Plasma Science and Fusion Center

MIT's Plasma Science and Fusion Center (PSFC) is known internationally as a leading university research center for the study of plasma and fusion science and technology. It is also 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 through the Francis Bitter Magnet Laboratory. Broadly, the Center's research focuses on six general areas:

- The science of magnetically confined plasmas in the development of fusion energy
- General plasma science, including plasma–surface interactions, development of novel high-temperature plasma diagnostics, and theoretical and computational plasma physics
- The physics of high-energy-density plasmas
- The physics of waves and beams: gyrotron and high-gradient accelerator research, beam theory development, non-neutral plasmas, and coherent wave generation
- Development of high-field superconductors and superconducting magnet systems
- Research in magnetic resonance, including NMR, MRI, and electron paramagnetic resonance (EPR); NMR and MRI magnet development, and nanoscience condensed matter physics (quantum coherent behavior and spin transport).

PSFC research and development programs are principally supported by the US Department of Energy's Office of Fusion Energy Sciences (DOE-OFES) and by the National Institutes of Health (NIH). There are approximately 222 personnel associated with PSFC research activities. These include 28 affiliated faculty and senior academic staff; 51 graduate students, with participating faculty and students from (in alphabetical order) Aeronautics and Astronautics, Chemistry, Electrical Engineering and Computer Science, Mechanical Engineering, Nuclear Science and Engineering, and Physics; 81 research scientists, engineers, postdoctoral associates and fellows, and technical staff; 28 visiting scientists, engineers, and research affiliates; one visiting student; 14 technical support personnel; and 19 administrative and support staff.

For more than 25 years, the Alcator C-Mod Program has been PSFC's largest research division. In fall 2016, the Alcator C-Mod tokamak completed its final experimental campaign. To begin to compensate for the closure of this major fusion experiment at MIT, in the near to mid-term, PSFC's focus will shift to US DOE-supported domestic and international research collaborations where experiments designed by MIT scientists, engineers, and graduate students will be carried out in a number of major tokamak experiments around the world.

Closure of the Alcator C-Mod tokamak will result in a decline in PSFC research volume until the lost funding is replaced. For almost two years, PSFC senior leadership has been pursuing other sources of support and a broader base of support. For example, PSFC is seeking new funding pathways for high-field magnetic fusion research through means such as the MIT Energy Initiative's Low-Carbon Energy Centers and other private-sector sponsors. In addition, new initiatives are taking place through outreach to the rest of campus—for example, the proposed siting of the MIT Cryogenics Laboratory (Professor John Brisson, Mechanical Engineering) at PSFC, the upcoming Watt Energy Laboratory at PSFC (Professor Ju Li, Nuclear Science and Egineering), and work on accelerator ion sources (Professor Janet Conrad, Physics).

In light of PSFC's changing circumstances, in March 2017 Director Dennis Whyte announced a reorganization of the center's research divisions to optimize the PSFC divisional structure for these new realities and to better respond to new opportunities. The new divisional organization is as follows.

Magnetic Fusion Experiments (MFE).This roughly replaces the Alcator division, and remains PSFC's largest division. Unique among the divisions, it has two subdivisions that both report to the division head Dr. Earl Marmar. A subdivision for collaborations (reporting to Assistant Head Anne White) will coordinate and focus PSFC's multiple off-campus collaborations in MFE, including diagnostic development collaborations that had been in the old Physics Research Division. These collaborations will be a critical part of maintaining our scientific and educational excellence in MFE. A Future MFE Facilities subdivision (reporting to Assistant Head James Irby) will be involved in the design and implementation of any major new magnetic fusion energy experiment at the PSFC.

Plasma Theory and Computation. This becomes a stand-alone division that approximately replaces the Physics Research Division (although several experimental projects previously located in Physics Research will move to other divisions). Paul Bonoli is division head and Nuno Loureiro is assistant head.

High-Energy-Density Physics (HEDP). This division remains unaltered. Richard Petrasso is head of the division; Chikang Li was named associate head and Johan Frenje was named assistant head.

Plasma Science and Technology. This roughly replaces and expands on the Waves and Beams Division. The organizing principle of this division is to gather together all the plasma science and applications that are not aimed directly at fusion energy. In addition to the research traditionally carried out in Waves and Beams, this division will include the gyrotron rock-drilling work and the use of low-temperature plasmas and ions in the modification of materials. The division head is Richard Temkin and the assistant head is Paul Woskov.

Magnets and Cryogenics. The Fusion Technology and Engineering Division's work on advanced magnets has been placed into this division. A major addition here is the anticipated integration of the MIT Cryogenics Laboratory into the PSFC over the next few years. The superconducting magnet and cryogenic research are highly complementary and PSFC hopes to build synergies between these efforts with the new division. Joe Minervini is division head and John Brisson was named assistant head.

Magnetic Resonance. This division encompasses the research focused on the use of magnetic resonance for scientific investigation and the development of experimental tools to carry out those investigations. It replaces the Francis Bitter Magnet Laboratory Division. Robert Griffin remains head and Mei Hong is assistant head.

PSFC research funding in fiscal year 2016 (through September 30, 2016) was $34.1 million. New funding for FY2017 (through September 2017) is expected to decrease to approximately $26.5 million, a drop of $7.6 million relative to FY2016. This decrease is caused almost exclusively by the difference in the funding profiles of the old DOE Cooperative Agreement and the new, post-Alcator-C-Mod DOE Cooperative Agreement. FY2017 Funding, by division, and as a percentage of total funding, is as follows: Magnetic Fusion Experiments ($12.3 million, 46.4%), Magnetic Resonance ($6.0 million, 22.6%), Plasma Theory and Computation ($2.5 million, 9.4%), High Energy Density Physics ($2.3 million, 8.8%), Plasma Science and Technology ($2.2 million, 8.5%), and Magnets and Cryogenics ($1.2 million, 4.4%).

In January 2017, PSFC welcomed its newest faculty member, Assistant Professor Zachary Hartwig of the Department of Nuclear Science and Engineering (NSE). Hartwig's interests include accelerator-based nuclear science and fusion diagnostics, Monte Carlo particle transport and fusion neutronics, magnetic fusion energy reactor design, and digital pulse processing and data acquisition systems for radiation detectors. He will work with the PSFC Magnetic Fusion Experiments Division. In addition, Professor Nuno Loureiro was granted tenure at MIT.

Magnetic Fusion Experiments Division

The new Magnetic Fusion Experiments Division, created in 2016, represents the transition from magnetically confined fusion experiments primarily carried out at one tokamak, Alcator C-Mod, in the Alcator Division, to several large-scale off-campus experimental facilities. This division remains the largest within PSFC and is home to leading experts in all areas of magnetic confinement fusion research, including boundary physics, core transport physics, radio frequency (RF) physics, and pedestal physics. Division Head Earl Marmar is a senior research scientist in MIT's Department of Physics and the Plasma Science and Fusion Center, and is the principal investigator (PI). Unique among the divisions at PSFC, the MFE Division has two subdivisions that report to Dr. Marmar: Collaborations and Future MFE Facilities. The Collaborations subdivision is led by Professor Anne White, who coordinates on-campus elements of multiple off-campus collaborations with large tokamak and stellerator facilities around the world. Work in this subdivision includes diagnostic development collaborations that were previously situated in the Physics Research division. Collaborations are critical to maintaining scientific and educational excellence in magnetic fusion experiments. The Future MFE Facilities subdivision is led by Dr. James Irby. Work in that subdivision focuses on planning and options for a new tokamak facility to explore plasma-wall interactions, divertor physics, and plasma sustainment using advanced radio-frequency and microwave systems; and planning for applications of advanced superconductors to burning plasma experiments and fusion pilot plant designs.

Figure 1. Mercator projection of the interior of the Alcator C-Mod tokamak, which broke the record for plasma pressure in a fusion device in September 2016 during the program's final experimental campaign.

The operations of the Alcator C-Mod tokamak (Figure 1) were successfully completed on September 30, 2016. Many important results and milestones were achieved in the final research campaign, with a total of 17.4 research weeks accomplished for the federal 2016 fiscal year. These included extended operation at the highest available toroidal magnetic field strength (8 tesla on the axis of the plasma), culminating in the production of world-record volume averaged plasma pressure on the last day of operations, exceeding 2 atmospheres for the first time ever in a magnetically confined plasma. The plasma conditions approached those required for a net energy-producing tokamak reactor. The body of research on Alcator C-Mod, which operated from 1992 through 2016, has validated the high magnetic field approach to tokamak fusion energy. The wealth of information stored in the archived C-Mod database will be maintained with anticipated funding from the DOE Office of Science, and can be expected to provide many new results, presentations, and journal articles. This data will continue to be a key research resource in the coming years for the group's scientists and students.

The MFE Division team consists of a full-time equivalent staff of 69 personnel, including four faculty or senior academic staff, 15 research scientists, 16 engineers and technical staff, 11 technicians, 13 graduate students, two postdoctoral fellows, five information technology staff, and three administrative and support staff. In addition, typically about 10 undergraduate students are involved in research in the division, many participating through the Undergraduate Research Opportunities Program. Current annual funding levels for all of these activities totals $12.3 million. This includes funding under the umbrella of a five-year MFE cooperative agreement with the DOE Office of Science, Fusion Energy Sciences; carryover funding from the Alcator C-Mod cooperative agreement (set to be completed on August 31, 2017); and a number of smaller three-year grants from the DOE Office of Science. The five-year MFE cooperative agreement started on September 1, 2015, and runs through August 31, 2020.

Research in the Collaborations subdivision during the past year has focused on exploring the foundational science behind high-performance plasma confinement. State of the art experiments were carried out this year at off-campus facilities, such as the Axially Symmetric Divertor Experiment (ASDEX) Upgrade in Germany, the Experimental Advanced Superconducting Tokamak (EAST) in China, the DIII-D National Fusion Facility in San Diego, California, the Korea Superconducting Tokamak Advanced Research (KSTAR) facility in South Korea, and the Tokamak à Configuration Variable (TCV) in Switzerland. The experiments were in the critical science areas of transport, edge pedestal, and I-mode physics, as well as in plasma integration areas involving advanced tokamak and burning plasma science. Many of the experiments were in direct support of urgent International Thermonuclear Experimental Reactor (ITER) research needs. Other experimental efforts supported the new Wendelstein 7-X, which is the world's largest stellarator fusion device .

International Collaborations

Gas Puff Imaging Wendelstein 7-X Stellarator

At Wendelstein 7-X (W7-X), the PSFC team is developing a new gas-puff imaging system for boundary physics. The overarching goal of this project is to facilitate the study of fluctuations and plasma structure at the plasma edge and in the heat-exhaust (divertor) region. Understanding the mechanisms that transport heat and particles into and through the plasma boundary is critical to creating a predictive capability for the design of three-dimensional divertors, which is a core goal of the US collaboration with W7-X. Work on this project is being led by the Principal Investigator (PI), Dr. Jim Terry, PSFC research scientist Dr. S. G. Baek, and NSE graduate student Sean Ballinger. Ballinger is on-site at W7-X for the summer of 2017, along with MIT undergraduate Kevin Tang (Figure 2), who obtained funding to work on this project in Germany for the summer through the MIT International Science and Technology Initiatives program.

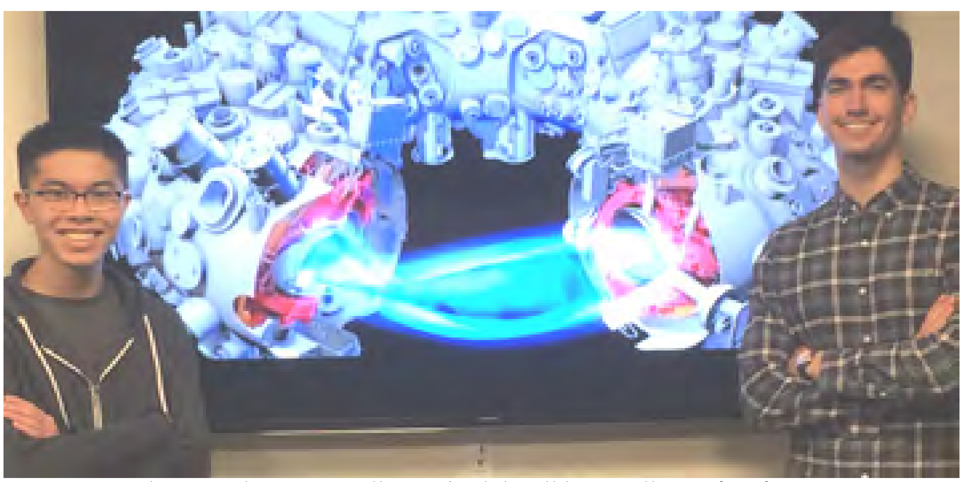

Figure 2. Graduate student Sean Ballinger (right) will be installing a fast-framing camera capable of detecting the structure and time scales of turbulence in the boundary of the hot plasma in summer 2017 at the Wendelstein 7-X Stellarator (W7-X) in Germany. Kevin Tang (left), an MIT International Science and Technology Initiatives Program student, will be helping Sean as well as drafting engineering drawings, from different vantage points, of W7-X's plasma-facing hardware. Kevin and Sean are shown flanking an artist's rendition of the W7-X plasma and the surrounding vacuum vessel.

Phase Contrast Imaging for Wendelstein 7-X Stellarator

Funding of the phase contrast imaging (PCI) project commenced in FY2016. The PI of the project is Professor Miklos Porkolab; Dr. Eric Edlund, PSFC staff scientist, leads the project in terms of design and diagnostic development. This project was funded at an initial award level of $666,000, with a subsequent add-on of $114,000 in the spring of 2016 and a recent addition of $225,000 to support a postdoctoral researcher and the purchase of some additional hardware. The project enjoys strong collaboration with Dr. Olaf Grulke of the Max Planck Institut für Plasmaphysik (IPP) in Greifswald, Germany, IPP postdoctoral researcher Adrian von Stechow, and IPP graduate student Lukas-Georg Böttger.

During FY2017, the system design was finalized and all hardware purchases completed. A final design review was held and met with a favorable assessment by a team of scientists and engineers at the Max Planck Institut für Plasmaphysik. All major equipment has been delivered to IPP. Over the course of multiple trips cumulatively exceeding three months, Dr. Edlund has assembled the PCI diagnostic with the assistance of researchers from IPP. The diagnostic was first assembled in a laser lab for testing, and in late May the entire system was transferred to the experimental facility for final installation. The PCI system is expected to be operational by the start of the next W7-X experimental campaign, which is scheduled to begin on August 28, 2017.

Correlation Electron Cyclotron Emission and n-T Phase Angle Diagnostic for ASDEX Upgrade

At ASDEX Upgrade, the PSFC team is developing a new correlation electron cyclotron emission (CECE) and n-T phase angle diagnostic for core transport physics. The overarching goal of this project is to facilitate the study of fluctuations and plasma structure at the plasma core and in the pedestal region. Detailed measurements of the turbulence are used along with synthetic diagnostics to test and validate advanced transport models using data from current tokamaks, in order to develop reliable predictive capabilities for ITER and other burning plasma experiments in the future. Work on this project is being led by the PI, Professor Anne White, IPP postdoctoral associate Simon Freethy, and NSE graduate student Alex Creely. Creely is on-site at ASDEX Upgrade for the summer of 2017. PSFC engineers Willy Burke and David Terry helped design a new upgraded receiver for the CECE diagnostic earlier this year. The ASDEX Upgrade can operate with plasma density, plasma pressure, and reactor relevant plasma wall interactions. The ASDEX Upgrade features a flexible geometry and a variety of plasma heating methods (ion cyclotron resonance heating, electron cyclotron resonance heating, and neutral beam injection), which allows for novel experiments to probe core turbulent transport. MIT has been collaborating with IPP at ASDEX Upgrade on core turbulence and transport and gyrokinetic model validation for several years. The new upgraded CECE system was installed for the summer 2017 campaign, and features a highly modular, low-noise electronic design that has enabled highly detailed measurements of the turbulence. New high-resolution measurements of electron temperature fluctuations at ASDEX Upgrade using the recently upgraded diagnostic are enabling cross-machine validation of transport codes to critically test predictive capabilities for ITER and beyond. This project has been funded by DOE for another two years.

As another strong indication of the high scientific productivity and impact of this project, the program committee for the upcoming American Physical Society's Division of Plasma Physics meeting in November 2017 has selected Simon Freethy for an invited talk on "Experimental Investigations of Turbulent Temperature Fluctuations and Phase Angles in ASDEX Upgrade."

Collaboration on the Alfvén Eigenmode Active Diagnostic

Professor Porkolab leads this project from MIT, with past participation by Dr. Paul Woskov, PSFC senior research engineer, and Dr. Valentin Aslanyan, postdoctoral research associate. This program supports experiments at the Joint European Torus (JET), the world's largest tokamak, located near the Culham Centre for Fusion Energy, UK, where Valentin is permanently based. It involves collaboration between PSFC, the group headed by Professor Ambrogio Fasoli of the Centre de Recherches en Physique des Plasmas, Lausanne, Switzerland, and a group under Professor Ricardo Galvao of the Instituto de Física, University of Sao Paulo, Brazil. Each of these institutions has provided specialized equipment and expertise to a significant engineering upgrade of the amplifiers and control electronics to drive a set of in-vessel antennas. The set of six operational phase-controlled antennas resonantly excite damped Alfvén eigenmodes of the tokamak plasma and the response is detected by external Mirnov coils. The drive frequency of the diagnostic is swept by a field-programmable gate array provided by MIT until such a resonance is detected. In addition to the frequency, the modes' damping rate is calculated from the quality factor of this resonance. Commissioning over the past year has demonstrated that the diagnostic is able to track the frequency of modes, as they change on the basis of the conditions in the plasma.

This system began collecting data in the last few days of JET operation before JET was shut down for a major upgrade this past April. Operations will resume once more in September 2017 when data will be collected on TAE wave phenomena, including identification of the toroidal mode numbers, measurement of damping rates, and comparison with gyrokinetic codes such as GTC (collaboration with Zhihong Lin, University of California, Irvine). The detection and damping measurements of Alfvén instabilities is important for future fusion devices, as they may be driven unstable by energetic particles, such as alpha particles, leading to a loss of fast fusion alpha particles. MIT has participated through the running of this diagnostic in recent JET experiments to study toroidal Alfvén eigenmodes and make extrapolations to future high-performance deuterium-tritium fusion on JET and the ITER tokamak under construction in France. MIT has also begun collaborative simulations to interpret these experiments and make predictive studies for the future. The grant for this project was renewed by DOE for another two years.

Collaboration on Control and Extension of High-Performance Scenarios to Long Pulse

Dr. P. Bonoli serves as the MIT PI of this multi-institutional international collaboration, which is led by General Atomics (San Diego, CA). As part of this collaboration, Bonoli, S. G. Baek, J.-P. Lee, S. Shiraiwa, and J. Wright collaborate with C. Yang and M. Li, and with Professor B. Ding of the Institute for Physical Sciences in Hefei, China, to carry out extensive ray tracing, full-wave, and Fokker-Planck simulations of lower hybrid current drive experiments in the

EAST tokamak in Hefei. They also collaborate with Y.-S. Bae on the modeling of advanced lower hybrid RF launcher concepts for the KSTAR tokamak in Daejeon, South Korea. A focus of their research during the past year was a detailed ray tracing and Fokker-Planck analysis of a series of high-performance discharges in the EAST device where lower hybrid current drive was used to systematically broaden the current profile.

R. Granetz, MIT graduate student A. Tinguely, and postdoctoral associate C. Rea collaborated extensively with D. Chen, X. Gu, S. Gu, B. Wang, B. Xiao, and Z. P. Luo at the Institute for Physical Sciences in Hefei on the development of disruption databases for the EAST tokamak. The ultimate goal of this work is to develop disruption warning algorithms for the EAST plasma control system that can be used to avoid damaging plasma disruption events during tokamak operation. This disruption database can be used to find predictors or "precursors" of disruptions. During the coming year, Granetz and co-workers will continue their disruption warning database work on EAST and extend these efforts to include the KSTAR tokamak.

New Projects Beginning at WEST and TCV

Additional new diagnostic development programs are being carried out in partnership with the Tungsten Environment Steady-State (WEST) tokamak at the Institute for Magnetic Fusion Research in Cadarache, France, and at the TCV tokamak at the Swiss Plasma Centre in Lausanne, Switzerland. At WEST, Dr. John Rice is involved with designing a new x-ray imaging crystal spectrometer for non-perturbative measurements of plasma ion temperature and rotation. At TCV, Dr. Robert Mumgaard and a graduate student are working on a new multispectral imaging system that can give detailed information about the internal magnetic structure in the tokamak plasma, useful for studying equilibrium and stability, as well as current drive. Dr. Amanda Hubbard collaborates with TCV on I-mode studies. She coordinates the I-mode working group, which focuses on cross-machine studies around the world.

US Collaborations

Overview of Experimental Research at DIII-D

The DIII-D tokamak in San Diego, CA, is operated by General Atomics for the Department of Energy through the Office of Fusion Energy Sciences as a user facility. Dr. Jerry Hughes, a research scientist at PSFC, is the facility coordinator for PSFC research carried out at DIII-D. New experimental work in diagnostic development is being carried out at DIII-D, with plans for installation of new suites of core impurity transport diagnostics, pedestal diagnostics, and high-field side launch current drive actuators under development. The most mature of these efforts involves installation of a laser blow-off system, work led by Dr. Nathan Howard, that will facilitate new studies of impurity transport, a critical area of work in support of ITER. In addition, Dr. Stephen Wukitch is leading efforts to explore possibilities for implementation of a next-generation current drive system, high field side lower hybrid at DIII-D.

In another example of scientific leadership at the national fusion facility, DIII-D, PSFC scientist Darin Ernst co-led an experiment to study the slowing and hollowing of the plasma rotation profile in the ITER baseline scenario, which leads to magnetohydrodynamic (MHD) instabilities that eventually lock and disrupt the plasma. Dr. Ernst also collaborates with researchers from the University of California, Los Angeles, on synthetic diagnostic development.

Dr. Nathan Howard led an experiment to probe the changes in the fine structure of density fluctuation turbulence in H-mode plasmas, obtaining data that will be used to test and validate the highest fidelity multi-scale turbulence simulations performed to date. Graduate student Pablo Rodriguez Fernandez is collaborating with General Atomics scientist Dr. Craig Petty and Princeton Plasma Physics Laboratory (PPPL) scientist Dr. Brian Grierson on understanding the propagation of "heat pulses" stimulated using electron cyclotron heating. Rodriguez Fernandez is also working with Nathan Howard to develop a new laser blow off system for DIII-D, which is used as an actuator for perturbative transport experiments. Graduate student Francesco Sciortino is working with Nathan Howard on impurity transport physics.

PSFC postdoc Theresa Wilks has been studying the pedestal characteristics of the QH-mode, which is a promising high-performance ELM–free regime of interest for future fusion reactors. This work is being led by Dr. Jerry Hughes, and will also involve graduate students, who will implement models such as EPED to study the high-performance plasmas.

Along with Robert Granetz, PSFC postdoc Christina Rea has been developing new machine-learning-based algorithms and analysis tools to study a database of disruption histories at DIII-D. Using these tools, it may be possible to identify hidden precursors to the disruptions, which could be used to ultimately predict and avoid disruptions altogether in tokamak fusion reactors. The team includes a graduate student who is enlarging the database to include results from C-Mod and the EAST tokamak. The team will ultimately produce a large, multi-machine database that can be used to better constrain predictive algorithms for disruptions.

Laser Blow-Off System in DIII-D

Laser blow-off systems are used to study core impurity transport under various configurations and confinement regimes. The new laser blow-off system being installed at DIII-D this year will provide a versatile system for injecting a wide range of impurities into DIII-D with controlled doses and known source parameters. Laser ablation of thin-film (~1 micron) coated slides can inject a wide range of impurities in trace amounts. The PSFC system is one of the most versatile in the world, with demonstrated operation with lithium, flourine, carbon, aluminum, silicon, calcium, nickel, chromium, niobium, molybdenum, and tungsten. Typical operation is non-perturbing to the background plasma conditions. Injection of non-recycling impurities eliminates unknown sources and enables a cleaner interpretation. This project, led by Dr. Nathan Howard, involves two graduate students who will use the system to study impurity and perturbative transport at DIII-D for their PhD dissertation projects.

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

Experimental studies continue using the phase contrast imaging (PCI) diagnostic installed as part of the suite of fluctuation diagnostics on the DIII-D tokamak at

General Atomics. The Principal Investigator for this work is Professor Porkolab, and the experiments are funded by two DOE diagnostic grants. The experiments measure incoherent turbulence, which is responsible for heat transport and critical to the overall performance of fusion-grade plasmas; propagation of externally generated RF waves, which are key to understanding heating of high-performance plasmas; and unstable coherent modes, which are responsible for the degradation of energy confinement, stability, and RF heating of plasmas.

The year has seen the completion of a multi-year project to add new measurement capabilities to the long-established PCI diagnostic on DIII-D by extending the detection range to include long-wavelength fluctuations not detectable by traditional PCI. The work, primarily directed by graduate student Evan Davis, adds a new imaging and detection stage to the system while sharing the laser and machine access windows of the previous system, demonstrating how future diagnostics can effectively share the limited space on future fusion-grade devices. The most recent work has focused on optimizing the signal-to-noise ratio to provide effective measurements of broadband turbulence. The new measurement, when correlated with data from the existing interferometer chord, provides a measurement of the internal toroidal structure of magnetohydrodynamic modes. The DOE grant that funded development of the upgrade has been extended for two more years to allow further exploitation of the new capabilities in physics studies.

In addition, the PCI diagnostic and PCI personnel have supported experiments under many topics of interest at DIII-D. For example, the sensitivity of PCI to sheared turbulence provides a unique contribution to recent studies of a new high-performance plasma regime known as wide-pedestal QH-mode, where the PCI measures the sensitivity of various unstable modes to the velocity shear in the edge plasma. The PCI also continues to contribute to studies of energy transport in the core plasma. Recent work has studied energy transport in plasmas that model more closely the characteristics of future fusion reactors, resulting in predictions of reduced energy confinement compared with extrapolations from current experiments with significant torque input. This work included extensive computer modeling using the state-of-the-art code GYRO and detailed comparisons with PCI measurements using a synthetic diagnostic.

Analysis of results from Alcator C-Mod continued. Previous experimental work studying the effect of impurities and density on turbulent transport has been extended to plasmas with higher current. Extensive comparisons of PCI measurements with predictions from the GYRO code were made as part of an effort to validate the mode. These studies are helping to assess the capabilities of the models to predict the performance of reactor plasmas during the critical start-up phase of the plasma discharge.

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

The goal of this project is the development of a technique for quantitative, spatially resolved measurements of high-frequency RF waves and application of the technique to the measurement of waves in the DIII-D tokamak. Waves to be studied include ion cyclotron emission, which on the DIII-D is excited at tens of MHz, and the 476 MHz helicon wave current drive project currently under development for DIII-D, along with any associated high-frequency parametric decay waves. The technique is being implemented as a modification to the phase contrast imaging diagnostic, using the existing imaging system and 32-element detector array. The new system will modulate the laser amplitude at RF frequencies to optically mix the measurement of the RF wave down to the range of low-noise cooled photoconductive arrays ($f < 1$ MHz). Phase contrast imaging with modulated laser amplitude is the only proven technique that provides absolutely calibrated measurements of the amplitude and wave structure of RF density fluctuations in a plasma. Previous work, including pioneering work performed on the Alcator C-Mod tokamak to validate models of RF heating and parametric decay, were based on a system of acousto-optic modulators and could be operated over only a very narrow range of frequencies. The system under development will be simpler and capable of studying waves over a range of 5 to 500 MHz without change to the optics, exploiting the greater flexibility of electro-optic modulation. The new system will be applicable to physics studies on DIII-D, providing measurements that will allow testing of theoretical models as well as quantitatively testing the predictions from computer models. It will also serve as a prototype of a measurement applicable to a wide range of RF heating techniques on small plasma devices to reactor-relevant experiments.

The project is currently in the design and fabrication stage, after a feasibility study which found that adequate modulation depth could be achieved with a custom-built electro-optic modulation (EOM) system, and would perform better than the alternatives. EOMs for infrared lasers are not commercially available; PSFC is identifying a vendor that can produce a Pockels cell with a cadmium telluride crystal installed in it. RF drivers will be developed in-house with the help of General Atomics personnel.

Contributions to NSTX Research and the NSTX-U Engineering Recovery Effort

In collaboration with the Princeton Plasma Physics Laboratory, Professor White's graduate student Juan Ruiz Ruiz (NSE) is using turbulence data sets from the National Spherical Torus Experiment (NSTX) from a high-k scattering diagnostic that measures the electron scale density fluctuations directly to compare them with theory and simulation. A new synthetic diagnostic under development is being used to interpret past data and predict characteristics of the turbulence and transport in future experiments planned for the NSTX upgrade (NSTX-U). In addition, the group is collaborating with Dr. David Mikkelsen at PPPL to compare two turbulence simulation codes with experiments from C-Mod to probe the importance of electron-scale turbulence in I-mode plasmas.

PSFC engineering and science personnel are also heavily engaged in assisting the NSTX-U recovery, including serving on multiple review committees and panels, and taking responsibility for engineering design of replacement and upgraded hardware. PSFC engineers are heavily involved in the design of the new poloidal field coils, bringing the coil winding facility back into operation, and working on the design of a toroidal field (TF) core mock-up facility that will assess shear stresses across turn-to-turn interfaces.

Dr. Brian LaBombard, a research scientist at PSFC, is the facility contact for PSFC work carried out at PPPL in support of NSTX-U recovery efforts.

Research Highlights

Machine Learning Applied to Reduced Model Validation in Tokamak Plasmas

Typically, validation of turbulent transport codes is done by varying one or two input parameters within error bars and then comparing them with only high-level quantities such as heat flux rather than measured turbulence. Only once a heat flux matched simulation is obtained are the simulation outputs compared to measured turbulence. This approach is inefficient and does not strongly constrain the model, but its widespread use is driven by computational challenges encountered when trying to change multiple input parameters at once while constraining a simulation to match multiple targets' objective functions.

By developing an innovative machine-learning-based tool, MIT graduate student Pablo Rodriguez Fernandez, in collaboration with scientists at General Atomics and DIII-D, has been able to use a new reduced turbulence model, the Trapped Gyro-Landau-Fluid (TGLF) model, to vary multiple input parameters at once, while also enforcing the constraints that the model must match both the ion and electron heat flux from the experiment, and the measured electron temperature fluctuation level. The research shows that only the new version of the TGLF model, which includes a new cross-scale coupling term that links effects of small and large turbulence eddies, can match experiments.

Rodriguez Fernandez developed a new tool that employed several machine-learning concepts, such as Gaussian processes, gradient-based batch optimization, and sampling and training set construction. This work is an example of the fruitful collaboration that exists between the Plasma Science and Fusion Center and off-campus experimental and theory groups in the United States.

Plasma Theory and Computation Division

The mission of the Plasma Theory and Computation Division is to conduct basic and applied plasma theory and simulation in support of domestic and international toroidal confinement devices. Funding is predominately from the US Department of Energy's Office of Fusion Energy Sciences. The division head is Senior Research Scientist Paul Bonoli and the assistant head is Associate Professor Nuno Loureiro from the Department of Nuclear Science and Engineering. Dr. Bonoli is also the lead PI for the multi-institutional SciDAC Center for Simulations of Wave-Plasma Interactions (CSWPI) and the PI at MIT for the International Collaboration on Control and Extension of High-Performance Scenarios to Long Pulse. Professor Loureiro carries out research that is funded by a National Science Foundation (NSF) Career Award, an NSF-DOE basic plasma science and engineering grant, and an MIT Reed Fund grant. PSFC principal research scientists Jesus Ramos and Abhay Ram lead the group's efforts in the SciDAC Center for Extended MHD Modeling (CEMM) and NSTX-U research at PPPL, respectively. Research Scientists John Wright and Jungpyo Lee are involved in the CSWPI. Darin Ernst is the PI at MIT for the SciDAC Center for the Study of Plasma Microturbulence and also derives support from the PSFC Theory grant as well as from the PSFC/DIII-D Collaboration. Finally, retired professor Jeffrey Freidberg is a plasma theorist who further enhances the PSFC theory effort.

New Parallel Computing Cluster

In early 2017, a new PSFC compute partition made up of 100 nodes each with 32 processing cores per node was successfully installed in the Engaging cluster at the Massachusetts Green High Performance Computing Center facility in Holyoke, Massachusetts. This work was done in close collaboration with NSE, which procured 32 identical compute nodes for their own partition. The compute partition has already been used in several research papers and invited talks.

Plasma Theory, Computation, and Discovery Science

Impurity Behavior in Tokamak Pedestals

A narrow pedestal region with strong radial density gradient separates the core and edge of tokamak plasmas during a high (H) confinement mode of operation. Measurements in Alcator C-Mod and other tokamaks normally 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 Dr. Catto have recently demonstrated in two publications that not only the impurity density in-out asymmetry, but also the poloidal flow has a major impact on the radial impurity flux direction. This realization provides a new method of measuring the radial flux from available diagnostics (such as charge exchange recombination spectroscopy and Thomson scattering), without the need of a computationally demanding kinetic calculation of the full bulk ion response. The method affords insight into optimal H mode operation to avoid impurity accumulation while allowing natural fueling and it allows heating techniques to be employed to actively modify the poloidal variation of the potential to control the radial impurity flux. Improved or I mode operation maintains the beneficial good energy confinement of H mode, while also providing fueling to compensate for impurity removal. Espinosa and Catto have shown that outward collisional radial impurity flux is the robust characteristic feature that distinguishes between I and H mode operation; the turbulent weakly coherent mode cannot always be observed.

Electromagnetic Zonal Flow Residual Responses

Near-marginal stability turbulence-generated poloidal flow shear acting to control the amplitude of the turbulence is referred to as zonal flow. In the electrostatic limit, a single check of tokamak turbulence codes shows that an initial poloidally varying zonal flow damps to a level having a non-zero residual in collisionless plasma due to finite orbit (or polarization) magnetic drift effects. However, these turbulence or gyrokinetic codes are typically fully electromagnetic. For electromagnetic tests, poloidal variation must be retained. Work by Dr. Catto with Professors Parra (University of Oxford) and Pusztai (Chalmers University of Technology, Göteborg, Sweden) has generalized the zonal flow residual calculation to determine 15 independent code tests, which include the poloidal dependence of the perturbed perpendicular and parallel magnetic field responses.

Nonlinear Critical Density Gradient for Trapped-Electron Mode Turbulence

Darin Ernst continued development of a model for the nonlinear upshift of the critical density and temperature gradients for onset of trapped electron mode turbulence and ion temperature gradient-driven turbulence respectively—the main causes of particle and energy loss in tokamak fusion devices. The model accurately calculates the Dimits Shift for ion temperature gradient turbulence as well as the trapped electron mode nonlinear critical density gradient. Sixty nonlinear simulations were carried out using the Gyrokinetic Electromagnetic Numerical Experiment gyrokinetic code, verifying the collisionality scaling found previously with the GS2 code (a gyrokinetic flux tube initial value and eigenvalue solver for fusion plasmas) and reproduced by the model. Results were presented at the 2017 Sherwood International Fusion Theory Conference.

Magnetohydrodynamics and Extended Magnetohydrodynamics Simulations

Jungpyo Lee and Jeff Freidberg have improved the previous modeling on the maximally achievable elongation in a tokamak against a vertical instability to include the effect of plasma density and temperature profiles, in collaboration with Martin Greenwald and Professor Antoine Cerfon at New York University. They found an analytical formula for the elongation in terms of many physics parameters. The results were presented at 2016 the International Atomic Energy Agency Fusion Energy Conference in Kyoto, Japan.

Heating, Current Drive, and Nonlinear Dynamics

The efficient coupling of RF wave power to plasmas in a fusion device is of prime importance. Abhay Ram and Professor Kyriakos Hizanidis (National Technical University of Athens) started theoretical studies on the scattering of RF waves by fluctuations in the edge region of fusion plasma. Their pioneering research led to a multi-institutional effort encompassing theoretical, computational, and experimental studies on the effect of fluctuations on wave propagation in plasmas. 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. In Lausanne, Switzerland, a comprehensive effort on the plasma devices TORPEX and TCV is under way to directly measure the effect of fluctuations on radio frequency waves and compare the results with theory and computations.

Dr. Jungpyo Lee, in collaboration with Dr. E. Valeo and Dr. N. Bertelli at PPPL, has developed a model that couples an ion cyclotron wave code and a Fokker-Planck code to ensure self-consistent wave propagation and damping. The coupled code was used to simulate ITER scenarios and the results were presented at the 2017 RF Topical Conference on Radio Frequency Power in Plasmas, held in Aix en Provence, France. Additionally, the quasilinear diffusion coefficients for the coupling were modified theoretically for toroidal geometry and this modification resulted in more accurate simulations, both numerically and physically.

The quasilinear operator for radio frequency heating and current drive in a tokamak is derived with magnetic drifts retained. The derivation requires retaining the magnetic moment to higher order in both the unperturbed and perturbed kinetic equations. To simplify the kinetic derivation further, some terms in the linearized kinetic equation must be evaluated explicitly. The final result is a straightforward generalization of the constant magnetic field result, since only the argument of the delta function is modified. However, the justification for this change is rather involved and requires the novel treatment employed. Their kinetic solution of the linearized equation does not employ Fourier decomposition in the poloidal angle. As a result, they obtain a compact representation of the perturbed distribution function with poloidal angle dependent coefficients for full wave code use.

Reconnection in Magnetized Plasma Turbulence

Professor Nuno Loureiro obtained an NSF Career Award to support research into the origin and evolution of cosmic magnetic fields. He continued his research into magnetic reconnection. In collaboration with University of Wisconsin–Madison Professor Stanislav Boldyrev, Professor Loureiro iniated a novel research direction by examining the effect of reconnection in magnetized plasma turbulence. This has so far led to three publications, including one in *Physical Review Letters*. The key result is that disruption of turbulent eddies by reconnection is unavoidable and leads to a fundamentally different route to energy dissipation than that predicted by the Kolmogorov-like phenomenology.

High-Performance Computing Initiatives

SciDAC Center for Simulation of Wave–Plasma Interactions

As part of research carried out in the CSWPI, a new approach for solving for the propagation of ion cyclotron waves in tokamak plasmas was developed recently by John Wright and Shunichi Shiraiwa. The approach has been migrated to completely open source tools, allowing it to be used on the new PSFC Engaging cluster, as well as at larger Department of Energy facilities. This model was used to calculate heating efficiencies of several ion cyclotron range of frequencies (ICRF) scenarios in different tokamaks. The work was presented in an invited talk by Dr. Wright at the 2017 Topical Conference on Radiofrequency Power in Plasmas in Aix en Provence, France. The simulation result (Figure 3) demonstrates a three-dimensional model simulation of ICRF wave propagation in Alcator C-Mod that includes important details of the edge plasma and wall geometry. The model successfully predicts the heating efficiency of ICRF heating scenarios where a dilute “minority” ion species is present in the plasma. During the past year, CSWPI was successfully reconfigured and will now become the Center for Integrated Simulation of Fusion Relevant RF Actuators.

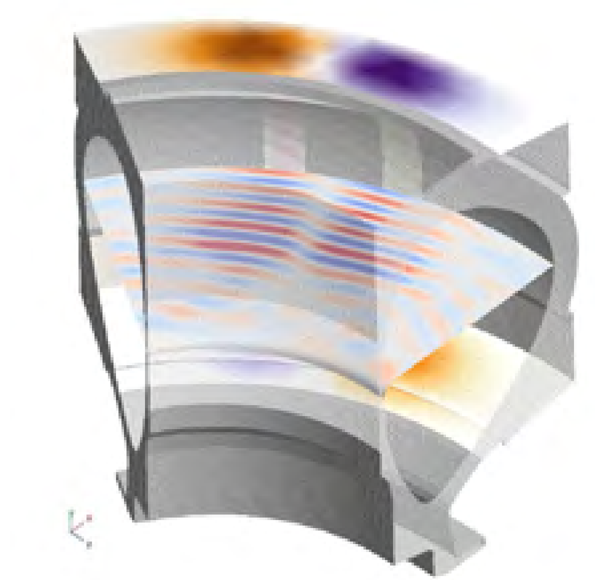

Figure 3. Sectional view of a three-dimensional simulation of ion cyclotron range of frequencies wave propagation in the Alcator C-Mod tokamak. Contours of the wave electric field at the mid-plane of the tokamak plasma and at the antenna straps are shown.

Navigational Data Management Project

John Wright is also involved in the Navigational Data Management (NDM) Project, along with Martin Greenwald and Joshua Stillerman. The NDM Project, funded by the National Science Foundation, aims to encode metadata and provenance connections in an application that permits navigation and searches of distributed but related experimental and simulation data. The first application being developed aims to link electronic notebook entries, engineering data, and experimental measurements from new high-field, high-temperature superconducting magnetic technology being developed at PSFC.

SciDAC Center for Simulation of Plasma Microturbulence

Darin Ernst participates in both the SciDAC Center for Simulation of Plasma Microturbulence and the PSFC/DIII-D domestic collaboration. Because of these dual roles, he is able to bring high-performance computing resources in the form of gyrokinetic simulations to the PSFC/DIII-D research. The SciDAC Center for Simulation of Plasma Microturbulence was also successfully reconfigured during the past year and will now become the Partnership for Multiscale Gyrokinetic (MGK) Turbulence.

Domestic and International Collaborations

PSFC–DIII-D Collaboration

In collaboration with the University of California, Los Angeles, Darin Ernst developed full-wave simulations of the Doppler backscattering millimeter-wave-based diagnostic that measures turbulent fluctuations in the the DIII-D tokamak. The simulations guided a new semianalytic description of the measurement spot size. Turbulence simulations using the GYRO gyrokinetic code, with a new synthetic diagnostic based on the new spot size calculation, closely reproduce measured spectra without adjustment while also matching transport fluxes of particles, energy, and momentum within measurement uncertainty, both with and without strong electron heating. A discrete band of trapped electron modes in the inner plasma core was observed and reproduced by simulations. This work was presented in an invited talk at the Joint EU–US Transport Task Force Meeting in Leysin, Switzerland, in 2016, and in an oral talk at the IAEA Technical Meeting on Fusion Data Processing and Analysis in 2017.

Ernst also co-led a DIII-D experiment to study the slowing and hollowing of the plasma rotation profile in the ITER baseline scenario, which leads to MHD instabilities that eventually lock and disrupt the plasma. The results showed that the rotation slowing and hollowing is due to shorter wavelength electron turbulence and not to low mode number core tearing modes as previously believed.

Simulations in Support of the Theory Performance Target

Research carried out as part of the International Collaboration on Control and Extension of High-Performance Scenarios to Long Pulse has been reported under the PSFC Collaborations subdivision section of this report. Research was also carried out for the EAST tokamak in Hefei, China, as part of this collaboration, which is cross-cutting with research carried out in the PSFC Theory Group. Lower hybrid current drive will be indispensable for driving off-axis current during long-pulse operation of future burning plasma experiments, including ITER, since it offers important leverage for controlling damaging transients caused by magnetohydrodynamic instabilities. However, the experimentally demonstrated high efficiency of lower hybrid current drive is not completely understood. As part of a high-level DOE theory performance target in FY2017, massively parallel, high-resolution simulations were carried out by Jungpyo Lee, Paul Bonoli, and John Wright using a full-wave radio-frequency field solver and a continuum Fokker-Planck code to elucidate the roles of toroidicity and full-wave effects. These coupled simulations were enabled by using a workflow manager called the Integrated Plasma Simulator in collaboration with Donald Batchelor at the Oak Ridge National Laboratory. In the coming year, these simulation predictions will be compared with experimental data from the EAST device.

High-Energy-Density Physics Division

This was an outstanding year for the High-Engergy-Density Physics (HEDP) Division's scientists and students. Chikang Li, Richard Petrasso, and Fredrick Seguin (Figure 4) were chosen as recipients of the American Physical Society's 2017 John Dawson Award for Excellence in Plasma Physics Research for their development of the new multiple-monoenergetic-particle source (MMPS). Li, Petrasso, and Seguin also applied the MMPS to a wide range of physics experiments involving the observation and measurement of laboratory plasma phenomena and associated electromagnetic fields through radiography and other means. The MMPS is a laser-driven capsule containing D^3He fuel, which produces monoenergetic charged fusion products, including 3.0 MeV protons, 14.7 MeV protons, and 3.6 MeV alpha particles during a 0.1 nanosecond time interval. It can be used either as a backlighter for multiple monoenergetic particle radiography or as a source of monoenergetic particles for other non-imaging experiments, such as quantitative studies of ion stopping in plasmas. The particles from the MMPS provide uniform illumination and enable quantitative analysis that is only possible with an isotropic, monoenergetic particle source. The many subjects the division has studied with multiple monoenergetic particle radiography include plasma jet propagation scaled from astrophysical contexts (e.g., the Crab Nebula), magnetic reconnection, and inertial confinement fusion (ICF) experiments at the OMEGA Laser Facility (University of Rochester) and the National Ignition Facility (NIF) of the Lawrence Livermore National Laboratory.

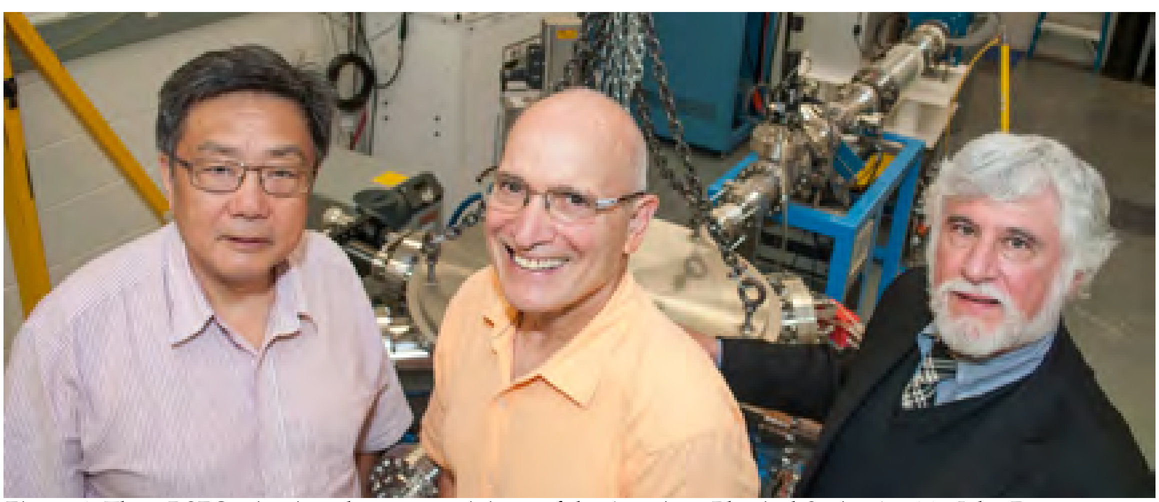

Figure 4. Three PSFC scientists chosen as recipients of the American Physical Society's 2017 John Dawson Award for Excellence in Plasma Physics Research, standing in front of the target chamber of the HEDP Division's accelerator facility. From left to right: Chikang Li, Richard Petrasso, and Fredrick Seguin.

The MIT scientists shared the Dawson Award with three scientists from other institutions (Andrew MacKinnon, Lawrence Livermore National Laboratory; Marco Borghesi, Queen's University, Belfast, Northern Ireland; and Oswald Willi, Heinrich Heine University, Düsseldorf, Germany). These scientists had applied a different kind of proton source to radiography of plasmas, using target normal sheath acceleration, in which a laser pulse strikes a planar target and generates a strong electric field, charge separation, and resultant picoseconds-duration proton beam with a continuous energy spectrum.

The MMPS has been used by several division students in research critical to their PhD dissertations. These include Mario Manuel and Michael Rosenberg, who received the American Physical Society's Rosenbluth Outstanding Doctoral Thesis Award in 2014 and 2016, respectively, and Alex Zylstra, who has now been nominated for the same award. Manuel used it for radiographic studies of the Rayleigh-Taylor instability, Rosenberg used it for radiographic studies of magnetic reconnection, and Zylstra used it as a source of monoenergetic ions in experiments concerning the slowing of ions in warm dense matter.

Other important division accomplishments include experimental measurements by Maria Gatu Johnson of nuclear reactions relevant to stellar and big-bang nucleosynthesis using high-energy-density plasmas at the OMEGA laser facility and the the National Ignition Facility. Johan Frenje studied ion stopping in plasmas, with particular emphasis on its relevance to DT-alpha stopping in the context of inertial confinement fusion for understanding ignition margins in various ICF implosion designs. He also worked with postdoctoral associate Cody Parker and graduate student Christopher Wink on the design of a transformational diagnostic called the magnetic recoil spectrometer for measuring the time history of the fusion neutron spectrum at the NIF. Wink has just completed his master's degree with a thesis based on his work with the magnetic recoil spectrometer design.

HEDP Division PhD students Hong Sio, Brandon Lahmann, Neel Kabadi, Graeme Sutcliffe, and Raspberry Simpson made many important strides in the development of new diagnostic methods and in laboratory studies of HEDP and ICF physics during the year. For example, Hong Sio recently implemented the Particle X-ray Temporal Diagnostic (PXTD) on OMEGA for simultaneous time-resolved measurements of several nuclear products as well as the x-ray continuum produced in HEDP. That system enables, for the first time, accurate and simultaneous measurements of x-ray emission histories, nuclear reaction histories, their time differences, and measurements of $T_i(t)$ and $T_e(t)$ from which an assessment of electron-heat conduction and ion-electron equilibration rates can be made. A new PhD student, Patrick Adrian, will join the division in the fall, and undergraduate student Marta Manzin is already becoming an expert on particle detection since beginning work with the division in June.

The PXTD diagnostic developed by Sio demonstrates the major impact the PSFC students have in the HEDP field. PXTD is the 11th major diagnostic instrument that MIT has developed for the OMEGA laser facility (a 12th is under development), and there are eight critical MIT-developed diagnostics at the NIF (three more are under development). These diagnostics, together with the wide-ranging plasma physics research the division does, and the trained HEDP scientists that it educates, support the conclusion that MIT is the only university with such a major presence in the HEDP field.

The HEDP Division is affiliated with the Department of Energy's National Nuclear and Security Administration(NNSA). NNSA's Brigadier General Michael Lutton and Njema Frazier, head of the National Inertial Confinement Fusion Program, recently spent a day visiting with students and staff (Figure 5).

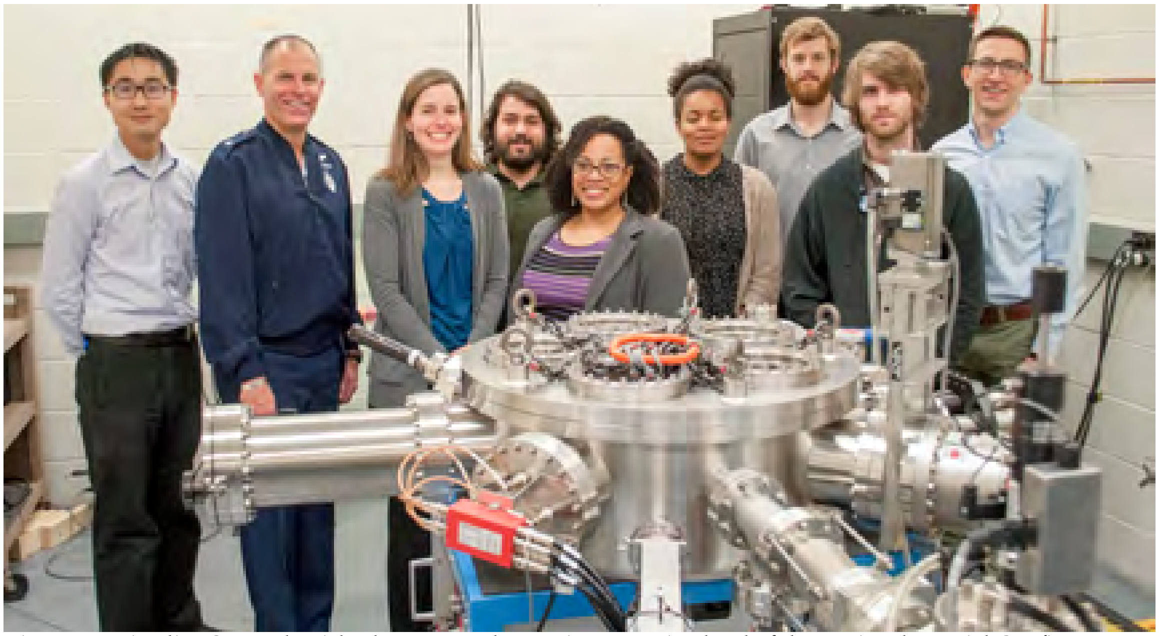

Figure 5. Brigadier Genenal Michael Lutton and Dr. Njema Frazier, head of the National Inertial Confinement Fusion Program, with PSFC graduate students and postdocs at the HEDP Division's Accelerator. From left are Hong Sio, Geeral. Lutton, postdoc Cody Parker, Neel Kabadi, Dr. Frazier, Raspberry Simpson, Graeme Sutcliffe, Brandon Lahmann, and Chris Wink. All experiments that MIT fields and implements at the NIF, the Omega Facility at the University of Rochester, and the Z Facility at Sandia National Laboratory are first tested and developed at the Division's Accelerator facility.

Plasma Science and Technology Division

In FY2017, the Plasma Science and Technology Division was formed to bring the research of the former Waves and Beams Division and plasma surface interactions science under the same roof. The former Waves and Beams Division focused on gyrotron and accelerator research and research on gyrotron drilling for geothermal energy; it was led by Paul Woskov, senior scientist and assistant division head. The plasma surface interactions science work was directed by Professor Dennis Whyte and Kevin Woller. The new division is headed by Richard Temkin, senior scientist in the Physics Department and associate director of the PSFC.

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 program of NMR research on biomolecules. These high-power applications require vacuum electron devices operating at frequencies in the range of 90 to 500 GHz, at power levels from watts to megawatts. The gyrotron, a form of electron cyclotron maser operating at high magnetic fields, is ideally suited for these applications, although interest is growing in extending the frequency of more compact sources, such as klystrons and TWTs, into this frequency range. Research on gyrotrons is aimed at increasing the efficiency of a 1.5 MW, 110 GHz gyrotron with an internal mode converter and a depressed collector. In academic year 2017, PSFC completed a 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, showing that the converter provides a compact gyrotron system with an efficiency comparable to conventional gyrotrons equipped with much larger converters. The 1.5 MW gyrotron is also being used to study breakdown in gases and in vacuum. The accelerator research group at the SLAC National Accelerator Laboratory is preparing accelerator structures at 110 GHz for test in vacuum using pulses from the gyrotron. PSFC is also continuing research on low-loss microwave (170 GHz) transmission lines in collaboration with the US ITER Project, which has headquarters 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 into higher order modes, which can cause high losses and possibly damage transmission lines. In AY2017, PSFC tested a pair of motorized polarizers that will be used on the ITER transmission line and successfully compared the results with theory. PSFC also collaborated with the QST research group in Mito, Japan, on testing a concept for eliminating unwanted parasitic modes in transmission lines.

In AY2017, PSFC continued its program to build high-power vacuum microwave devices that are based on slow-wave structures, including traveling wave tubes, backward wave oscillators, and klystrons, at frequencies from the microwave to the terahertz region. These devices use electromagnetic waves with phase velocity that is lower than the speed of light, in contrast to fast-wave gyrotron sources. PSFC also obtained more than 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 subwavelength components, such as split rings, which yield changes to the permittivity and permeability of the medium. The output power was found to arise from a cyclotron-Cherenkov mode. PSFC has recently found that theory predicts operation in the observed mode. In addition, PSFC built the first version of an oversized klystron at 94 GHz as part of a Defense Advanced Research Projects Agency (DARPA) program to innovate high-frequency microwave devices, extending to the terahertz frequency region. High-power testing will begin later this year.

Research on high-gradient accelerators is focused on high-frequency linear electron accelerators that may greatly reduce the size and cost of future accelerators. Research is conducted using 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 AY2017, PSFC completed a renovation of this laboratory to move and modernize the control room. Researchers also obtained first results on studies of internal dark current in a high-gradient accelerator structure using small holes in the structure sidewall to measure the electron stream. Dark current is current emitted by field emission from surfaces of the accelerator wall that may lead to breakdown. The measurements are being compared with code predictions.

Geothermal Energy and Deep Nuclear Waste Storage

Low-cost access into deep basement rock would enable virtually limitless geothermal energy for climate-friendly base power on a large scale and would also provide a secure option for deep borehole nuclear waste storage far from the earth’s biosphere. Under the leadership of Principal Investigator 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 if boring into deep hard rock and sealing holes with millimeter-wave directed energy is feasible. MMWs can succeed, where infrared beams from laser sources have not, in enabling deep full-bore directed-energy penetration into hard rock because of fundamental physics and technology advantages. Longer wavelength MMWs more readily penetrate past small particulates into a borehole creating environment and are more efficiently guided over long distances at high power in borehole scale dimensions. Technologically, the average power of gyrotrons is almost 100 times higher than and more than twice as efficient as the most advanced fiber lasers.

During FY2017, Woskov, along with Professor Herbert Einstein at the MIT Rock Mechanics Laboratory in the Department of Civil Engineering, and Ken Oglesby of Impact Technologies, LLC, completed a small business technology transfer contract funded by DOE's Office of Nuclear Energy to research the application of this technology to deep borehole nuclear waste storage. The work was primarily focused on sealing holes in rock with melted rock. Initial plans for collaborative experiments with the Air Force Research Laboratory at Kirtland Air Force Base and its 100 kW, 95 GHz gyrotron system were put off when the gyrotron was accidentally damaged during modifications for the planned experiments. Instead, several predrilled cylinders of granite and basalt were prepared and filled with melted rock and nuclear waste glass matrixes using the 10 kW, 28 GHz gyrotron at MIT. Significant borehole wall damage was observed with the granite and basalt melts, in part due to the longer dwell times—up to 20 minutes per inch were necessary with the lower-power gyrotron. The lower-melting-temperature nuclear waste glasses sealed with little apparent wall damage, requiring dwell times of less than five minutes per inch. Alta Rock has taken an option from MIT on this technology for geothermal energy and venture capital funding is being explored.

Additive Manufacturing Measurements

The advent of 3D fabrication to build up components and new materials from small metal and ceramic particles with intense energy beams brings new capability to manufacturing products with shapes and properties not previously possible. This additive manufacturing approach and the computer tools used to design and optimize components are advancing rapidly, with very promising results so far. A concurrent advance in metrology is needed to monitor, analyze, and control the process in real time to achieve the full potential. Dr. Paul Woskov is working with Sandia National Laboratories in the Born Qualified Grand Challenge to advance additive manufacturing by investigating, developing, and implementing in-process analysis methods and technologies. In FY2017, he developed and delivered a dual receiver millimeter wave system at 137 GHz for measuring the emissivity of alloy melts used in the additive manufacture of components. He has participated on site in setup and measurement activities.

Magnets and Cryogenics Division

In academic year 2017, the divisions within the PSFC were reorganized. The Fusion Technology and Engineering Division was reorganized into the Magnets and Cryogenics Division to better reflect the division's strategic interest in developing magnet systems for future higher magnetic field fusion reactors. The division is headed by Dr. Joseph

Minervini. Recognizing the tight integration required between superconducting magnets and cryogenic engineering, the deputy director of the division is Professor John Brisson, who also heads the MIT Cryogenics Engineering Laboratory. The PSFC has previously proposed to MIT's vice president for research that the Cryogenics Engineering Laboratory be absorbed by the Plasma Science and Fusion Center and that the laboratory's aging liquefaction plant be replaced by an entirely modern cryogenic helium liquefaction and gas recovery system that would better serve the MIT research community.

The Magnets and Cryogenics Division conducts research on conventional and superconducting magnets for fusion devices and other large-scale power and energy systems. Recent R&D (research and development) has been directed toward applying rare earth barium copper oxide (REBCO) high-temperature superconducting (HTS) materials to an advanced, very high-field tokamak concept, where magnetic fields can be as high as 22 tesla at the Toroidal Field (TF) coils. Our laboratory-scale R&D has been focused on staged development of high-current conductors using REBCO HTS materials. Since HTS conductors can have very high engineering current densities at temperatures well above 4.2°K liquid helium, one of our graduate student's research is focused on using either supercritical forced flow helium in a temperature regime of 10–20°K, or using forced-flow supercritical hydrogen as a coolant in the temperature range of 15–30°K.

The final year of research was concluded 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. The studies were focused on all-superconducting machines with both the magnetic field windings and the armature windings made from HTS wires or tapes. At this time there is no follow-on to this contract.

In keeping with our intensified R&D efforts into REBCO HTS materials, the division was recently awarded a research grant under a collaboration with Superconductor Technologies, Inc. (STI) in Austin, TX. STI is the prime recipient of the $4.5 million program award from DOE's Office of Energy Efficiency and Renewable Energy, on behalf of the Advanced Manufacturing Office, for its Next Generation Electric Machines program. Other collaborators are TECO-Westinghouse Motor Company, an industry-leading manufacturer of electric generators and motors, and the University of North Texas. The team will focus on improving the manufacturing process of superconductive wires to improve performance and yield, while reducing cost, at high enough temperatures where nitrogen can be used as the cryogenic fluid.

A continuing research focus area has been in highly compact superconducting cyclotrons for proton radiotherapy. Work this year continued under the final year 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. The division is 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 in which 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.

Within this medical research area, work also continued on lightweight superconducting bending magnets to be used on PBRT rotating gantries, funded by Ion Beam Applications, Inc., the world's leading company for PBRT system installations.

Magnetic Resonance Division

Five Principal Investigators led the research activities of the Magnetic Resonance Division of the PSFC, formerly the Francis Bitter Magnet Laboratory Division. They are Professors Robert Griffin and Mei Hong (Chemistry), Dr. Yukikazu Iwasa (PSFC), and Drs. Jagadeesh Moodera and Richard Temkin (Physics). Research activities of the first four investigators are discussed below. The research activities of Dr. Temkin, who is associate director of the PSFC and who also has research activities related to plasma science and fusion, were described in the Plasma Science and Technology Division section.

Robert G. Griffin, Professor, Chemistry

Research in the Griffin group covers four different areas: development of new NMR methods for measurement of distance and torsion angles via dipolar recoupling, structure determination of amyloid fibrils, structure and mechanism of membrane protein function, and development of high-frequency dynamic nuclear polarization and electron paramagnetic resonance to enhance NMR signal intensities. Three are described below.

Dipolar Recoupling, Spectral Assignments, and Distance and Torsion Angles Measurements

In the late 1980s and early 1990s, the Magnetic Resonance Division introduced the concept of dipolar recoupling to solid-state NMR via the rotational resonance experiment to measure 13C–13C distances. Shortly afterward, the division published the rotary resonance recoupling experiment to measure 13C–15N and other heteronuclear distances. These two papers and the rotational echo double resonance experiment of Gullion and Schaefer nucleated a substantial worldwide research effort to develop methods to measure homo- and heteronuclear distances and torsion angles. The effort resulted in the publication of pulse sequences such as RF-driven recoupling, frequency-selective rotational echo double resonance, dipolar assisted rotational resonance, DREAM SPR-5, and so on.

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 magic-angle spinning (MAS) PAR spectrum obtained from U-13C/15N–AβM01-42 fibrils and recorded at $\omega 0H/2\pi$ = 800MHz was essential in determining the structure. The resolution was excellent and the distance information obtained from it and similar spectra were essential to solving the structure of Aβ1-42. In addition, during the past year, the Griffin group developed a new approach to optimizing PAR and performing 15N–15N correlation experiments. The group demonstrated a novel three-dimensional NNC magic-angle spinning NMR experiment that generates 15N−15N internuclear contacts in protein systems using an optimized 15N−15N PAR mixing period and a 13C dimension for improved resolution. The optimized PAR condition permits the acquisition of high signal-to-noise ratio, 3D data that enable backbone chemical shift assignments using a strategy that is complementary to current schemes. The spectra can also provide distance constraints. The utility of the experiment is demonstrated on an M0 Aβ1-42 fibril sample that yields high-quality data that are readily assigned and interpreted. The three-dimensional NNC experiment, therefore, provides a powerful platform for solid-state protein studies and is broadly applicable to a variety of systems and experimental conditions.

The pulse sequences that we are developing consist of evolution under multi-quantum magic-angle spinning excitation to obtain an isotropic 17O dimension and recoupling to 13C/15N, 1H, or both. Accordingly, we have recorded 17O spectra of [70% 17O, 100% 13C, 15N]-N-Ac-VL, and obtained an isotropic 17O spectrum. We have also recorded MAS 15N–17O and 13C–17O correlation spectra. Clearly, signal-to–noise ratio is going to be an issue in these experiments and the group plans to incorporate dynamic nuclear polarization (DNP) into the scheme. The group is working on developing methods to decrease the cost of producing 17O and to find ways to produce 13C/15N and 17O label proteins.

Structure of Fibrils of $A\beta_{1-42}$, the Toxic Species in Alzheimer's Disease

Protein misfolding and aggregation, and the subsequent formation of amyloid fibrils, is established as part of the pathology of more than 40 human diseases, including Parkinson's disease, dialysis-related amyloidosis, and Alzheimer's disease. Of these, Alzheimer's disease is the most devastating of the neurodegenerative diseases, in terms of both case numbers and severity. In the US alone, there are currently about 5.5 million patients with Alzheimer's disease. 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 Alzheimer's disease 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 providing structures of amyloid fibrils and oligomers.

The Griffin group has been using these methods to examine proteins that form fibrils, such as β2m and ΔN6, associated with dialysis-related amyloidosis. In addition, the group completed a study that determined the structure of Aβ1-42, which is the toxic species in Alzheimer's disease. Researchers recorded two-dimensional 13C-13C NMR spectra from fibrils and extracted more than 500 distance constraints. These constraints are divided into sequential, medium range, and long range categories, which determine the structure of the monomer. In addition, the fibril consists of two molecules arranged back to back and generate the fourth category, intermolecular constraints. The structure of Aβ1-42 is a dimer. The root mean square deviation 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.

Dynamic Nuclear Polarization

Dynamic nuclear polarization is theoretically able to enhance the signal in nuclear magnetic resonance experiments by a factor of 658. However, DNP enhancements used in high-field, high-resolution biomolecular magic-angle spinning NMR are still well below this limit, mainly because the continuous-wave DNP mechanisms that are currently employed in these experiments scale as ω_0^{-n} (where (n ~ 1–2). In contrast, pulsed DNP methods such as nuclear orientation via electron spin-locking (NOVEL), in which the DNP efficiency is independent of the strength of the main magnetic field, represent a viable alternative approach for enhancing nuclear signals. At 0.35 T/15 MHz/9.8 GHz, the NOVEL scheme was recently demonstrated to be efficient in frozen solution samples doped with stable radicals, generating ^{1}H NMR enhancement factors up to 430. However, a major impediment in the implementation of NOVEL at high fields is the requirement for increasingly high electron microwave power to fulfill the on-resonance polarization-transfer matching condition, $\omega_{01}= \omega_{1S}$, where ω_{01} and ω_{1S} are the nuclear Larmor and electron Rabi frequencies, respectively. During the past year, the group exploited a generalized matching condition that states that the effective Rabi frequency, ω_{1S}^{eff}, matches ω_{01}. Thus, the electron resonance offset relaxes the requirement of high microwave power. By using this generalized matching condition, the group was able to generate a ^{1}H NMR signal enhancement factor of 266 (roughly 60% of the on-resonance NOVEL enhancement) with $\omega_{1S}/2\pi$=5 MHz. The group investigated experimentally the conditions for optimal transfer of polarization from electrons to ^{1}H both for the NOVEL mechanism and for the solid-effect (SE) provide, and provide a unified theoretical description for the two historically distinct forms of DNP.

The Griffin group also explored time domain experiments such as NOVEL, which matches the electron Rabi frequency to the nuclear Larmor frequency to mediate polarization transfer. However, satisfying this matching condition at high frequencies is technically demanding. As an alternative, the group here reports frequency-swept integrated solid effect experiments that allow low-power sweeps of the exciting microwave frequencies to constructively integrate the negative and positive polarizations of the solid effect, thereby producing a polarization efficiency comparable with that of NOVEL (approximately 10% difference). Finally, the microwave frequency modulation results in field profiles that exhibit new features that are called the "stretched" solid effect.

A third approach to pulsed DNP uses a ramped-amplitude nuclear orientation via electron spin locking (RA-NOVEL) sequence that utilizes a fast arbitrary waveform generator to modulate the microwave pulses together with samples doped with narrow-line radicals such as 1,3-bisdiphenylene-2-phenylallyl (BDPA), sulfonated-BDPA, and trityl-OX063. Similar to ramped-amplitude cross polarization in solid-state NMR, RA-NOVEL improves the DNP efficiency by a factor of up to 1.6 compared with constant-amplitude NOVEL (CA-NOVEL), but requires a longer mixing time. For example, at τ_{mix} = 8 μs, the DNP efficiency reaches a plateau at a ramp amplitude of ±20 MHz for both SA-BDPA and trityl-OX063, regardless of the ramp profile (linear vs. tangent). At shorter mixing times (τ_{mix} = 0.8 μs), the tangent ramp is superior to its linear counterpart; in both cases, there exists an optimum ramp size and therefore ramp rate. The results suggest that RA-NOVEL should be used instead of CA-NOVEL as long as the electronic spin lattice relaxation T1e is sufficiently long, or the duty cycle of the microwave amplifier is not exceeded, or both. To the best of the group's knowledge, this is the first example of a time domain DNP experiment that utilizes modulated microwave pulses. The results also suggest that a precise modulation of the microwave pulses can play an important role in optimizing the efficiency of pulsed DNP experiments and that an arbitrary waveform generator is an elegant instrumental solution for this purpose.

Mei Hong, Professor, Chemistry

The Hong group develops and employs solid-state NMR techniques to investigate structural biology and biophysical questions of contemporary interest. The group currently focuses on disease-relevant viral membrane proteins, energy-relevant plant cell wall materials, and amyloid fibrils involved in diseases and in chemical catalysis.

Structure and Dynamics of Influenza M2 Proteins

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

Since 2007, the Hong group has been investigating 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 in phospholipid bilayers, and have revealed the structure and dynamics of the crucial proton-selective residue, a histidine in the TM domain. In AY2017, two new studies were completed in this long-term project. The first was designed to understand how the protein conducts protons asymmetrically, from the N-terminus to the C-terminus. Electrophysiology data indicate that this asymmetric conductance is controlled by a tryptophan (Trp) residue. By mutating this Trp to a phenylalanine, Mandala et al. showed that the protons become accessible to the proton-selective histidine from the C-terminus in addition to the N-terminus and alter the protonation equilibria of the histidine. Thus, Trp's functional role in wild-type M2 is to prevent C-terminal acid activation of the channel. The second study addressed how cholesterol binds M2 to mediate membrane scission. The cholesterol-bound structure of membrane proteins is difficult to determine by other structural techniques because of the non-crystalline and dynamic nature of this molecule and the requirement of lipid bilayers for such studies. Using a novel combination of carbon-13, flourine-19, and deuterium solid-state NMR techniques and sophisticated analysis, Elkins et al. determined the cholesterol binding site and binding stoichiometry to M2 and the structure of the bound cholesterol. This work is significant because it is the first NMR-determined structure of a cholesterol-bound membrane protein, and it suggests the molecular structural basis for M2-mediated membrane scission.

Structure and Lipid Interactions of Viral Fusion Proteins

Viral fusion proteins mediate the entry of enveloped viruses 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 importance. Most class I viral fusion proteins, such as those of influenza and human immunodeficiency virus, contain two hydrophobic domains, an N-terminal fusion peptide domain and a C-terminal TM domain, which interact with the lipid membrane to cause membrane curvature. In AY2017, the Hong group completed a study to determine the oligomeric structure and assembly of the TM domain of the PIV5 fusion protein. This was achieved by measuring fluorine-19–fluorine-19 dipolar couplings in site-specifically fluorinated peptides. The data directly showed that the TM domain assembles as trimers, thus providing the first structural evidence of the intermolecular association of the TM domain of class I viral fusion proteins in lipid bilayers.

Structures of Amyloid Proteins

In AY2017, the Hong group carried out a novel study of the spatial distribution and dynamics of water associated with the amyloid fibrils formed by the Alzheimer's β-peptide. While there is a large body of literature about solid-state NMR structure determination of neurodegenerative amyloid fibrils, the behavior of amyloid-associated water is almost completely unknown, despite the fact that water is essential in driving the folding and self-assembly of these peptides. Using hydrogen-1 and carbon-13 solid-state NMR and site-resolved relaxation time measurements, Wang et al. showed that Aβ fibrils have two pools of highly mobile water that are in slow exchange. This very unusual behavior can only be explained by the presence of interfibrillar water that "lubricates" the fibrils and that is separated from the bulk water by the micron-length fibrils. This finding may have implications for the diagnosis of disease-relevant amyloid fibrils.

Plant Cell Wall Polysaccharides

Plant cell walls are rich in polysaccharides, including cellulose, hemicellulose, and pectins. Cell walls provide mechanical strength to plant cells but at the same time can be loosened to enable plant growth. Elucidating the plant cell wall structure at the molecular level is important not only for better understanding of fundamental plant biochemistry but also for giving insight into converting plant biomass to energy. The Hong group investigated the structure and dynamics of plant cell wall polysaccharides using multidimensional carbon-13 and hydrogen-1 solid-state NMR techniques. In AY2017, Phyo et al. conducted two studies on how matrix polysaccharides interact with cellulose on the molecular level. In fast-growing inflorescence, the cell walls were found to contain an unusually high level of pectins and relatively low concentrations of cellulose compared with seedling cell walls. Moreover, the concentration of pectins directly correlates with the growth rate and loosening ability of the cell wall. This is an important result, as it adds the growing evidence that pectins play an important role in wall mechanics and loosening, unlike the traditional model of plant cell wall structure. In a second study, Phyo showed that cleavage of homogalacturonan chains by genetic mutations causes distinct changes to the dynamics of the polysaccharides. Cellulose and matrix polysaccharides show weaker interactions, thus explaining the fast-growing phenotype of the low-molecular-weight mutant.

The M2 project and viral fusion protein project are funded by the National Institutes of Health. The plant cell wall project is funded by an Energy Frontier Research Center grant from Pennsylvania State University.

Yukikazu Iwasa, Senior Research Scientist

From July 1, 2016, through June 30, 2017, the Magnet Technology Group, under Dr. Iwasa's leadership, was involved in three NIH-supported programs on NMR and MRI magnets. Each is 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 low-temperature superconducting (LTS)/HTS NMR magnet (modified Phase 3B) study 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 (30.5 THz) using high-temperature REBCO superconductors.

Liquid Helium–Free Persistent-Mode HTS Magnets for NMR and MRI Applications

This project has two specific aims that should enable REBCO-based double-pancake coils to operate free of liquid helium (LHe) in persistent mode: to build REBCO double-pancake coils, each terminated with a superconducting joint; and to design, build, and operate persistent-current switch viable to these REBCO double-pancake coils operating in the range of 4.2 K to 77 K. The project is supported by the National Institute of Biomedical Imaging and Bioengineering. It began on July 1, 2016, and its end date is April 30, 2018.

Tabletop Liquid-Helium-Free, Persistent-Mode 1.5-T/70-mm Osteoporosis MRI Magnet

Supported by the National Institute of Biomedical Imaging and Bioengineering and begun on April 1, 2017, this project has two specific aims: completion of a tabletop, LHe-free, persistent-mode, solid nitrogen (SN2)–cooled superconducting magnesium diboride (MgB2) MRI magnet prototype for phalangeal scanning for osteoporosis research; and, in the fifth year, a demonstration, by Dr. Jerome Ackerman (co-investigator) of the Martinos Center, Massachusetts General Hospital, of the benefits of MgB2/SN2 technology for MRI magnets in the context of a very compact affordable scanner. Using the distal phalanx of the left hand, Ackerman will measure true 3D bone mineral density, 3D bone matrix density, and trabecular microstructure.

Jagadeesh Moodera, Senior Research Scientist

Jagadeesh Moodera is a senior research scientist and a group leader in the Department of Physics, with his research lab located in the Francis Bitter Magnet Laboratory. His research effort is in nanoscience condensed matter physics (quantum coherent transport in nanodevices, investigation of Majorana fermions, molecular spintronics, and so on) with funding from ONR, NSF, and the John Templeton Foundation (collaborator: Professor Patrick Lee, Physics).. He is also part of the large, NSF-funded, five-year Science and Technology Center on Integrated Quantum Materials (C-IQM). This is a partnership involving Harvard University, Howard University, MIT, and the Boston

Museum of Science, complemented by international collaborators. C-IQM also has a network of investigators and teachers from Mount Holyoke, Olin, and Wellesley colleges in the Boston area, as well as Gallaudet University and Prince George's Community College in the Washington, DC, area. Based on its success during the past four years, this program is in the final stages of being renewed for another five years.

Dr. Moodera has collaborations with various faculty members at universities in the US, Canada, the UK, Germany, Spain, India, Italy, and Russia, and with scientists at Oak Ridge National Laboratory and Brookhaven National Laboratory. Currently he focuses on two-dimensional quantum coherent and dissipationless transport, interface-induced magnetic and electronic effects at the molecular level, with an emphasis on topological insulators—one of the most significant topics in physics. During the past year, his group was investigating a ferromagnetic/superconductor hybrid system to reveal the exchange coupling phenomena at the interface. The goal was to understand the basic physics and to develop superconducting spintronics (memory, sensing, and logic). His group investigated nanostructures, searching for quantum coherent behavior of charge and spin transport in these novel systems. Another exciting research effort is the search for the exotic Majorana fermions and manipulating spins in organic molecules.

Dr. Moodera's group, along with his collaborators, published several articles in journals such as *Nature Communications, Science Advances,* and *Physical Review Letters.* Dr. Moodera serves on the organizing committees of international scientific workshops. He delivered invited talks at universities and international conferences in the United States, Japan, China, India, and Europe, and delivered lectures at Fukuoka University in Japan and Shenzhen University of Science and Technology in China as an invited visiting scientist.

Dr. Moodera's group continues to lead the field in its studies on novel quantum materials and superconducting spintronics. The quantum anomalous Hall effect is believed to have unique potential for applications in electronic devices with low-power consumption. The dissipationless spin polarized edge current flow in a topological insulator is expected to have a significant influence on the development of low-power spin-based storage and communication technologies of the future. Currently, the group is investigating such behavior in nano devices. If these could be exploited, they could have a transformational influence on data storage and communications. Thus, in condensed matter physics with research focused on nanoscience, particularly related to quantum coherent phenomena, Dr. Moodera's group continues to make significant contributions in both fundamental and applied sciences.

Using state of the art molecular beam epitaxy systems, Moodera's research group seeks to contribute to the understanding of the quantum state exhibited by many novel materials. To investigate the behavior of atoms and molecules on various interacting surfaces, a custom-designed low temperature (280 millikelvin) scanning tunneling microscope and atomic (conducting) force microscope system capable of operating in high magnetic fields (in-plane with precise sample orientation capability) are in operation. One of the major projects for this new sophisticated tool is the investigation of Majorana bound states in nano structures and their entanglement properties. It is clear that this state of the art, highly versatile and sensitive equipment should lead to new discoveries and collaborations and open up many technological possibilities.

Five postdoctoral scholars, visiting scientists (from Brazil and the UK), a graduate student, and five high school students have taken part in Dr. Moodera's research. The high school students in the past have won several science competitions; some of them have joined the MIT undergraduate program. Multiyear research funding was successfully obtained from ONR, NSF, and John Templeton Foundation grants. Other grant applications (submitted to DOE and DARPA) are under consideration.

Dr. 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. He has taken part in national-level magnetism policy committees and meeting initiatives. He is a review board member for the "Superspin" project at the University of Cambridge. He serves on the scientific boards of international meetings. Dr. Moodera was invited to be part of an international review board to set scientific orientations and objectives on nanosciences at the frontiers of nanoelectronics by the National Center for Scientific Research in France; Trinity College Dublin, in Ireland; and the Indian Institute of Technology.

Educational Outreach Programs

Paul Rivenberg, communications and outreach administrator of the PSFC, plans and organizes the Plasma Science and Fusion Center's educational outreach program. The program conveys the excitement of advances in plasma physics and fusion energy research to the general public, the national and international scientific communities, and the MIT community. A particular focus of the program is heightening the interest of grade school, middle school, and high school 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 PSFC 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 students who volunteer to assist are key to the success of the tours. The experience helps them develop skill in communicating complex scientific principles to those without an advanced science backgrounds. This year, the PSFC hosted more than 1,300 people.

The PSFC has continued to receive attention from lawmakers this year, facilitated by MIT alumnus Reiner Beeuwkes '67. These included visits by Kristy Gogan, cofounder of Energy for Humanity; David Simas, White House assistant to the president; Cherry Murray, director of the DOE's Office of Science (Figure 6); Senator John Tester (D–Montana); Senator Evan Bayh (D–Indiana); and Senator Sheldon Whitehouse (D–Rhode Island). The PSFC also hosted Massachusetts environmental leaders Matthew Beaton (secretary of Energy and Environmental Affairs), Ed Woll (Sierra Club) and George Bachrach (outgoing president of the Environmental League of Massachusetts). All toured the Alcator C-Mod control room and experimental cell to learn more about the benefits of fusion energy.

Figure 6. Dennis Whyte (right) tours the Alcator C-Mod tokamak with Dr. Cherry Murray (center), director of the Department of Energy's Office of Science, and Professor Anne White of the Department of Nuclear Science and Engineering.

The PSFC continued its educational collaboration with the MIT Energy Club, bringing a variety of interactive plasma demonstrations to MIT Energy Night in October. This event, held on Family Day weekend, was attended by hundreds of MIT students and their families, who learned about the latest directions in plasma and fusion research.

The PSFC continues to collaborate with other national laboratories on educational events. An annual Teachers 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 meeting. Paul Rivenberg continues to organize the Plasma Sciences Expo. This year, 17 exhibitors representing laboratories and schools around the US provided hands-on plasma and physics demonstrations for local students and the general public. The PSFC booth, staffed by Paul Rivenberg, NSE Administrator Valerie Censabella, and PSFC graduate students, introduced students to MIT's Alcator C-Mod fusion project with a video game that encourages participants to work cooperatively to confine a fusion plasma in a tokamak vacuum chamber.

The PSFC participated in the American Association for the Advancement of Science (AAAS) Family Science Days, over the Presidents' Day weekend (February 18–19). Rivenberg, along with seven graduate students, spent two days presenting hands-on demonstrations on electromagnetism, superconductivity, and fusion to more than 5,000 guests at the Hynes Auditorium in Boston. The PSFC booth attracted publicity from NOVA/PBS and Quartz Media.

Associate Director 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, taking turns presenting their latest research in a relaxed environment. PSFC deputy director, Dr. Martin Greenwald, has helped organize PSFC's annual Open House seminars during Independent Activities Period as well as special visits from alumni and dignitaries, including US and Massachusetts lawmakers.

The PSFC continues to be involved in 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 this group on goals that include strengthening appreciation of the plasma sciences by obtaining endorsements from industries involved in plasma applications and addressing environmental concerns about plasma science. Like Dr. Temkin, Paul Rivenberg is a member of the CPS Steering Committee. He works with CPS on new initiatives and is editor of the Coalition's Plasma Page, which summarizes CPS news and accomplishments of interest to members and the media. Rivenberg also heads a subcommittee that created and maintains a website to help teachers bring the topic of plasma into their classrooms. He is currently overseeing improvements to the CPS website. He also works with the Coalition's technical materials subcommittee to develop material that introduces laypeople to different aspects of plasma science.

Honors and Awards

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

A team of technicians from the PSFC (Figure 7) was honored with a 2017 Infinite Mile Award. Recognized at a May 16 luncheon for their contributions to the success of the PSFC's fusion research project, Alcator C-Mod, the team comprised 12 Research Development and Technical Employees Union technicians: Susan Agabian, David Arsenault, David Bellofatto, Charles Cauley, James Chicarello, Timothy Davis, Mark Iverson, Richard Lations, GeorgeMacKay, Ronald Rosati, Maria Silveira, and David Tracey. A testimonial read at the luncheon recognized how the team stepped up to meet the challenges of running an experiment that was headed toward its final run (September 2016).

Figure 7. PSFC's Infinite Mile–award winning technicians gather in the Alcator C-Mod tokamak control room. From left to right: (sitting) Rick Lations, Maria Silveira, and Dave Arsenault; (standing) Charlie Cauley, Mark Iverson, George Mackay, Jim Chicarello, Dave Tracey, Ron Rosati, and Dave Bellofatto. Not in photo: Sue Agabian and Tim Davis.

Graduate student Alexander (Sasha) Soane received the Best Student Paper Award at the IEEE 18th International Vacuum Electronics Conference , held in London in May 2017. Selected from 80 students who submitted papers for consideration, Soane, a PhD candidate in the Department of Electrical Engineering and Computer Science, competed with four other finalists. He impressed five judges on the Technical Program Committee with a concise eight-minute summation of his research to win the award, which included an engraved plaque and a €500 check.

Cui-zu Chang received the 2017 C10 Young Scientist Prize at a ceremony during the American Physical Society – Division of Condensed Matter Physics and Division of Material Physics meeting held in March 2017 in New Orleans. The award recognizes exceptional achievement in the study of the structure and dynamics of condensed matter by scientists at a relatively junior stage of their career. The citation for his work praises him "for the discovery of quantum anomalous Hall effect in magnetically doped 3D topological insulator films."

Professor Robert Guy Griffin, head of the Magnetic Resonance Division, won the 2017 Richard R. Ernst Prize in Magnetic Resonance, sponsored by the Bruker BioSpin Corporation. The Ernst Prize, which comes with an award of €10,000, was awarded to Griffin on July 2 at the European Magnetic Resonance conference in Warsaw, Poland. The Ernst Prize is widely considered to be the second most prestigious prize in the magnetic resonance community (after the Laukien Prize, which Griffin received in 2007).

Although Mike Rosenberg received his PhD from MIT (Department of Physics) in September 2014, his work at the PSFC is still getting attention. Rosenberg received the American Physical Society – Division of Plasma Physics Marshall N. Rosenbluth Outstanding Doctoral Thesis Award. The award, sponsored by General Atomics Inc., was established to recognize exceptional young scientists who have performed original doctoral thesis research of outstanding scientific quality and achievement in the area of plasma physics.

In his third year at MIT, Nuclear Science and Engineering graduate student Alex Creely has figured out enough about the hot, turbulent plasmas necessary for creating fusion energy that his research has been honored with the Innovations Award, offered by DOE's Office of Nuclear Energy, Science, and Technology. Creely is using data from the Alcator C-Mod tokamak to validate simulations of fusion plasmas. The effort could provide researchers with confidence that their simulations will accurately predict what will happen in a working fusion device, which could influence the design of future machines. Creely also received MIT's Manson Benedict Award, presented to a graduate student in NSE for excellence in academic performance and professional promise.

Three members of the Plasma Science and Fusion Center's High-Energy-Density Physics Division have been notified they will receive the American Physical Society's John Dawson Award for Excellence in Plasma Physics Research. Division Head Richard Petrasso, Senior Research Scientist Chikang Li, and Research Scientist Frederick Seguin were selected, along with peers from three other laboratories, to share the award for "the pioneering use of proton radiography to reveal new aspects of flows, instabilities, and fields in high-energy-density plasmas."

Principal Research Engineer Leslie Bromberg of PSFC's Magnets and Cryogenics Division shared the 2017 AMA Association for Sensor and Measurement Innovation Award with team members Alexander Sappok and Paul Ragaller of the CTS Corporation, Boston Innovation Office. CTS acquired the MIT spin-off company, Filtering Sensing Technology, Inc., in 2015. The high-frequency-based diesel and gasoline particle filter sensor that won the award provides real-time values and enables feedback control, allowing the actual charge state of particle filters and catalyzers to be measured with an on-board sensor, which previously had not been possible.

Appointments

In the *Magnetic Fusion Experiments Division, Dr. Cristina Rea was appointed postdoctoral associate.*

In the Plasma Theory and Computation Division, Dr. Pallavi Bhat was appointed postdoctoral associate and Dr. Ryan White was appointed postdoctoral fellow.

In the High-Energy-Density Physics Division, Dr. Cody Parker was appointed postdoctoral associate.

In the Plasma Science and Technology Division, Dr. Kevin Woller was appointed research scientist and Dr. Paul Woskov was appointed research engineer.

In the Magnetic Resonance Division, Dr. Loren Alegria, Dr. Jiho Lee, and Dr. Yumbo Ou were appointed postdoctoral associates. Dr. Jia Song was appointed research specialist and Dr. Dongkeun Park was appointed magnet engineer.

In PSFC's headquarters, Devin Mead-Ward and Thomas Hedderick were appointed fiscal officers.

Promotions

In the Magnetic Fusion Experiments Division, *Dr. Seung Gyou Baek, Dr. Daniel Brunner, and Dr. Theodore Golfinopoulos were promoted to research scientist positions.*

Graduate Degrees

Nuclear Science and Engineering conferred the following degrees: Christopher Wink, MS; Kevin Woller, PhD; Mark Chilenski, PhD; Ian Faust, PhD; and Christian Haakonsen, PhD.

The Department of Chemistry awarded Shu-Yu Liao and Eric Keeler the PhD.

Dennis Whyte
Director
Head, Nuclear Science and Engineering
Hitachi American Professor of Engineering