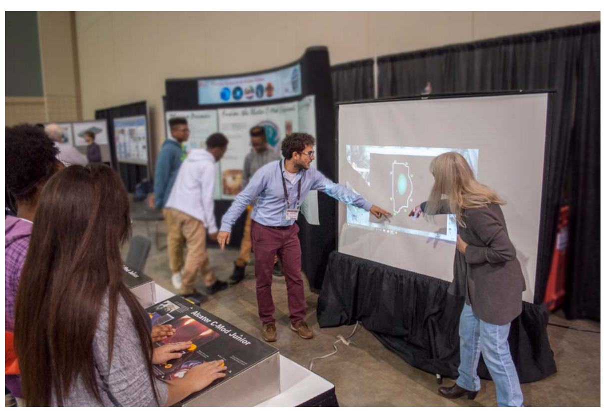

Figure 3: Graduate student Juan Ruiz Ruiz (middle) and PSFC administrator Valerie Censabella (right) work the Tokamak Video Game at the 2015 APS-DPP Plasma Sciences Expo in Savannah, GA.

booth, staffed by Rivenberg, NSE Administrator Valerie Censabella, and PSFC graduate students introduced the public 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.

The USA Science and Engineering Festival in Washington, DC (from April 15 to 17) was a first for the PSFC. Paul Rivenberg, Ted Golfinopoulos, data systems manager Joshua Stillerman, and Valerie Censabella spent Patriots Day weekend representing the fusion power plant as part of the National Academies' "Decision Town." The PSFC shared prime convention center space with a diner, patent office observatory, brain center, police station, and arctic research station, each stop requiring participants to make a decision based on information provided. To help visitors decide on the value of pursuing fusion research, PSFC staff demonstrated electromagnetism and its effects, helped visitors create plasma (potential fusion fuel) with a neon sword, used a video game to encourage their skills at confining hot plasma, and took them on a virtual tour of the inside of MIT's Alcator C-Mod tokamak. The power plant staff found visitors overwhelmingly in favor of funding fusion research.

Figure 4: Postdoctoral associate Ted Golfinopoulos (left) teaches students about magnetism at the USA Science and Engineering Festival in Washington, DC.

A team of filmmakers from the British Broadcasting Corporation (BBC) arrived at the MIT Plasma Science and Fusion Center in February to film a segment about fusion for the BBC News program *Horizons*. Host Adam Shaw interviewed Dennis Whyte about the laboratory's current project, the Alcator C-Mod tokamak, and about plasmas and fusion in general. The segment on MIT was included in a half-hour program that explains the science behind fusion, as well as the practical applications going forward. The BBC film, "A Slice of the Sun," also features two of the PSFC's international collaborations: ITER and the Wendelstein 7-X stellarator in Germany. The program aired in June 2016.

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. The PSFC's deputy director, Martin Greenwald, has also helped organize annual IAP Open House seminars, as well as special visits from alumni and dignitaries, including US and Massachusetts lawmakers.

The 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. Richard Temkin is working with the coalition on goals such as strengthening appreciation of the plasma sciences through endorsements from industries involved in

Figure 5: PSFC director, Dennis Whyte (left) speaks with Adam Shaw of the BBC World News in the Alcator C-Mod Control Room.

plasma applications, and addressing environmental concerns about plasma science. Temkin and Paul Rivenberg are members of the CPS steering committee. Rivenberg is working with CPS on new initiatives and is editor of the coalition's *Plasma Page*, which summarizes CPS news and accomplishments of interest. 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.

Finally, the PSFC launched a revised website in order to improve electronic outreach about its research and educational activities.

Honors and Awards

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

In May, five members of the community received 2016 MIT Infinite Mile Awards. Postdocs Dan Brunner (PhD '13), Ted Golfinopoulos (PhD '14), Zach Hartwig (PhD '14) and Bob Mumgaard (PhD '15) were honored for helping revitalize the fusion energy research mission at the PSFC. Dennis Whyte noted that their efforts "completely opened our eyes to a new way of doing and supporting our fusion energy mission in the private sector." A separate Infinite Mile Award went to technical supervisor William Parkin, who is responsible for most of the custom electronics infrastructure in the PSFC's Alcator C-Mod tokamak.

Graduate student Alex Creely was awarded a National Defense Science and Engineering Graduate Fellowship. This highly competitive, portable fellowship is awarded to graduate students who have demonstrated the ability and special aptitude for advanced training in science and engineering, and who intend to pursue a doctoral degree in one of 15 supported disciplines. Creely received this fellowship in physics for his graduate studies exploring turbulence and transport in fusion plasmas with Professor Anne White.

Miklos Porkolab was elected an external member of the Hungarian Academy of Sciences at the 187th meeting of the general assembly of the Academy in Budapest, on May 2, 2016. Founded in 1825, the Hungarian Academy of Sciences is the oldest institution devoted to science in Hungary. The external membership is given to individuals of Hungarian heritage who conduct science internationally and who make exceptional contributions to scientific research.

Nathan Howard received a 2016 Early Career Award for High Impact Science from the National Energy Research Scientific Computing Center. He was honored on March 22 at the 2016 NERSC users group meeting in Berkeley, CA, where he presented his scientific results. The award recognizes NERSC users whose work "has, or is expected to have, an exceptional impact on scientific understanding, engineering design for scientific facilities, and/or a broad societal impact."

Robert Griffin received the E. Bright Wilson Award in Spectroscopy at the spring awards symposium of the American Chemical Society Division of Physical Chemistry. Griffin was honored for his pioneering contributions to the field of nuclear magnetic resonance spectroscopy.

Jungpyo Lee's article "Turbulent Momentum Pinch of Diamagnetic Flows in a Tokamak" was selected to be a part of the *Nuclear Fusion* 2014 Highlights collection. The collection features 22 papers chosen for their outstanding quality and valuable contribution to the fusion research community.

Robert Mumgaard was accepted into the 2015–2016 Translational Fellows Program (TFP), supported by the MIT Innovation Initiative. First introduced in 2013, the TFP supports fellows for one day a week for a full academic year to encourage them to "pursue commercialization of a technology that originated in MIT research." The program connects MIT researchers with experienced technology entrepreneurs and business leaders to explore possible markets, customer constraints, funding-strategies, and IP protection for MIT-derived research.

PSFC mechanical engineer Jeff Doody received a "Best Paper Award" on October 9 at the COMSOL Conference 2015. The paper, "Structural Analysis of the Advanced Divertor eXperiment's Proposed Vacuum Vessel," describes how Doody used COMSOL multiphysics modeling software to predict loads and stresses on the vacuum vessel in the initial design for the Advanced Divertor eXperiment (ADX), a proposed high-field, high-power-density fusion tokamak.

Effective July 1, 2015, Martin Greenwald was appointed deputy director of the PSFC. Previously, Greenwald had served as associate director. This new title reflects

Greenwald's increased responsibilities in the day-to-day management and scientific guidance of the center.

Joe Minervini was named assistant director of the MIT Plasma Science and Fusion Center beginning November 1, 2015.

Dennis Whyte was named the new head of the Department of Nuclear Science and Engineering , effective September 9, 2015.

Appointments

Alcator Division: Theresa Wilks was appointed as a postdoctoral associate.

Physics Research Division: Valentin Aslanyan was appointed as a postdoctoral associate.

High Energy Density Physics Division: Andrew Birkel was appointed as a research specialist.

Waves and Beams Division: Guy Rosenzweig and Jacob Stephens were appointed as postdoctoral associates.

Fusion Technology and Engineering: Peter Marston was appointed as a research engineer and Franco Mangiarotti was appointed as a postdoctoral associate.

FBML Division: Juan Pedro Cascales Sandoval was appointed as a postdoctoral associate/postdoctoral fellow.

Promotions

Alcator Division: Nathan Howard was promoted to research scientist.

Physics Research Division: Alessandro Marinoni was promoted to research engineer.

Graduate Degrees

Nuclear Science and Engineering: Sergey Arsenyev, PhD; Jennifer Sierchio, MS; Franco Manigiarotti, PhD; Jason Hummelt, PhD; Christian Haakonsen, PhD

Physics: Paul Ennever, PhD; Jiexi Zhang, PhD

Aeronautics and Astronautics: Spenser Guerin, MS; Juan Ruiz Ruiz, MS

Mechanical Engineering: Jiayin Ling, PhD

Dennis Whyte
Director
Hitachi American Professor of Engineering