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 nuclear magnetic resonance (NMR) spectroscopy and in advanced magnet development.

Broadly, the center focuses on the following research: 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; magnetic resonance—including nuclear magnetic resonance, electron paramagnetic resonance (EPR), and magnetic resonance imaging (MRI); NMR and MRI magnet development; and nanoscience condensed matter physics (quantum coherent behavior and spin transport).

The PSFC is made up of six research divisions: Magnetic Fusion Experiments, Plasma Theory and Computation, High-Energy-Density Physics, Plasma Science and Technology, Magnets and Cryogenics, and Magnetic Resonance.

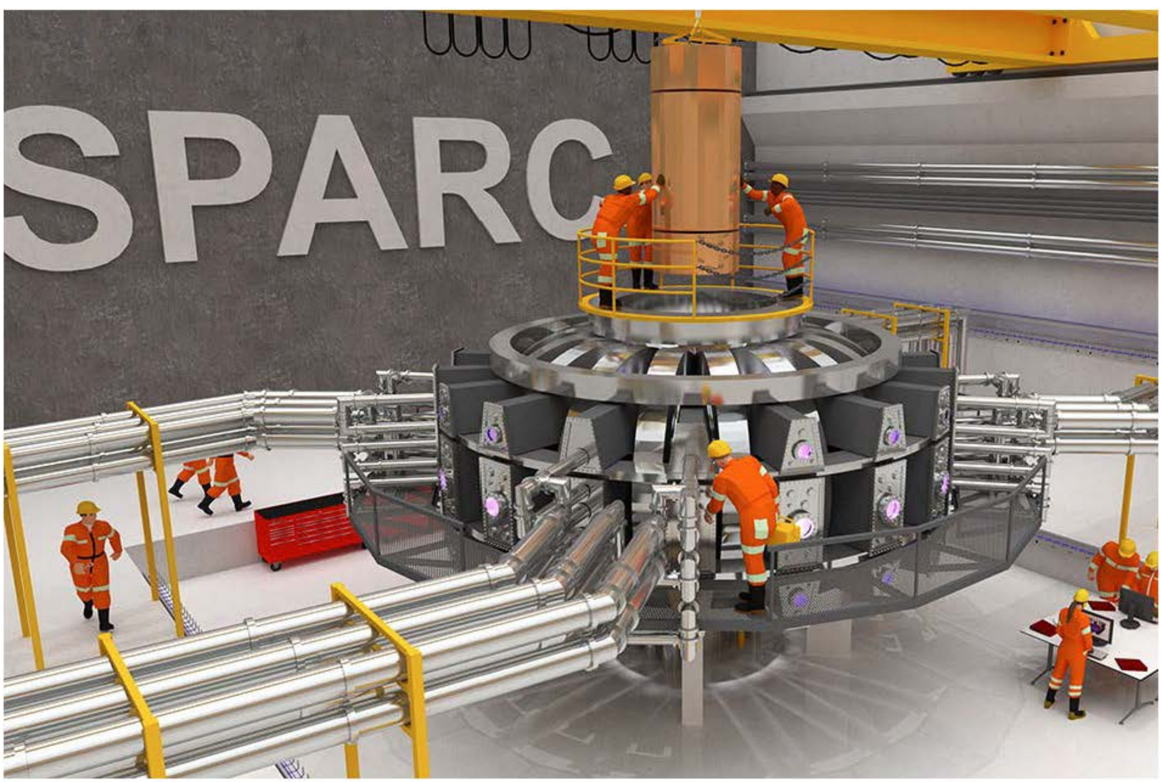
The center's research and development (R&D) programs are principally supported by the US Department of Energy (DOE) Office of Fusion Energy Sciences (OFES) and the National Institutes of Health (NIH). There are approximately 230 personnel associated with PSFC research activities. They include 28 affiliated faculty and senior academic staff and 52 graduate students, with participating faculty and students from Aeronautics and Astronautics, Chemistry, Electrical Engineering and Computer Science (EECS), Nuclear Science and Engineering (NSE), and Physics; 88 research scientists, engineers, postdoctoral associates/fellows, and technical staff; 27 visiting scientists, engineers, and research affiliates; one visiting student; 14 technical support personnel; and 19 administrative and support staff.

PSFC research funding in 2017–2018 remained at a level approximately consistent with previous years (about $35 million per year). While there was a decrease in DOE funding (approximately $8 million) due to cessation of Alcator C-Mod operations, this loss was balanced by the advent of funding for the SPARC (Soonest/Smallest Privately Funded Affordable Robust Compact) tokamak, which will be at a minimum of $10 million per year. The SPARC research agreement was formalized on June 1, 2018, so exact funding levels are difficult to calculate. Nevertheless, it is fair to state that the PSFC research funding profile remains strong.

Magnetic Fusion Experiments Division

The Magnetic Fusion Experiments (MFE) Division at the PSFC, created in 2016, has now successfully transitioned from magnetically confined fusion experiments primarily carried out at the Alcator C-Mod tokamak to several large-scale off-campus experimental facilities and SPARC. This division remains the largest within the PSFC and is home to world-leading experts in all areas of magnetic confinement fusion research, including boundary physics, core transport physics, radio frequency (RF) physics, and pedestal physics. A new working group in 2017 focused on exploration of the I-mode, the naturally edge localized mode (ELM)–free high-performance operating regime. A second new working group in the area of machine learning for fusion research also began in 2017, focused on applications of advanced algorithms to tokamak disruption prediction and avoidance, core transport, and pedestal physics. The division head, Earl Marmar, is a senior research scientist at PSFC and in the Department of Physics.

Unique among the divisions at PSFC, MFE has two sub-divisions that report to the division head: Collaborations and SPARC. The Collaborations sub-division is led by Professor Anne White, who coordinates on-campus elements of multiple off-campus collaborations with large tokamak and stellarator facilities around the world. Collaborations are critical to maintaining scientific and educational excellence in magnetic fusion experiments at the PSFC. The SPARC project sub-division is led by Professor Zach Hartwig and Jim Irby, and work there focuses on (1) research and development of advanced superconductors and fusion pilot plant designs and (2) the design and ultimately construction of a new high field tokamak aimed at being the world's first net energy magnetic confinement fusion facility. Collaborations research is primarily funded through a combination of a five-year cooperative agreement and multiple smaller grants from the DOE Office of Fusion Energy Sciences. Figure 1 shows a rendering of a preconceptual design for SPARC. SPARC research is mainly funded by a private company, Commonwealth Fusion Systems, through the MIT Energy Initiative (MITEI).



Concept for the SPARC net energy deuterium-tritium fusion tokamak.

Alcator C-Mod operations were successfully completed on September 30, 2016. 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 continue to provide new results, conference presentations, and journal articles, including key contributions to PhD student thesis research.

The MFE team consists of about 90 full-time-equivalent staff, including faculty and senior academic staff, research scientists, engineers and technical staff, graduate students, postdoctoral fellows, information technology staff, and administrative/support staff. In addition, undergraduate students are involved in the division's research, many participating through the Undergraduate Research Opportunities Program (UROP). Current annual funding for all of these activities totals more than $18 million. This includes funding under the umbrella of the five-year MFE cooperative agreement with the DOE Office of Fusion Energy Sciences, multiple smaller three-year grants from the Office of Fusion Energy Sciences, and the SPARC activities funded through MITEI.

Research in the collaborations sub-division during the past year focused on exploring the foundational science behind high-performance plasma confinement. State-of-the-art experiments were carried out at off-campus facilities including the ASDEX Upgrade (AUG), EAST, DIII-D, KSTAR, and TCV 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 are in direct support of urgent International Thermonuclear Experimental Reactor (ITER) research needs, whereas others support the recently commissioned Wendelstein 7-X (W7-X), the world's largest and most advance stellarator fusion device.

International Collaborations

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

The Wendelstein 7-X stellarator is a major experimental fusion research facility located in Greifswald, Germany. The overarching goal of our collaborative project with W7-X is to facilitate the study of fluctuations and plasma structures 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 (3D) divertors, which is a core goal of US collaborations with W7-X. The W7-X project is under the direction of principal investigator (PI) Jim Terry, with total funding of $690,000 for the three-year period August 2015 to August 2018. The project supports MIT (NSE) graduate student Sean Ballinger.

The first three years of the project have been devoted to providing a design for a diagnostic system to measure turbulence and instabilities in the plasma boundary and divertor regions, a so-called gas-puff imaging (GPI) diagnostic. Additionally, the project has provided design, installation, and operation of a camera-based system for ultra-fast imaging on W7-X during its 2017–2018 experimental campaign. Sean Ballinger was on-site at W7-X in the summer of 2017 along with MIT undergraduate Kevin Tang, who obtained funding to work on the project through the MIT International Science and Technology Initiatives (MISTI) program. Funding for the project was recently renewed for the three-year period August 2018 through August 2021 at a level of $890,000. During this period, the aim is to procure, test, and install the new GPI diagnostic. The work is being performed by PSFC research scientist Seung Gyou Baek, and Ballinger and is another example of the strong US-German collaboration effort on stellarator research. Olaf Grulke of the Max Planck Institut für Plasmaphysik (IPP) in Greifswald, Germany, is the project's W7-X scientific contact.

Wendelstein 7-X Phase Contrast Imaging Diagnostic Project

This project consists of designing and procuring optical components and installing a phase contrast imaging (PCI) system on the W7-X stellarator in Greifswald, Germany. This is to be followed by collecting and analyzing turbulence data with the PCI diagnostic and relating this information to energy and particle transport in an "optimized stellarator." The project is a collaboration among PSFC, the State University of New York (SUNY) at Cortland, and the Max Planck Institut für Plasmaphysik. The US side of the project is funded by the DOE Office of Fusion Energy Sciences. Additional funding for on-site support is provided by IPP. The project began in August 2015 and will conclude its first three-year phase in August 2018. Eric Edlund was the key experimentalist on the project from 2015 through fall 2017 and the key team member implementing the PCI system on W7-X. Edlund resigned from MIT on December 31, 2017, to begin teaching at SUNY Cortland in the spring semester of 2018. The first phase of the experiments (OP1.1a) concluded in December 2017, and initial data has been collected and is being analyzed. Professor Edlund returned to Greifswald for the period June 1 to August 20, 2018, to participate in the OP1.2b phase of the experiments, which will commence in July and continue through October. After that, a two-year shutdown of the W7-X facility is planned to accommodate major upgrades, including installation of water-cooled tiles and neutral beam heating inside the machine to allow long pulse operation in the next phase of the experiment, which will begin in 2020.

Assisting the PCI project from IPP, Greifswald, are Professor Olaf Grulke, postdoctoral associate Adrian von Stechow, and graduate student Lukas-Georg Böttger, as well as other technical support staff. In addition, four undergraduate students from Germany, the United States, the United Kingdom, and China will participate in the experiments this summer.

Professor Miklos Porkolab traveled to Greifswald in October 2017 and will do so again the first week of September 2018. He visited for a period of one week and worked with Professor Thomas Klinger, associate director of IPP, as well as other scientists from IPP and various international collaborating partners. Presentations on the PCI project at W7-X were given at the 22nd Topical Conference on High Temperature Plasma Diagnostics in San Diego, CA, and a refereed paper is being published in *Review of Scientific Instruments*. Also, poster presentations were given by Eric Edlund and colleagues at the American Physical Society (APS) Division of Plasma Physics (DPP) meeting in Milwaukee, WI, in November 2017.

Initial studies of turbulence seem to indicate that there are significant changes in both the amplitude and wavenumber distribution of the density fluctuations under variations in magnetic configuration and pellet fueling, increasing the mean density of the W7-X plasmas. While there are some theoretical and computational studies that indicate trends in turbulence as these parameters are varied, these studies are exceptionally difficult and there is a fair amount of uncertainty in these predictions. The PCI measurements are important in this regard as they offer insight into how turbulence responds under actual experimental conditions wherein temperature and density profiles may change with variations in magnetic configuration.

In addition to turbulent spectra, coherent Alfvén waves have been observed across a relatively wide range of plasma conditions. Given the absence of any direct ion heating mechanism that would create high-energy ions, it must be concluded that these waves are excited by the gradients of plasma electrons (or trapped particles). This is a somewhat unusual phenomenon, and further studies are under way to more closely determine additional details of these waves. It is expected that similar waves will be excited, possibly in greater number or at higher amplitude, in the presence of energetic ions, and hence there is significant interest in understanding their characteristics.

A proposal for renewed funding of the project was submitted by Professor Porkolab and Eric Edlund in fall 2017. The proposal was approved in spring 2018 at an amount of $900,000 over three years (August 2018 to August 2021).

Correlation Electron Cyclotron Emission and Phase Angle Diagnostic for the ASDEX Upgrade

At the 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 structures 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 future burning plasma experiments. Work on the project is being led by PI Anne White, IPP postdoctoral researcher Simon Freethy, and NSE graduate students Alex Creely and Rachel Bielajew. Creely is on-site at AUG for the summer of 2018, continuing development of his new cross-machine validation project, which focuses on trying to distill from advanced transport models more simple rules for when cross-scale turbulence coupling impacts predictions of temperature profiles in tokamaks.

Another MIT graduate student, Pablo Rodriguez Fernandez, whose thesis research with Professor White focuses on model validation using data from C-Mod and DIII-D, is also on-site at AUG for summer 2018 as a MISTI intern. He is working to incorporate measurements from MIT turbulence diagnostics as constraints in a new machine learning–based framework called VITALS. At the same time, he is working on implementing an integrating modeling tool, PRIMA, to study cold pulse propagation in AUG. Both of these projects are being done in collaboration with Professor White and with Clemente Angioni and Emiliano Fable of IPP. Rodriguez Fernandez will also spend a week at DIFFER in the Netherlands in August 2018, working with Jonathan Citrin on implementing a new turbulent transport model, QuaLiKiz, in the VITALS framework.

The new CECE diagnostic developed in 2016 by PSFC engineers Willy Burke and David Terry was deployed for a variety of high-impact core transport model validation studies, as well as new measurements of the weakly coherent mode in I-mode. The latter will be the focus of research conducted by new graduate student Rachel Bielajew, who started working with the group in spring 2018. AUG can operate with plasma density, plasma pressure, and reactor-relevant plasma wall interactions. AUG features a flexible geometry and a variety of plasma heating methods, allowing for novel experiments to probe core turbulent transport. MIT has been collaborating with IPP at AUG on core turbulence and transport and gyrokinetic model validation for several years. The new, upgraded CECE system operated throughout the 2017 campaign and features a highly modular, low-noise electronic design that has enabled extremely detailed turbulence measurements. New high-resolution radial profile measurements of electron temperature fluctuations and the cross-phase angle between density and temperature fluctuations were performed at AUG using the recently upgraded diagnostic, and the data are used to critically test predictive modeling capabilities for ITER and other future tokamaks such as SPARC. This project will be funded by DOE for another two years, including a supplement that will support a new postdoctoral associate.

The scientific productivity and impact of the collaboration between MIT and IPP are very high. Simon Freethy, the IPP postdoc working on the ASDEX Upgrade collaboration with PSFC, and IPP scientist Tobias Goerler gave invited talks on experimental investigations of turbulent temperature fluctuations and phase angles in the ASDEX Upgrade at the APS DPP meeting in October 2017. Goerler also gave a talk, "Recent gyrokinetic turbulence insights with GENE and direct comparison with experimental measurements," at the same conference.

Collaboration on the Alfvén Eigenmode Active Diagnostic

Professor Porkolab leads this project from MIT, with active on-site participation at the Joint European Torus (JET) by postdoctoral researchers Valentin Aslanyan and Nicolas Fil. Work related to the project is performed at JET, the world's largest tokamak located near the Culham Centre for Fusion Energy in the United Kingdom. The project includes a collaboration among the PSFC, the Swiss Plasma Center (in Lausanne, Switzerland), and EUROFUSION/Culham Laboratory scientists. The experimental program is centered around measuring the damping rates of toroidal Alfvén eigenmodes excited by six phase-controlled antennas installed in the vacuum vessel at JET, which are driven by six transmitters (in excess of 1 kW each) that resonantly excite damped Alfvén eigenmodes in the tokamak plasma. The response is detected by external Mirnov coils. The drive frequency of the diagnostic is swept by a field programmable gate array (FPGA) provided by MIT until such a resonance is detected. In addition to frequency, the modes' damping rate is calculated from the quality factor of this resonance. Commissioning and an upgrade of the JET Alfvén Eigenmode Active Diagnostic (AEAD) system over the past few years have demonstrated that the diagnostic is able to track the frequency of modes as they change based on the conditions in the plasma. The AEAD system began collecting data in the last few days of JET operations in 2016 before being shut down in 2017 for a major upgrade. Operations were expected to resume in September 2017 but were delayed due to vacuum leaks in some components, mostly in the neutral beam lines and pumps. Subsequently operations were again delayed, due to continued technical problems, and tokamak physics operations are not expected to resume until October 2018. Meanwhile, MIT staff and collaborators continued further calibrating and upgrading the AEAD system.

In terms of physics research, much of last year was spent on analyzing data, including identification of the mode numbers of toroidal Alfvén eigenmodes, measurement of damping rates, and comparisons with gyrokinetic codes such as GTC. Detection and damping measurements of Alfvén instabilities are important for future fusion devices, as they may become unstable as a result of energetic particles such as alphas, leading to a loss of fast fusion alpha particles. To aid in interpreting the experimental results, a strong collaboration has been initiated with the group of Professor Zhihong Lin at the University of California, Irvine, to model the experiments with the GTC "particle in cell" gyrokinetic code and thus help identify the important physics parameters that control the excitation and damping of modes. The main results to date indicate that the n=6, m=5,6 mode located around psi=0.12 fits the observed laboratory frame frequency and damping rate. It should be noted that radiative damping based on mode conversion to kinetic Alfvén waves dominates over other damping rates, and, in particular, continuum damping is negligible. Based on the JET results, we should be able to make reliable predictions regarding the importance of such modes and their impact on the transport (e.g., loss) of alpha particles in a burning plasma such as ITER and in future reactor-scale devices burning deuterium and tritium fuel. The grant for this project was renewed by DOE for another year.

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

Paul Bonoli serves as the MIT PI of this multi-institutional international collaboration that is led by General Atomics (San Diego, CA). As part of the collaboration, Bonoli, Seung Gyou Baek, Jungpyo Lee, Syun'ichi Shiraiwa, and John Wright work with the Institute for Physical Sciences to carry out extensive ray tracing, full-wave, and Fokker-Planck simulations of lower hybrid current drive (LHCD) experiments at the EAST tokamak in Hefei, China. They also collaborate on the modeling of advanced lower hybrid RF launcher concepts for the KSTAR tokamak in Daejeon, South Korea. During the past year, Shiraiwa has worked at EAST on the development of a control-level algorithm for lower hybrid current drive and power deposition that can be incorporated into systems codes and fast transport solvers used to control and study EAST discharges. In addition, Baek has assisted with the development, fabrication, installation, and testing of an array of RF probes at EAST that will be used to detect ion cyclotron sidebands and ion sound waves that can be nonlinearly generated in LHCD experiments through a parametric decay instability process. Shiraiwa, Baek, and Bonoli have also carried out extensive ray tracing/Fokker-Planck studies and parametric dispersion relation analyses of lower hybrid current drive discharges at EAST in order to understand the role of increasing RF source frequency in experiments done at 2.45 GHz and 4.6 GHz.

Robert Granetz, graduate student Alex Tinguely, and postdoctoral associate Cristina Rea work extensively with their collaborators at the Institute for Physical Sciences on the development of disruption databases for the EAST tokamak. The ultimate goal of this effort 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. These algorithms can be used to find predictors or "precursors" of disruptions.

The group has been extensively developing disruption prediction algorithms based on an artificial intelligence method known as random forests and has been trained on our C-Mod, DIII-D, and EAST databases. The group has found that the plasma parameters that are most relevant for disruption prediction are different on different machines. Furthermore, the prediction success rates for random forests trained on each machine database vary significantly. Recently, the group has begun training recurrent neural networks on the EAST database. These networks have the ability to incorporate past information when classifying current disruption probability. During the past 12 months, team members have made three trips to Hefei.

In 2017–2018, Robert Granetz and co-workers continued their disruption warning database work at EAST and extended these efforts to include the KSTAR tokamak. Last July, DOE requested a collaboration with Korea's National Fusion Research Institute to begin developing and populating a database of disruption-relevant parameters for KSTAR as a complement to our existing Alcator C-Mod, DIII-D, and EAST databases. This is synergistic with our goal of determining whether or not a reliable universal disruption warning algorithm can be developed for ITER and future reactors based on today's operating tokamaks. During the past 12 months, the PSFC team has made three trips to Daejeon to execute this task. Excellent progress has been made, but it will take another year of work before the KSTAR database is at the level of the other three databases.

Projects at WEST, TCV, MAST-U, and JET

The seminal results from Alcator C-Mod were made possible in large part due to the development and use of advanced plasma diagnostics. The MIT boundary group continues to leverage its diagnostic expertise at TCV and MAST-U (Mega Ampere Spherical Tokamak Upgrade). The group has two active projects with the TCV scientific team. A multi-spectral imaging diagnostic that captures simultaneous spectrally filtered images at four wavelengths from a common sight view (e.g., divertor region) was assembled, tested, and calibrated. It is presently located at TCV and will be used for divertor physics experiments. A Gas-Puff Imaging diagnostic has been refurbished and is being tested at MIT. It is being prepared for installation on TCV in late 2018. MIT will participate in TCV experiments using these diagnostics. MIT is also collaborating with MAST-U scientists to develop FPGA–based operations of mirror Langmuir probes (MLPs). This development will greatly facilitate more general use of MLPs.

Other new diagnostic development programs are being carried out in partnership with the WEST tokamak at the Institute for Magnetic Fusion Research in Cadarache, France, and the TCV tokamak at the Swiss Plasma Center at the École polytechnique fédérale de Lausanne (EPFL) in Switzerland.

Amanda Hubbard collaborates with TCV on I-mode studies and coordinates the I-mode working group, which focuses on cross-machine studies around the world. A major activity was setting up, on a dedicated MIT server, a new International Tokamak Physics Activity (ITPA) confinement database. I-mode discharges from both C-Mod and AUG have been contributed. MIT proposals were made for upcoming campaigns on AUG and WEST. Experimental proposals were also made for JET (with ITER support) and DIII-D (in collaboration with AUG) but were not allocated time.

At WEST, John Rice is involved with designing a new X-ray imaging crystal spectrometer for non-perturbative measurements of plasma ion temperature and rotation. The MIT transport group also participated in the WEST run planning forum and is the lead for an experiment on I-mode that will test the device size and toroidal magnetic field dependence of I-mode confinement and access.

At TCV, Bob Mumgaard and a graduate student continued work on a new multi-spectral imaging system that can give detailed information about the internal magnetic structure in the tokamak plasma, which is useful for studying equilibrium and stability as well as current drive.

In addition, research at WEST on lower hybrid physics and modeling was initiated. Greg Wallace and Syun'ichi Shiraiwa visited the Institute for Magnetic Fusion Research to collaborate on modeling of lower hybrid current drive experiments. Design work with their collaborators on slotted waveguide arrays will inform the future design of high field side (HFS) launch LHCD at WEST. They also discussed stark effect LH field measurements for WEST and the deployment of the piScope data visualization tool.

PSFC scientists and researchers from AUG and several other EU laboratories participated in the first experiments on TCV in July 2017. Despite good technical performance and a high LH threshold with unfavorable drift direction, no I-mode was seen. This was likely due to the low field (1.35 T) in these experiments. AUG continues to have the most active I-mode research program.

The main JET collaboration involved ion cyclotron resonant frequency (ICRF), and collaboration has been added to the T17-06 group at JET for antenna and edge RF modeling efforts. We have also begun work with the T17-07 group for ICRF modeling using the AORSA and CQL3D codes. John Wright traveled to the Barcelona Super Computing Center and worked with the RF group there on JET radio frequency optimization and scenarios. Also, Wright trained the Barcelona group on running the AORSA code and applying it to JET discharges.

As an example of the high impact of this collaboration, the team published a *Nature* article in 2018 on novel RF heating scenarios in JET. Also, members of the team were recently honored with the 2018 Landau-Spitzer Award, which recognizes an individual or group of researchers for outstanding theoretical, experimental, or technical contributions in plasma physics and for advancing collaboration and unity between the European Union and the United States through research. Scientists from MIT (Steve Wukitch and John Wright) and JET (Yevgen Kazakov and Jef Ongena) were jointly recognized for the award.

Collaborations in the United States

Overview of Experimental Research at DIII-D

The DIII-D tokamak in San Diego, CA, is operated as a user facility by General Atomics for the Department of Energy through the Office of Fusion Energy Sciences. 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 the installation of new suites of core impurity transport diagnostics, pedestal diagnostics, and high field side launch current drive actuators. The most mature of these efforts, led by Nathan Howard, involves installation of a laser blow-off (LBO) system that will facilitate new studies of impurity transport, a critical area of work in support of ITER. In addition, Stephen Wukitch is leading efforts to deploy a next-generation current drive system HFS lower hybrid at DIII-D.

In another example of scientific leadership at 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 instabilities that eventually lock and disrupt the plasma. Ernst also collaborates with researchers at the University of California, Los Angeles, on synthetic diagnostic development.

Nathan Howard led an experiment to probe 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 Craig Petty and Princeton Plasma Physics Laboratory (PPPL) scientist Brian Grierson on understanding propagation of “heat pulses” stimulated through electron cyclotron heating (ECH). Rodriguez Fernandez is also working with Howard to develop a new LBO system for DIII-D, which is used as an actuator for perturbative transport experiments. Graduate student Francesco Sciortino is working with 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, being led by Jerry Hughes, will also involve graduate students who will implement models such as EPED to study high-performance plasmas.

In the area of rotation physics and momentum transport, the PSFC team has also collaborated with DIII-D. The magnitude and scaling of intrinsic toroidal rotation in C-Mod H- and I-mode plasmas agree with the predictions of a fluctuation entropy balance model that gives a Mach number proportional to ρ^*. This model is being applied to DIII-D data. The MIT transport group proposed and led a one-day DIII-D experiment (“Core Momentum Transport and Intrinsic Rotation in Wide Pedestal QH-mode with ECH”) in February 2018.

Along with Robert Granetz, Cristina 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. This work includes a graduate student who is extending the database to incorporate 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.

In 2018, for the first time at any tokamak, a trained random forest algorithm was painstakingly adapted, installed, and run in real time in the plasma control system (PCS) at DIII-D. This technical achievement required Cristina Rea to work closely with General Atomics software engineers to incorporate the machine learning–based code into the PCS. To this purpose, a collaboration with PPPL was established to adapt the DPRF (Disruption Prediction via Random Forests) code into the PCS. Our disruption prediction algorithm ran continuously for more than four months of operations through the end of the DIII-D run campaign, gathering data on about 850 discharges. We are encouraged by our algorithm's prediction performance, as well as its computational speed, and we are currently analyzing the results in detail.

High Field Side Lower Hybrid Current Drive at DIII-D

Efficient, robust, reliable steady-state current drive is a requirement for a viable tokamak fusion reactor. The use of waves in the lower hybrid range of frequency (LHRF), when launched from the high field side of a tokamak, alleviates many unresolved current drive issues. Launching LHRF waves from the HFS opens the "accessibility window," allowing for use of a lower parallel refractive index, n//, for a given plasma density and on-axis magnetic field. The lower n// waves damp in a region of higher temperature, resulting in increased current drive efficiency and a damping profile shifted closer to the mid-radius as compared with a low field side launch. Moving the LHRF antenna to the quiescent scrape-off layer (SOL) on the HFS reduces the likelihood of detrimental wave scattering from density fluctuations, as well as ameliorating the plasma-material interaction and wave coupling challenges. Additional benefits with respect to fast particle and neutron fluxes can be realized by moving to the HFS. An engineering assessment of HFS launch shows that it is feasible to implement an HFS LHRF system on existing tokamaks, with fewer hurdles anticipated for future tokamaks built with HFS antenna systems integrated into the design from the start.

The first experimental opportunity to begin assessing HFS LHCD physics and technological challenges has targeted DIII-D. For DIII-D, efficient off-axis current at r/a~ 0.6-0.8 with peak current density approaching 0.4 MA/m2 is sought for advanced tokamak plasmas. With HFS launch, existing DIII-D discharges have been analyzed and LHCD scenarios have been identified that can drive current peaked off axis, r/a~0.6-0.8, and driven current up to 0.39 MA/MW couple with single pass absorption. This provides an opportunity to validate the physics and engineering benefits (wave coupling, propagation, absorption, and current drive efficiency) of HFS LHCD. Utilizing GENRAY/CQL3D, wave penetration was found to be strongly influenced by local q values. In advanced tokamak discharges, the wave penetration is dominated by the poloidal upshift, resulting in good wave penetration. Practically, a small inner gap and a metallic launcher at the plasma edge were thought to be potential issues. Experiments were performed to assess the compatibility of a small inner gap, and a mock-up launcher was installed and operated. The small inner gaps were found to have a negligible impact on plasma performance. With up to 10 MW beam power in inner-wall limited discharge, the plasma mock-up coupler interaction was restricted to the carbon protection tiles. No significant Mo source was observed in any discharge, and the core Mo contamination was subtle to nonexistent. These experimental and simulation results indicate that HFS LHCD has the potential to provide efficient off-axis current drive on DIII-D.

Laser Blow-Off System on DIII-D

Laser blow-off systems are used to study core impurity transport under various configurations and confinement regimes. In the summer and fall of 2017, an LBO instrument was installed on DIII-D consisting of both a laser source sited in the existing Thomson scattering lab and a vacuum interface on the 105 R+1 port. MIT delivered the laser in August. In September, MIT and General Atomics worked to install a new port and gate valve and connected this valve to the LBO support structure, vacuum system, optical system, and CPCI/digitizer. Subsequently the laser was installed and aligned down the Thomson beam line, and beam shape and energy were optimized. The hazardous work authorization for Thomson operation was updated to incorporate the LBO laser. The LBO instrument was commissioned successfully during winter DIII-D operations and then was utilized for physics in several experiments, supporting research in impurity transport and cold pulse dynamics. The new LBO system serves as a versatile unit for injecting a wide range of impurities into DIII-D with controlled doses and known source parameters. Laser ablation of thin-film (approximately 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. Typical operation is non-perturbing to background plasma conditions. Injection of non-recycling impurities eliminates unknown sources and enables a cleaner interpretation of injection. This project is being led by Nathan Howard and involves two graduate students who will use the system to study impurity and perturbative transport at DIII-D for their PhD thesis projects. Hardware upgrades are being carried out to allow more flexibility in operations for the next DIII-D campaign, which will begin in 2019.

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

In FY2018, experimental studies continued on the DIII-D tokamak at General Atomics using the PCI diagnostic as part of the suite of fluctuation diagnostics. This work, performed under the leadership of PI Miklos Porkolab, is funded under a DOE diagnostic grant. Research staff supported in part by this grant include Chris Rost, Alessandro Marinoni, and postdoctoral associate Evan Davis. Experiments performed over the past year included a study of short-scale turbulence in the edge and core of the plasma, which are responsible for transport of heat and particles across the magnetic field, and a study of large-scale coherent modes, which are expected to be involved in transport of high-energy particles in future fusion devices.

This year saw the final stage of an extended project to add absolutely calibrated detection of long wavelength modes to the PCI by including a parallel stage of fluctuation detection using an external reference path (the "interferometer" method). This work was described in an invited talk by PhD student Evan Davis at the 2018 High Temperature Plasma Diagnostics Conference in San Diego and in a paper accepted for publication in the *Review of Scientific Instruments*. The final step was optimization of the system to improve the signal-to-noise ratio, which was achieved by replacing the commercial control electronics component with a custom home-designed one, thereby meeting the theoretical optimal limit. Before the final upgrade, the new system was used primarily to measure coherent magnetohydrodynamic instabilities. With the improved signal-to-noise ratio, the system capabilities were expanded to include measurements of long-wavelength broadband turbulence to complement the original PCI short-wavelength measurements. These capabilities were deployed in a recent study of multi-scale turbulence on DIII-D. The primary PCI system recorded electron-scale turbulence in the plasma core driven by electron cyclotron heating, present only when the ECH heating location was just inside the PCI beam path. The long-wavelength system simultaneously measured quasi-coherent turbulence, tentatively identified as micro-tearing modes near the plasma edge. Further analysis will proceed after multiscale turbulence modeling has been completed, allowing for validation of the model using the PCI experimental measurements.

The PCI system has continued to support a wide array of experiments at DIII-D, exploiting the large frequency bandwidth and excellent spatial resolution of the diagnostic. Recently, a comparison of plasma heating methods was performed in plasma discharges designed with properly matched shapes and scaled plasma parameters to permit predictions for ITER, the international test reactor currently under construction. Turbulence measurements from PCI were compared with results from the GYRO gyrokinetic model, showing that the transport in ITER baseline plasmas depends on fluctuations at both ion and electron scales and is sensitive to changes in ion and electron temperature profiles. This work also demonstrates that PCI personnel have developed significant expertise in the complex process of setting up and running the state-of-the-art computer models and in making detailed comparisons of the results with experimental measurements.

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

The goal of this project is to develop a technique for quantitative, spatially resolved measurements of RF waves and apply the technique at the DIII-D tokamak. A novel modification of the Phase Contrast Imaging diagnostic will allow detection of RF waves across the 5 MHz to 500 MHz range through modulation of the laser beam and optical mixing. Waves to be studied include ion cyclotron emission and the helicon wave, along with parametric decay waves. Previous work, including pioneering work performed on the Alcator C-Mod tokamak to validate models of RF heating and parametric decay, was based on a system of commercial acousto-optic modulators with a very narrow range of frequencies, up to 80 MHz only. 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 project's design phase has been completed, and a vendor has been identified for the modulator crystal and cavity. The crystal has been fabricated and installed in the cavity and is in house. No commercial vendors were able to produce a high-voltage RF source capable of driving the crystal, so DIII-D personnel (including Charles Moeller) were relied on for an in-house design. A prototype low-frequency driver circuit has been constructed, and performance assessment with a test crystal will begin soon. A production circuit and modulation crystal will be installed on the DIII-D PCI system late this year for first operation in spring 2019. A high-frequency driver will be installed when high-power helicon heating is installed on the tokamak, which is expected to occur during 2019–2020.

Development of an Ultra-High-Bandwidth Phase Contrast Imaging System

This initiative, designed to create an ultra-high-bandwidth PCI system to detect electron scale turbulence and gigahertz radiofrequency waves, was funded by DOE as a two-year high-risk exploratory project. The plan is to fabricate a phase plate with a groove depth of 0.2 microns and a width of 1–2 mm (this has been achieved) and modify a standard PCI system employing a near infrared laser (10.6 microns) and fast detector with the goals of increasing the wavenumber bandwidth by a factor of 10 and increasing the frequency bandwidth by four orders of magnitude. These types of lasers and detectors are now common in the communications industry and are widely available at reasonable prices. The first stage, currently in progress, involves testing of the performance of the optics and laser, specifically the components of an imaging interferometer, an application that depends on beam coherence and wave-front flatness. The subsequent stage will involve testing of a complete PCI detection system using sound waves for calibrating wavenumber response and signal to noise. Sensitivity to aberrations and non-linear effects is expected to increase significantly relative to PCI using a mid-infrared laser. The effects on signal-to-noise, system stability, and vibration sensitivity must be quantified to allow an evaluation of the expected performance. A successful result will lead to a new proposal to design and install a full-scale system on a large plasma fusion experiment such as DIII-D. If successful, the system would be capable of measuring not only low-frequency turbulence but also RF waves such as ICRF and helicon waves (476 MHz) at DIII-D and possibly elsewhere.

PSFC 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 NSTX [National Spherical Torus Experiment]) from a high-k scattering diagnostic that measures electron-scale density fluctuations directly to compare with theory and simulations. A new synthetic diagnostic under development is being used to interpret past data and predict characteristics of turbulence and transport in a future experiment planned for the NSTX Upgrade (NSTX-U). Ruiz Ruiz recently returned from visits to three major fusion laboratories in Europe, the Swiss Plasma Center at École polytechnique fédérale de Lausanne, the Max Planck Institute for Plasma Physics in Germany, and the French Alternative Energies and Atomic Energy Commission in France, where he presented seminars on his research.

In addition, the MFE core transport group collaborated with David Mikkelsen at PPPL in 2017 to compare two gyrokinetic turbulence simulation codes with experiments from C-Mod as a means of assessing the importance of electron-scale turbulence in I-mode plasmas. This work, published in early 2018, represents one of the few nonlinear gyrokinetic cross-code comparisons carried out in actual experimental plasmas and the first such effort with C-Mod data.

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 involved in the design of the new coils, bringing the coil winding facility back into operation and working on the design of a toroidal field core mock-up facility that will assess shear stresses across turn-to-turn interfaces. In addition, Rui Vieira is part of a committee reviewing the organization of the entire PPPL facility.

Research Highlights

Influence of High Magnetic Fields on Access to Stationary H-Modes and Pedestals

Recently proposed tokamak concepts, including ARC (Affordable Robust Compact) and SPARC, use on-axis magnetic fields as strong as 12 T to reduce size and cost. Despite the promise of this approach, experience with tokamak operation at these fields is limited because most modern tokamaks operate at on-axis magnetic fields below 4 T. Developing and codifying an understanding of tokamak behavior at high magnetic fields is thus important to the design and operation of next-generation high-field devices.

Of particular importance is an understanding of the behavior of the I-mode and H-mode high confinement regimes at high magnetic fields, since achieving these regimes is essential to meeting Q-related goals. A set of experiments from the 2016 C-Mod run campaign aim to achieve and characterize H-modes at 7.8 T, the highest magnetic field available in any tokamak. Analysis of the experiments was the subject of a prize-winning invited plenary talk by physics graduate student Elizabeth Tolman at the 2017 US/EU Transport Task Force meeting, and the results were published in 2018.

The analysis focused on three areas of particular importance to the planning of next-generation experiments. First, an analysis showed that L-H transitions at 7.8 T occur at power levels roughly equivalent to those predicted by the ITPA scaling law, which was developed using lower magnetic field data. However, the low-density branch was not well represented by an existing model. Second, the work considered the operational space at high magnetic fields of each of the three H-mode types observed on C-Mod (ELMy, ELM free, and enhanced D_α [EDA]), showing that the 7.8 T results followed experimental trends observed on C-Mod at lower magnetic fields (mainly around 5.4 T).

Finally, previous studies of pedestal characteristics in the two steady-state regimes, EDA and ELMy, were extended to higher magnetic fields. In particular, 7.8 T ELMy H-mode pressure pedestals were compared with EPED model predictions, and a scaling law developed for the height of the EDA density pedestal was updated to include a wider range of magnetic fields. The results show that operation at high magnetic fields is roughly consistent with the experience at lower fields, increasing confidence in the ability to extrapolate knowledge developed at lower fields to high magnetic field devices while also identifying areas where future experiments with these devices will be able to clarify trends.

Advanced Superconductor Research and the SPARC Project

SPARC activities have so far focused on research into a high-temperature superconducting (HTS) magnet, with a three-year goal of producing a full-scale toroidal field magnet. Multiple approaches to HTS cable development are being pursued. As the magnet development progresses, the team will increasingly turn its attention to the design and then construction of the SPARC tokamak facility, aiming to be the first magnetic confinement experiment to achieve net energy production from deuterium-tritium fusion.

Plasma Theory and Computation Division

The mission of the Plasma Theory and Computation Division is to conduct basic and applied plasma theory and simulation work in support of domestic and international toroidal confinement devices. The division's predominant source of funding is the DOE Office of Fusion Energy Sciences. The division head is senior research scientist Paul Bonoli, and the assistant head is Associate Professor Nuno Loureiro from NSE. Bonoli is also the lead PI for the new multi-institutional SciDAC (Scientific Discovery Through Advanced Computing) Partnership for Integrated Simulation of Fusion Relevant RF Actuators (RF SciDAC), the PI for the PSFC Theory Grant on Theoretical Research in Advanced Physics and Technology, the PI at MIT for the AToM Integrated Modeling SciDAC Partnership, 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 and an NSF-DOE basic plasma science and engineering grant. PSFC principal research scientist Abhay Ram leads the group's efforts in NSTX-U research at PPPL. Principal research scientist John Wright and research scientist Syun'ichi Shiraiwa are involved in RF SciDAC and the Navigational Data Management Project. Darin Ernst is the PI at MIT for the SciDAC Partnership for Multiscale Gyrokinetic Turbulence and is also part of the PSFC/DIII-D collaboration. Finally, Professor Jeffrey Freidberg (retired) from NSE is a plasma theorist who further enhances the PSFC theory effort.

New Parallel Computing Cluster

Usage of the PSFC computer partition on the Engaging Cluster at the Massachusetts Green High Performance Computing Center in Holyoke, MA, continued to grow in 2017–2018. To manage increased demand, heavy users with established workflows have been encouraged to use the National Energy Research Supercomputing Facility in Berkeley, CA. This frees up usage for testing, development, and small production runs on the Engaging Cluster. We have also added queues for debugging and very long serial jobs to facilitate those workflows. As planned, compute cycles are shared between the PSFC and NSE partitions to balance loads during times of heavy usage in one of the groups and to permit larger simulations that the groups could not manage alone.

Plasma Theory, Computation, and Discovery Science

Impurity Behavior in Tokamak Pedestals

A narrow pedestal region with a strong radial density gradient separates the core and edge of tokamak plasmas during high (H) and improved (I) confinement modes of operation. I-mode operation maintains the beneficial improved energy confinement of H-mode operation while also providing natural fueling to compensate for impurity removal. Measurements in Alcator C-Mod revealed strong poloidal variation in impurity density, with significant variation of the radial electric field and even the impurity temperature. Former graduate student and now postdoctoral researcher Silvia Espinosa (NSE) and Peter Catto have recently demonstrated that impurity density and poloidal flow have a major impact on radial impurity flux direction. They showed that outward collisional radial impurity flux occurs for I-mode, making it unnecessary to invoke turbulence to explain I-mode impurity removal. They proposed that the neoclassical radial impurity flux direction is a robust characteristic that differentiates between I-mode and H-mode operation, rather than the turbulent weakly coherent mode that sometimes cannot be detected. In both regimes the observed shear in the poloidal flow can act to break up eddies to reduce the turbulence level, leading to good bulk energy confinement.

Magnetohydrodynamics

Professor J.P. Freidberg, in collaboration with Professor A.J. Cerfon of New York University, has completed a formulation of the surface current model of a stellarator. The model allows for an arbitrary 3D cross section, arbitrary beta, arbitrary net toroidal current, and arbitrary aspect ratios. A code has been written to solve the resulting equations to determine equilibria for several stellarators: W7-X, LHD (Large Helical Device), NCSX, the University of Wisconsin stellarator, and the hybrid stellarator-tokamak at Auburn University. Preliminary results seem promising, and more complete results should be forthcoming later in the year.

Tokamak Reactor Studies

Professor Freidberg, Professor Anne White, and graduate student Daniel Segal have developed a self-consistent tokamak reactor model to investigate the benefits of high magnetic field on tokamak reactors. Their results show that, first, high field alone (i.e., no advanced tokamak physics) is sufficient for a successful short pulsed D-T experiment (namely SPARC). Second, high field contributes to but is not sufficient for the success of a compact steady state tokamak. Additional improvements are needed, either separately or in combination, to increase plasma confinement, current drive efficiency, and the bootstrap fraction. Third, high field helps pulsed reactors but still leads to relatively large-sized reactors. A major improvement occurs if high field ohmic heating transformers can be developed, leading to a significant reduction in reactor size.

Heating, Current Drive, and Nonlinear Dynamics

Abhay Ram, Professor Kyriakos Hizanidis (National Technical University of Athens), and Professor Ioannis Tigelis (National and Kapodistrian University of Athens) have continued their multi-institutional effort to study the effects of edge turbulence on the propagation of radio frequency waves in fusion plasmas. This research plays an important role in optimizing the efficiency of heating and current drive in radio frequency waves. Motivated by their own theoretical results, this group has developed advanced computational tools to study the effects of turbulence and plasma filaments on electromagnetic waves in scenarios beyond theoretical modeling. These studies have provided a stimulus for experimental research on the TORPEX plasma device in Switzerland. The group has started a theoretical program to model the effective permittivity of turbulent plasma in the edge region. This model is based on homogenization theory, previously used for scalar dielectrics. The basis for the homogenization theory in magnetized plasmas has been formulated within the past year.

Ram and Richard Temkin, along with Professor Hizanidis, have initiated a research program to study the use of high-frequency, short pulse, intensely powered (tens of megawatts) microwaves to heat and drive currents in fusion plasmas. The interaction of such microwaves with electrons in a plasma is highly nonlinear, with effects such as the ponderomotive force and particle trapping in waves playing a significant role. The group's studies were motivated by experiments carried out in the early 1990s in the MTX tokamak at the Lawrence Livermore National Laboratory. The results from a limited set of experiments were tantalizing enough to merit further research. The new initiative reveals that the current generated in a plasma device does not saturate with microwave power. Further studies will consider the viability of such a scheme in future fusion tokamaks.

Jungpyo Lee completed the formulation and implementation of the quasilinear RF diffusion coefficient first derived by Charles Kennel and Folker Engelmann in a form that guarantees positive definiteness in the ion cyclotron and LHRF. This work, done in collaboration with David Smithe from the Tech-X Corporation, John Wright, and Paul Bonoli, was published in the journal *Plasma Physics and Controlled Fusion* in late 2017. In early 2018, Lee took a position as an assistant professor in the Department of Nuclear Science and Engineering at Hanyang University in Seoul, South Korea.

Reconnection in Magnetized Plasma Turbulence

Professor Loureiro has continued his research on magnetic reconnection and turbulence in magnetized plasmas. Two noteworthy efforts are a study with postdoctoral researcher Pallavi Bhat on the theory of magnetic reconnection in so-called semi-collisional regimes, pertinent to existing and upcoming experiments, and the theoretical prediction of the existence of a range of scales in turbulent plasmas wherein the turbulent cascade is mediated by magnetic reconnection. Preliminary numerical simulations by Loureiro's collaborators, as well as by independent groups, and solar wind data seem to support these ideas.

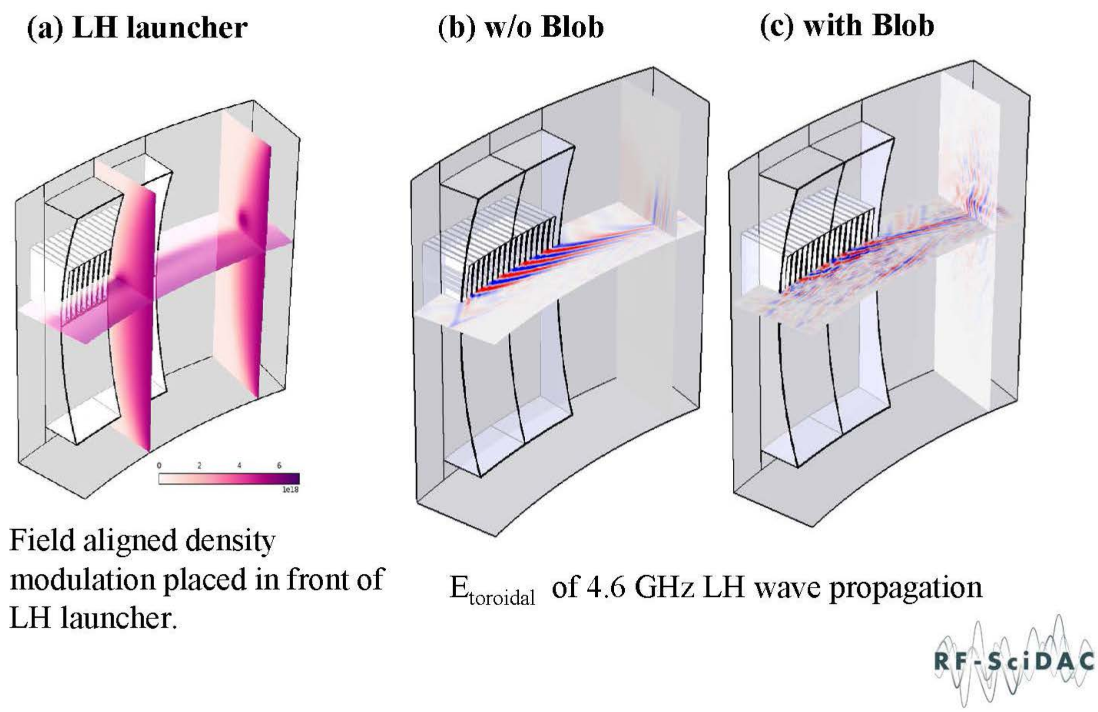
Loureiro continues to collaborate with Professor Sergey Lebedev's group at Imperial College London on laboratory studies of magnetic reconnection conducted with two interacting Z-pinch plasmas. This has led to interesting observations of plasmoid formations in parameters consistent with theoretical predictions made by Professor Loureiro as well as observations of anomalous ion heating, which is currently not understood but is under investigation.

Professor Loureiro's teaching activities over the past year included the development of a new graduate course on advanced topics in plasma physics.

High-Performance Computing Initiatives

SciDAC Partnership for Integrated Simulation of Fusion Relevant RF Actuators

In September 2017, the SciDAC Partnership for Integrated Simulation of Fusion Relevant RF Actuators began a five-year period of funding to replace the prior SciDAC Center for Simulation of Wave-Plasma Interactions. The goal of the partnership is to develop a simulation capability allowing exploration of the self-consistent interaction of RF power with the short mean free path scrape-off layer, including the effects of plasma sheaths, ponderomotive forces near an antenna, and turbulence and transport. The new simulation capability will make it possible to answer critical questions related to how RF power modifies properties of the scrape off layer, and how, in turn, the SOL affects the propagation and absorption of RF waves. Targeted problems include the impact of high-power RF systems on plasma facing materials, for example high-Z impurity sputtering and transport induced by large RF-induced sheath potentials, localized thermal loads, and antenna damage. Important initial results have been obtained by Syun'ichi Shiraiwa, who has used a new edge RF antenna code based on the scalable open source finite element library MFEM to demonstrate that lower hybrid wave resonance cones can be substantially altered by the presence of turbulent density fluctuations or "blobs" in the edge plasma. This can be seen in Figure 2, where a field aligned density modulation has been placed in front of a lower hybrid launcher (Figure 2a) in the Alcator C-Mod tokamak, and the resulting 3D toroidal RF electric field coupled by the launcher is shown without turbulent blobs (Figure 2b) and with turbulent blobs (Figure 2c). Scattering of the RF fields from the turbulence essentially destroys the "resonance cone" structure of the fields shown in Figure 2b.



Three-dimensional simulation of the effect of edge turbulence on the propagation of lower hybrid waves in the Alcator C-Mod Tokamak

SciDAC Partnership for Multiscale Gyrokinetic Turbulence

Darin Ernst leads the MIT effort in the SciDAC Partnership for Multiscale Gyrokinetic Turbulence (MGK), which is focused on developing practical algorithms to simulate important multiscale interactions in turbulence for eventual use in whole device modeling. In addition, Ernst leads experiments on the DIII-D tokamak as part of the PSFC/DIII-D domestic collaboration. This dual role allows him to leverage large-scale gyrokinetic simulations to interpret and explain these experiments; it also enables him to use the experiments to validate models and simulations. Development of new synthetic microwave diagnostics using realistic full-wave simulations of DIII-D diagnostics (in collaboration with the University of California, Los Angeles) plays an important role in these studies. In addition, Ernst continued developing a model for the nonlinear upshift, caused by zonal flows, of the critical gradients for turbulence driven by ion temperature gradients as well as trapped electrons. The model predicts strongly improved confinement with increasing mass, providing a possible explanation for this "isotope effect."

A main thrust of the MIT MGK effort involves further development and testing of an algorithm proposed by Ernst to exploit the factor-of-60 scale separation in the poloidal direction and in time between ion gyro-radius scale turbulence and electron gyro-radius scale turbulence. This algorithm sub-cycles electron gyro-scale simulations using a frozen snapshot of the ion gyro-scale fields, feeding nonlinear interactions from the electron scales back to the ion scale simulation.

The collision operators used in present gyrokinetic simulations of plasma turbulence utilize model field particle terms. Although they conserve the first three velocity moments, these models bear little resemblance to the Landau operator and are locally incorrect. Qingjiang Pan joined PSFC as a postdoctoral associate under MGK this year after developing a full-f version of the GENE gyrokinetic code suitable for the scrape-off layer. Pan and Ernst have formulated the first gyrokinetic linearized exact (not model) Landau collision operator in conservative form. This form explicitly preserves the symmetry between test-particle and field-particle contributions and can be discretized with a finite-volume or spectral method that preserves the numerical conservation laws. The new operator is being implemented in the GENE gyrokinetic code.

Navigational Data Management Project

John Wright is also involved in the Navigational Data Management Project along with Martin Greenwald and Joshua Stillerman. This project, funded by NSF, aims to encode metadata and provenance connections in an application that permits navigation and searches of distributed but related experimental and simulation data. The project ended its first year with the release of a prototype application linking electronic notebook entries, engineering data, and experimental measurements from new high field HTS magnetic technologies being developed at PSFC. Additional users in other physics areas at the University of Wisconsin–Madison and the University of California, Los Angeles, are interested in using the technology for their experiments.

High-Temperature Superconductor Magnets

John Wright is a co-PI of the High Temperature Superconductor development project at PSFC. HTS magnets have the potential to transform magnetic fusion energy. PSFC is working on using these materials, newly available and at industrial scales, to develop and demonstrate their viability for high field steady-state magnets in fusion energy. Wright and Syun'ichi Shiraiwa are responsible for the modeling part of this project. Tools developed for radio frequency wave modeling have been adapted for modeling the behavior of HTS magnets. This modeling will help inform prototype designs, and experiments with these designs will help validate the models and drive further development.

Domestic and International Collaborations

PSFC/DIII-D Collaboration

During the past year, Darin Ernst led two experiments on the DIII-D tokamak at General Atomics, presently the largest US magnetic fusion facility, aimed at qualifying the new wide pedestal quiescent H-mode regime for burning plasma operation with zero injected torque and dominant electron heating, key conditions expected in future reactors. These will be featured in an oral talk at the IAEA Fusion Energy Conference in India this fall.

In the first experiment, wide pedestal QH-mode was successfully sustained at up to 77% ECH power without edge localized modes or core magnetohydrodynamic activity, maintaining the same performance as with strong ion fueling and heating from neutral beams. As the electron cyclotron heating power was aimed more centrally, a new inner core transport barrier emerged in the electron temperature profile, attaining electron temperatures in excess of 12 keV. Fourier analysis of the response to modulated ECH revealed a strong inwardly directed electron heat flux.

The second experiment studied momentum and thermal transport at near-zero applied torque as the fraction of electron heating power was varied. The intrinsic torque profile was measured via neutral beam torque modulation, and electron thermal transport was simultaneously measured via modulated ECH. The energy confinement time in wide pedestal QH-mode showed strong non-monotonic behavior as ECH power was increased due to variations in core ion thermal confinement. Unlike other H-mode operating regimes at ITER collisionality, overall confinement improved with dominant electron heating. The impurity confinement time was also measured with the new MIT laser blowoff system injecting aluminum in every shot.

JET Modeling Collaboration

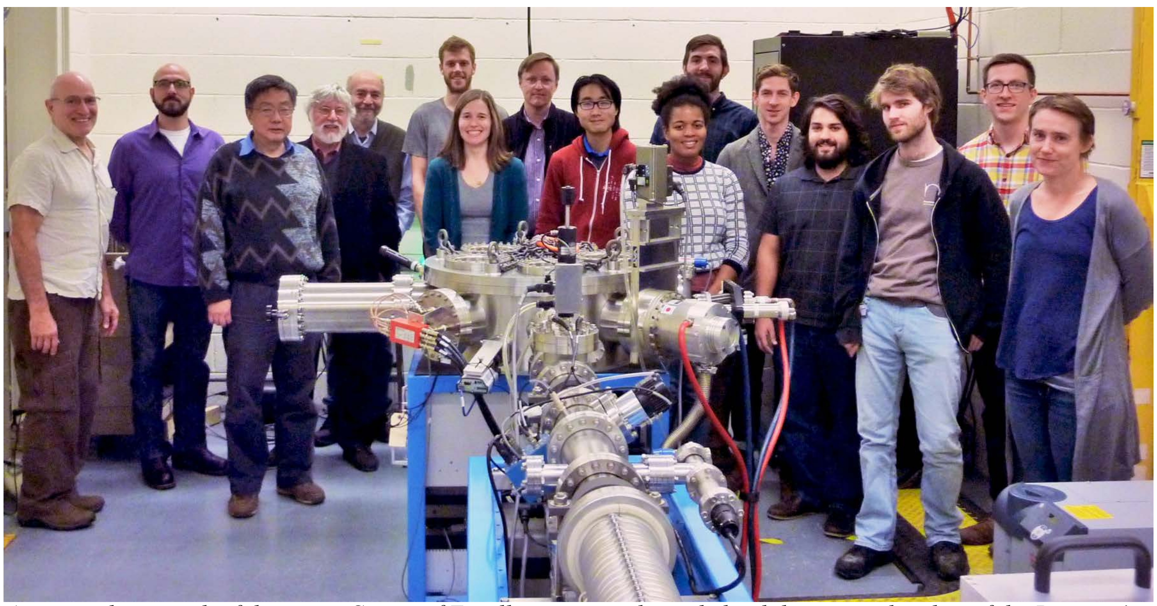
Under the SciDAC Partnership for Integrated Simulation of Fusion Relevant RF Actuators, John Wright established a research collaboration in radio frequency modeling with the Joint European Torus experiment in Culham, England. JET is Europe's and the world's largest operating tokamak fusion experiment. It is beginning an exciting campaign of deuterium and tritium fusion experiments; these fuels will be used in a future fusion power plant. Wright is participating in modeling and optimizing these upcoming experiments on JET. The focus is on radio frequency heating in deuterium and tritium along with preparatory experiments and antenna optimization. Wright participates remotely in weekly JET task force meetings.

Simulations in Support of the DOE Theory Performance Target

Research carried out for the EAST Tokamak in Hefei, China, as part of this collaboration is cross-cutting with research carried out in the PSFC Theory Group. Because it offers important leverage for controlling damaging transients caused by magnetohydrodynamic instabilities, LHCD will be indispensable for driving off-axis current during long-pulse operation of future burning plasma experiments including ITER. However, the experimentally demonstrated high efficiency of LHCD 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 RF field solver and a continuum Fokker-Planck code to elucidate the roles of toroidicity and full-wave effects. These coupled simulations (done in collaboration with Donald Batchelor at the Oak Ridge National Laboratory) were enabled through the use of a workflow manager called the Integrated Plasma Simulator. During late 2017 and early 2018, coupled simulations were performed at moderate numerical resolution that successfully demonstrated that convergence could be obtained between the electromagnetic field solver and the Fokker-Planck solver. These simulations are now being extended to high numerical resolution by second-year graduate student Samuel Frank as part of his doctoral thesis research.

High-Energy-Density Physics Division

On June 14, 2018, the Department of Energy offered the High-Energy-Density Physics Division the designation of a Center of Excellence through a new five-year cooperative agreement grant, marking the beginning of a new era for the division. The division has grown and increased in influence continuously over more than three decades and currently includes five scientists, two postdocs, and nine graduate students, and the new grant will make many more things possible. The grant's focus is on research in laboratory plasma physics in the fields of inertial confinement fusion (ICF), laboratory astrophysics, and basic plasma properties, as well as on development of new plasma diagnostic instrumentation. Experiments will be carried out at the OMEGA Laser Facility at the University of Rochester, MIT's own HEDP accelerator lab, the Lawrence Livermore National Laboratory, and Sandia National Laboratory. The center will include scientists at four other institutions—the University of Rochester, the University of Iowa, Virginia Tech, and the University of Nevada, Reno)—working with MIT. In addition to new and exciting physics, one of the primary goals of the center is the graduate education of a new generation of plasma scientists.

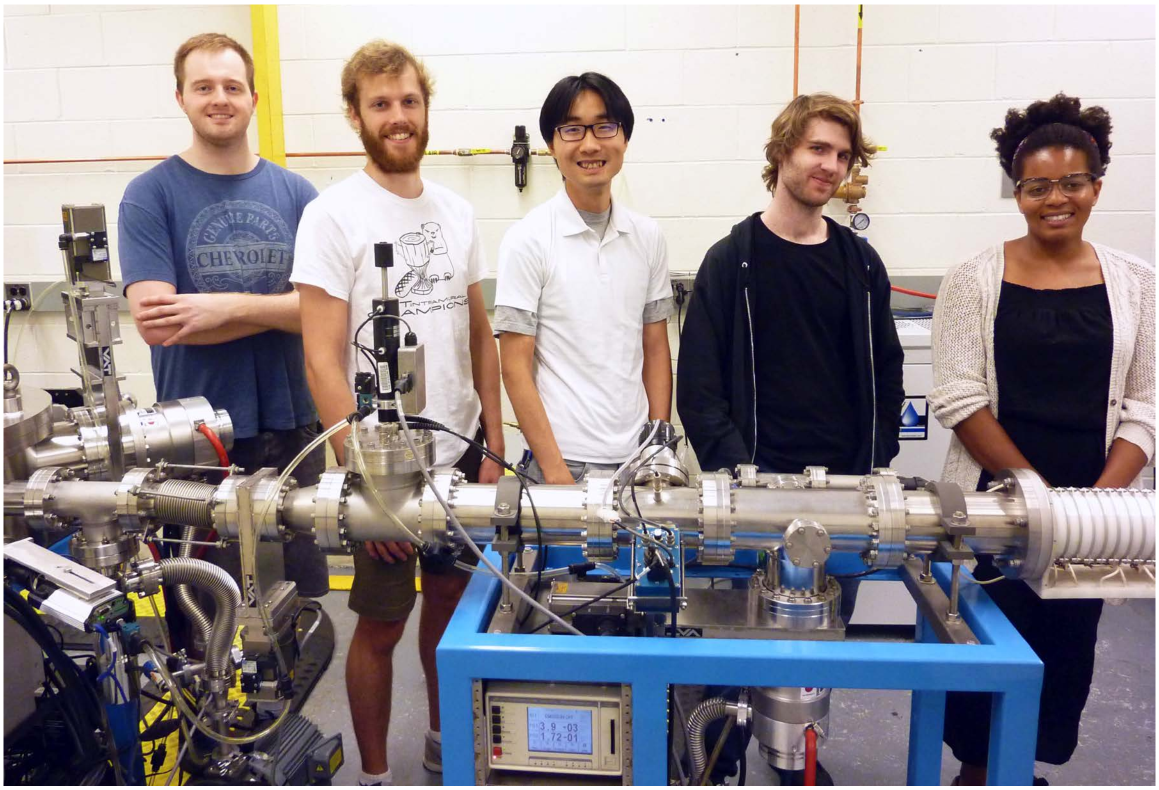


A recent photograph of the entire Center of Excellence team, shown behind the target chamber of the Division's Accelerator for HEDP research.

The division's work resulted in members receiving a number of awards this year, including several by current and recent MIT students. Recent PhD graduate Alex Zylstra received the prestigious 2018 Early Career Research Award from the DOE Office of Science for his work on nuclear astrophysics with inertial fusion implosions, which he began while he was our PhD student. This award comes with five years of financial support.

Current PhD students who won awards are shown in figure 4. Raspberry Simpson won a DOE NNSA (National Nuclear Security Administration) Laboratory Residency Graduate Fellowship, based on her recent research in ICF that will be used to develop plasma diagnostics. At a DOE symposium in February 2018 in Washington, DC, division graduate student Hong Sio received an Outstanding Poster award for "Implications of Differences Between Measured and Rad-Hydro-Simulated Reaction Histories in Hydro-Like

Implosions on OMEGA." As part of his presentation, Hong described a new diagnostic that will use eight scintillator channels to infer plasma electron temperatures from X-rays in the energy range 10–20 keV. At the February 2018 National Ignition Facility and Jupiter User Group Meeting in Livermore, CA, division graduate student Graeme Sutcliffe won the First Place by a Graduate Scholar award for his poster "A New Multi-Particle, Mono-Energetic Backlighting and Stopping-Power Platform for the NIF and OMEGA." Other awards at the OMEGA Laser User's Group meeting at the University of Rochester in April were won by students Patrick Adrian, Neel Kabadi, and Brandon Lahmann.



Division PhD students who won awards for their research during the last year. From left to right, they are Patrick Adrian, Graeme Sutcliffe, Hong Sio, Brandon Lahmann, and Raspberry Simpson. Missing in the photo is Neel

Finally, the American Physical Society's 2017 John Dawson Award for Excellence in Plasma Physics Research was presented to division scientists Chikang Li, Richard Petrasso, and Fredrick Seguin at the October 2017 APS DPP conference in Milwaukee. They were cited for their development of the technique of radiography with monoenergetic charged particles and for using the technique in a wide range of plasma physics experiments in ICF and laboratory astrophysics.

Individuals in the division have carried on other important new physics studies. For example, Chikang Li conducted innovative and breakthrough studies on astrophysically relevant, electromagnetic collisionless shocks in the laboratory. These studies led to the first ever demonstration that the structure and dynamics of astrophysical collisionless shocks can be modeled in the laboratory and provided new insight into the role of Weibel instability in electron heating and shock mediation. Johan Frenje reported on the first accurate validation of ion-stopping formalisms around the Bragg peak in well-characterized high-energy-density plasmas; this has important implications for our understanding of alpha heating in ICF ignition experiments. Gatu Johnson used the OMEGA laser facility inertial confinement fusion platform to uniquely study the T(t,2n) alpha reaction as a function of center-of-mass (c-m) energy, discovering a hitherto unexpected c-m energy dependence in the shape of the T+T neutron spectrum.

In the meantime, our contingent of graduate students has grown with the addition of new PhD students Timothy Johnson and Jacob Pearcy and SM student Alexander Sandberg. New postdoctoral researcher Arijit Bose has also joined the division.

Plasma Science and Technology Division

The Plasma Science and Technology Division conducts research on gyrotrons, advanced terahertz sources, and high-gradient electron acceleration, as well as research on gyrotron drilling for geothermal energy and additive manufacturing, and plasma-material interactions. The division is headed by Richard Temkin, senior scientist in the Department of Physics and associate director of PSFC. Paul Woskov, research scientist at PSFC, serves as assistant division head.

Gyrotron Research

Gyrotrons are under development for electron cyclotron heating of present-day and future plasmas, including the ITER plasma, for high-frequency radar, and for enhanced spectroscopy in the NMR research program on biomolecules. These high-power applications require vacuum electron devices operating at frequencies in the range of 100–600 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. 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 2017–2018, we conducted further tests of a novel internal mode converter in the gyrotron that couples 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 multipactor on dielectric surfaces in a vacuum. Results have been obtained on sapphire, alumina, and quartz samples. The accelerator research group at the SLAC National Accelerator Laboratory has prepared accelerator structures at 110 GHz for testing in a vacuum using pulses from the gyrotron. First tests of the structure have been completed and testing will continue at higher power in the near future. A semiconductor switch controlled by a 532-nm laser pulse has been used to reduce the gyrotron output power length from two microseconds down to as little as three nanoseconds. The group is also continuing research on low-loss microwave (170 GHz) transmission lines in collaboration with the US ITER project headquartered at the Oak Ridge National Laboratory. In 2017–2018, a pair of motorized polarizers was tested that will be used on the ITER transmission line and the results were successfully compared with theory for both the ellipticity of the microwave beam and its direction of rotation.

Advanced Terahertz Sources

In 2017–2018, we continued our 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 slower than the speed of light, in contrast to fast-wave gyrotron sources. In 2017–2018, we built the second version of an oversized klystron at 94 GHz as part of a Defense Advanced Research Projects Agency program focusing on innovative high-frequency microwave devices. The klystron is being tested and has shown excellent electron beam transmission. We have also designed devices for the 250 GHz frequency range. A backward wave oscillator using a disk-loaded waveguide structure has been built and is currently being tested. If successful, it will be followed by an amplifier of similar design.

High-Gradient Electron Acceleration

Research on high-gradient accelerators is focused on high-frequency linear electron accelerators that may greatly reduce the size and cost of future accelerators used in frontier research in high-energy physics. This research is conducted using the Haimson Research Corporation/MIT 25 MeV, 17 GHz electron accelerator, the highest-power accelerator on the MIT campus and the highest-frequency stand-alone accelerator in the world. In 2017–2018, we completed a unique study of internal dark current in a high-gradient accelerator structure using small holes in the structure sidewall to directly measure the current. Dark current is current emitted by field emissions from surfaces of the accelerator wall that may lead to breakdown and cavity heating. The measurements are in general agreement with code predictions. We have also designed, built, and tested a metamaterial structure for use in wakefield acceleration. The structure was tested at the Argonne National Laboratory's wakefield test accelerator. Up to 80 MW of power at 11.4 GHz was generated in 2-ns pulses. These results are promising for the design of future electron-positron linear colliders.

Geothermal Energy

A significant advance is needed over conventional mechanical drilling technology to penetrate into deep basement rock to enable virtually limitless geothermal energy. Under the leadership of Paul Woskov, high-power millimeter-wave (MMW) gyrotron sources, originally developed for heating and control of magnetic confinement fusion plasmas, are being pursued for directed-energy boring into deep hard rock. MMW directed energy overcomes the limitations of high temperature, rock hardness, and slow rates of penetration with mechanical systems and reduces inefficiencies with directed-energy infrared lasers. In past years feasibility has been established in the laboratory, and present efforts are focusing on scaling the research to high-power field systems.

During FY2018 AltaRock Energy Inc. purchased an option to license the technology from MIT, and it has been pursuing development funding from private and government sources. Two proposals were submitted to DOE by Aaron Mandell of AltaRock, with Paul Woskov, Professor Herbert Einstein of the Department of Civil and Environmental Engineering, Ken Oglesby of Impact Technologies LLC, and Anthony Baros of the Air Force Research Laboratory (AFRL) as key participants. The first proposal was submitted to ARPA-E (Advanced Research Projects Agency–Energy) for a three-year effort that would result in a 1 MW scale pilot gyrotron system at AltaRock's Newbury, OR, geothermal site. The second proposal was submitted to the Office of Energy Efficiency and Renewable Energy for a two-year effort aimed at carrying out experiments with AFRL's 100 kW gyrotron system. If awarded, these projects would start in FY2019.

Additive Manufacturing Measurements

The advent of 3D printing to manufacture parts with shapes and properties not previously possible has created a need for improved metrology to monitor, analyze, and control the process in real time. Paul Woskov is working with Sandia National Laboratories to advance additive manufacturing by investigating the improvement of in-process analysis methods and technologies. In FY2018, he participated in experiments at Sandia using a dual 137 GHz receiver millimeter wave system he developed and delivered to Sandia the previous year. Experimental methods were refined, and data on the emissivity of 316 stainless steel were obtained as it melted and re-solidified.

Plasma Material Interactions

This research focuses on the interface between the plasma and solid state and is led by Kevin Woller. One part of the experimental work has focused on the development of new in situ material erosion diagnostics through the use of nuclear "markers" in tiles exposed to plasma experiments. This has culminated in the first proof-of-principle demonstration of boron and fluorine depth markers and their application in the EAST tokamak in China. The other major research push in this area has been the development of in situ measurement techniques for lithium coatings using the DIONIS OS device.

Magnets and Cryogenics Division

Joseph Minervini has headed the Magnets and Cryogenics (M&C) Division since 1994. Minervini retired from his regular staff position on December 31, 2017. Since then, he has continued to be employed half time at PSFC. He continues in his role as division head, on an interim basis, in collaboration with the division's deputy director, Professor John Brisson of the Mechanical Engineering Department. Professor Brisson also heads the MIT Cryogenics Engineering Laboratory. Integration began last year between the Cryogenic Engineering Lab and M&C.

M&C conducts research on conventional and superconducting magnets for fusion devices and other large-scale power and energy systems. This past year's research and development continued to be focused on applying REBCO high-temperature superconducting materials toward an advanced very-high-field tokamak device in which magnetic fields can be as high as 22 tesla at the toroidal field coils. The DOE Office of Fusion Energy Sciences remained our primary sponsor of superconducting magnet technology development. Laboratory-scale R&D continues to focus on the staged development of high current conductors using the REBCO HTS superconductor. Since HTS conductors can have very high engineering current densities at temperatures well above 4.2 K liquid helium, our mechanical engineering graduate student Julien Barber completed his master's thesis research on the study of several different cryogenic fluids for cooling HTS magnets.

Makoto Takayasu of M&C completed the fabrication of a moderate-length (several meters) high-current REBCO twisted stack tape conductor. Takayasu invented and patented this conductor concept, and the sample he prepared was to be tested at a high magnetic field and current in a special magnet facility designed, built, and located at the National Institute for Fusion Studies (NIFS) in Gifu Prefecture, Japan. The conductor sample was shipped to Japan in May, and Takayasu visited NIFS and mounted the sample in July. However, the test could not be performed because the large superconducting magnet was not fully commissioned. We expect that the magnet commissioning will be completed by the end of August and the conductor test will take place in September.

Our R&D efforts involving REBCO HTS conductors continued to be supported under a research grant with Superconductor Technologies Inc. (STI), located in Austin, TX. STI is the prime recipient of the $4.5 million program award provided by the DOE Office of Energy Efficiency and Renewable Energy, on behalf of the Advanced Manufacturing Office, for its Next Generation Electric Machines program. The TECO-Westinghouse Motor Company, an industry-leading manufacturer of electric generators and motors, and the University of North Texas are also collaborating with STI in this work. The combined team focus is on improving the manufacturing process of superconductive wires to improve performance and yield while reducing costs at sufficiently high temperatures that nitrogen can be used as the cryogenic fluid. Our work this year included measurement of the critical properties of the REBCO tape supplied to us by STI.

In AY2018, we concluded 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 final result of this program is a complete conceptual design for an all-superconducting cyclotron wherein all iron is eliminated from the magnetic circuit, including the main iron poles and the iron yoke for return flux and shielding. The design study demonstrates that such a system can be much more compact and lightweight than existing resistive and superconducting systems, and it is also capable of producing a variable energy proton beam. All significant beam dynamic simulations for this study were competed by Daniel Winklehner from the Physics Department's Laboratory for Nuclear Science.

We have further collaborated with the Lab for Nuclear Science on Project 8, led by Professor Joseph Formaggio. The work carried out by Alexey Radovinsky of PSFC is focused on the design of an exotic superconducting magnetic trap for tritium atoms.

Magnetic Resonance Division

Five principal investigators lead the research activities of the Magnetic Resonance Division, formerly the Francis Bitter Magnet Laboratory: Professors Robert Griffin and Mei Hong (Chemistry), Yukikazu Iwasa (PSFC), and Jagadeesh Moodera and Richard Temkin (Physics).

Robert G. Griffin (Professor of Chemistry)

Research in the Griffin group covers four different areas: (1) development of new NMR methods for measurement of distance and torsion angles via dipolar recoupling, (2) structure determination of amyloid fibrils, (3) the structure and mechanism of membrane protein function, and (4) development of high-frequency dynamic nuclear polarization and electron paramagnetic resonance to enhance NMR signal intensities. Three of these areas are discussed here.

Dipolar Recoupling and Distance and Torsion Angle Measurements

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

Efforts in dipolar recoupling are continuing with the development of proton-assisted recoupling (PAR) and proton-assisted insensitive nuclei. PAR is examined by exploring optimal experimental conditions and magnetization transfer rates in a variety of biologically relevant nuclear spin systems, including simple amino acids, model peptides, and two proteins: nanocrystalline protein G and, importantly, amyloid beta 1-42 (M0 Aβ1-42) fibrils. A selective PAR protocol, SUBPAR (setting up better proton-assisted recoupling), is described to observe magnetization transfer in one-dimensional spectra, minimizing experiment time (in comparison with two-dimensional experiments) and thereby enabling an efficient assessment of optimal PAR conditions for a desired magnetization transfer. In the case of the peptide spin systems, experimental and simulated PAR data sets are compared on a semiquantitative level, elucidating the interactions influencing PAR magnetization transfer and their manifestations in different spin transfer networks. Using the optimum Rabi frequencies determined by SUBPAR, PAR magnetization transfer trajectories (or buildup curves) were recorded and compared with simulated results for short peptides. PAR buildup curves were also recorded for M0 Aβ1-42 and examined conjointly with a recent structural model. The majority of salient cross-peak intensities observed in the M0 Aβ1-42 PAR spectra are well modeled with a simple biexponential equation, although the fitting parameters do not show any strong correlation to internuclear distances. Nevertheless, these parameters provide a wealth of invaluable semiquantitative structural constraints for M0 Aβ1-42. The findings described here offer a complete protocol for recording PAR ^{13}C-^{13}C correlation spectra with high efficiency and using the resulting information in protein structural studies.

In addition, we explored ^{17}O NMR during the past year. The structures of two protected amino acids, FMOC-L-leucine and FMOC-L-valine, and a dipeptide, N-acetyl-L-valyl-L-leucine (N-Ac-VL), were studied via one- and two-dimensional solid-state NMR spectroscopy. Utilizing ^{17}O magic-angle spinning (MAS) NMR at multiple magnetic fields (17.6–35.2 T/750–1,500 MHz for ^{1}H), the ^{17}O quadrupolar and chemical shift parameters were determined for the two oxygen sites of each FMOC-protected amino acid and the three distinct oxygen environments of the dipeptide. One- and two-dimensional, ^{17}O, ^{15}N-^{17}O, ^{13}C-^{17}O, and ^{1}H-^{17}O double-resonance correlation experiments performed on the uniformly ^{13}C-^{15}N and 70% ^{17}O-labeled dipeptides proved the attainability of ^{17}O as a probe for structure studies of biological systems. The ^{15}N-^{17}O and ^{13}C-^{17}O distances were measured via one-dimensional REAPDOR and ZF-TEDOR experimental buildup curves and determined to be within 15% of previously reported distances, thus demonstrating the use of ^{17}O NMR to quantitate interatomic distances in a fully labeled dipeptide. Through-space hydrogen bonding of N-Ac-VL was investigated in a two-dimensional ^{1}H-detected ^{17}O-R3-R-INEPT experiment, furthering the importance of ^{17}O for studies of structure in biomolecular solids. We also need to develop methods to decrease the cost of producing ^{17}O and find ways to ^{13}C-^{15}N and ^{17}O label proteins. Thus, we see a number of exciting challenges on the scientific horizon.

Structure of Fibrils of Beta-2-Microglobulin

We have been using these methods to examine proteins that form fibrils such as beta-2-microglobulin (β_2m) and ΔN6 associated with dialysis-related amyloidosis. All amyloid fibrils contain a cross-b structure, a protein motif that is found in functional amyloid as well as in fibrils associated with disease. Recent progress in cryo-electron microscopy (cryo-EM) and MAS NMR has enabled elucidation of high-resolution structures of tau and Ab42 fibril 1-4 proteins that are intrinsically disordered in solution but that form amyloid in Alzheimer's disease. How these structures compare with amyloid formed from proteins associated with other diseases remains unknown. We combined cryo-EM and MAS NMR to determine the structure of an amyloid fibril formed from β_2m, the culprit protein of dialysis-related amyloidosis 5, at 3.9 Å resolution. The fibril is composed of two protofilaments assembled from identically folded subunits that bear no resemblance to β2m's native immunoglobulin fold. The fibrils share motifs with tau and Ab42 but also contain unique features, including p-stacking interactions perpendicular to the fibril axis within each layer of the cross-b structure and an intramolecular disulfide bond that stabilizes the subunit fold. We also described structures at lower resolution for different fibril polymorphs found within the same preparation, including single- and four-protofilament fibrils, and showed that each is built from the same core subunit fold. These results provide new insights into the origin of polymorphism in amyloid, the mechanisms of fibril formation, the commonalities and differences within the amyloid fold, and the possible inhibition of amyloid formation.

Dynamic Nuclear Polarization

Dynamic nuclear polarization (DNP) is theoretically able to enhance the signal in NMR experiments by a factor of 658. However, DNP enhancements used in high field, high-resolution biomolecular MAS 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. 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 ^1H 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, $\omega_{0I} = \omega_{1S}$ where ω_{0I} and ω_{1S} are the nuclear Larmor and electron Rabi frequencies, respectively.

As indicated above, the efficiency of continuous wave DNP experiments decreases at the high magnetic fields used in contemporary high-resolution NMR applications. To recover the expected signal enhancements from DNP, we explored time domain experiments such as NOVEL that match 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, we conducted frequency-swept integrated solid effect (FS-ISE) experiments that allowed 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 to (within 10%) NOVEL. The microwave frequency modulation resulted in field profiles exhibiting new features that we coined the "stretched" solid effect (S2 E).

We investigated the FS-ISE utilizing a high-power, broadband 94 GHz (3.35 T) pulse EPR spectrometer. The bandwidth of the spectrometer enabled measurement of the DNP Zeeman frequency/field profile, revealing two dominant polarization mechanisms, the expected ISE and the just-mentioned stretched solid effect. At 94 GHz, despite the limitations in the microwave chirp pulse length (10 μs) and the repetition rate (2 kHz), we obtained signal enhancements up to approximately 70 for the S2 E and 50 for the ISE. The results successfully demonstrate the viability of FS-ISE and S2 E DNP at a frequency 10 times higher than previous studies. Also, our findings suggest that these approaches are candidates for implementation at higher magnetic fields and that a precise modulation of microwave pulses can play an important role in optimizing the efficiency of pulsed DNP experiments.

Mei Hong (Professor of Chemistry)

The Hong group develops and employs solid-state NMR techniques to investigate structural biology and biophysical questions of contemporary interest. Current focuses are on disease-relevant viral membrane proteins, energy-relevant plant cell wall materials, and amyloid fibrils involved in diseases and in chemical catalysis. In 2017–2018, the Hong group made major strides in four scientific areas, as described below.

Structure and Dynamics of Influenza M2 Proteins

The Hong group discovered a millisecond-timescale conformational motion of the influenza M2 protein that explained this protein's slow rate of proton transport. The cooperative motion of the four-helix bundle between a low-pH conformer and a high-pH conformer provided the long missing link of the rate-limiting step in proton transport by this influenza ion channel.

Structure and Lipid Interactions of Viral Fusion Proteins

The Hong group determined the membrane-bound structure of an antibody-targeted region of the HIV viral fusion protein, gp41. They showed that the antibody-targeted segment resides on the membrane surface, while the transmembrane segment spans the lipid bilayer and the protein self-associates into trimers in the lipid membrane. This study is a first in that all prior structural studies used short peptide fragments of this domain of gp41, and few studies were carried out in native virus-mimetic lipid bilayers. The group's results resolve many conflicting reports in the literature and set the stage for future development of anti-HIV vaccines.

Structures of Plant Biopolymers

The Hong group carried out structure determinations of two important plant cell wall biopolymers, cellulose and sporopollenin. They elucidated the conformation of the most reactive moiety of cellulose, the hydroxymethyl group, using a ^{13}C-detected ^{1}H-^{1}H

distance NMR technique. The results indicate that the disordered β-(1,4) glucan chains on the cellulose microfibril surface adopt a different hydroxymethyl conformation from that of the interior crystalline chains. In a second study, using quantitative solid-state NMR and spectral editing methods, the Hong group determined the chemical structure of sporopollenin, the inert biopolymer that is responsible for the survival of plant spores and pollen grains and the migration of early plants onto land. This collaborative study with the Jing-Ke Weng laboratory (Department of Biology) represents the first discovery of the structure of this major plant polymer.

New Solid-State Nuclear Magnetic Resonance Methods

The Hong group developed two ^{19}F solid-state NMR approaches to measure internuclear distances to 1–2 nm. These ^{19}F-^{19}F and ^{13}C-^{19}F distance techniques, designed for high magnetic field and fast magic-angle-spinning conditions, overcome the bottleneck of obtaining long-range distance constraints for high-resolution structure determination using solid-state NMR.

Yukikazu Iwasa (Senior Research Scientist)

During the period July 1, 2017, through June 30, 2018, the Magnet Technology Group, under Iwasa's leadership, was involved in three NIH-supported programs on NMR and MRI magnets, each briefly summarized below.

NMR Magnet Program: Phase 3B

Modified Phase 3B of the 1.3 GHz LTS/HTS NMR magnet (1.3 G) program, supported by the National Institute of General Medical Sciences began on September 1, 2015; its end date is August 31, 2018. This project will likely be no-cost extended to a new end date of August 31, 2019. The goal of the project is to design a very high magnetic field NMR magnet (30.5 T) using high-temperature REBCO superconductors.

HTS Magnets for NMR and MRI Application

Supported by the National Institute of Biomedical Imaging and Bioengineering (NIBIB) and begun on July 1, 2016, this project had two specific objectives related to enabling REBCO-based double-pancake (DP) coils to operate liquid-helium (LHe) free in a persistent mode: (1) build REBCO DP coils that each terminated with a superconducting joint and (2) design, build, and operate a persistent-current switch viable to these coils and operating in the range of 4.2 K to 77 K. The project's end date was April 30, 2018. Because our subcontractor responsible for the joints was unable to make superconducting joints with REBCO tape, the first objective could not be completed. The second objective was successfully completed.

Tabletop Liquid-Helium-Free, Persistent-Mode MRI Magnet

Supported by NIBIB and initiated on April 1, 2017, this project has two specific aims: (1) completion of a tabletop LHe-free, persistent-mode, solid nitrogen (SN2) cooled superconducting (MgB2) MRI magnet prototype for phalangeal scanning in osteoporosis research and (2) demonstration of the benefits of MgB2/SN2 technology for MR magnets in the context of a very compact affordable scanner (with measurements of the distal phalanx of the left-hand true 3D bone mineral density, 3D bone matrix density, and trabecular microstructure). We have decided to purchase MgB2 wire for this magnet from Hitachi Research Lab, with which we are collaborating on the project. MgB2 joints made with and model coils wound with Hitachi MgB2 wire are being developed and built.

Jagadeesh Moodera (Senior Research Scientist)

Jagadeesh Moodera is a senior research scientist and group leader in the Department of Physics. His research efforts focus on nanoscience condensed matter physics (quantum coherent topologically driven phenomena in nanodevices, investigation of Majorana bound states, superconducting spintronics, molecular spintronics), with funding from the Office of Naval Research, NSF, and the John Templeton Foundation. He is also part of the large NSF-funded CIQM (Center for Integrated Quantum Materials) program, a collaboration involving MIT, Harvard, Howard University, and the Museum of Science, Boston. Based on its excellent success during the past five years, this program has been renewed for another five years (until 2023). Three other large multi-PI collaborative research proposals have been submitted to DOE, and a fourth is under preparation. A new project sponsored by the Army Research Office will begin in August 2018. Under this new project, a guest postdoctoral fellow will be placed in MIT under Moodera's supervision for a period of at least one year.

Moodera has collaborations with various universities in the United States, Brazil, the United Kingdom, Germany, Spain, India, Italy, Korea, and China, as well as with national laboratories (e.g., Oak Ridge, Brookhaven). Currently, he focuses on quantum coherent and dissipationless transport in topological systems, search of Majorana bound states, and topological superconductors—some of the most significant topics in physics. During the past few years, his group has been investigating ferromagnetic/superconductor hybrid system nano-constrictions to understand the basic physics and to develop superconducting spintronics (memory, sensing, and logic). In addition, his group investigates nanostructures, searching for quantum coherent behaviors of charge and spin transport in novel systems.

Moodera continues mentoring graduate, undergraduate, and high school students by providing research opportunities in his lab. Visiting scientists from Brazil and China took part in his research and extensive collaborative discussions during the past year. He continues to help out other young faculty members and their students from the Departments of Physics, Mechanical Engineering, Materials Science and Engineering, and Electrical Engineering and Computer Science.

Moodera's group and his collaborators published several articles in journals such as *Science Advances* and *Physical Review.* Research results have been disseminated at international conferences. He is a member of the organizing committees of several international scientific workshops, and he delivered many invited talks at universities and conferences in the United States as well as Germany, Mexico, and Sweden.

His group continues to lead the field in novel quantum materials and superconducting spintronics, following their notable research accomplishments in the areas of superconducting spin switch, the quantum anomalous Hall (QAH) effect, and the dissipationless chiral spin polarized edge current flow. The QAH effect is believed to have unique potential for applications in electronic devices with low power consumption. The dissipationless spin polarized edge current flow is expected to have significant influence on the development of future low power spin–based storage and communication technologies. Currently, Moodera's group is investigating such behavior in nano devices. If these devices can be exploited, they can be expected to have a transformational influence on data storage and communication. Thus, in research on nanoscience condensed matter physics, the group continues to make significant contributions in both fundamental and applied sciences.

Using the state-of-the-art molecular beam epitaxy systems, Moodera's research group seeks to understand the quantum state exhibited by many novel materials. In order to investigate the behavior of atoms and molecules on various interacting surfaces, a custom-designed low-temperature (280 mK) scanning tunneling microscope/atomic (conducting) force microscope system capable of operating in high magnetic fields is under operation. One of the major projects incorporating this new, sophisticated tool is an investigation of Majorana bound state in nanostructures and their entanglement properties. This versatile and sensitive equipment should lead to new discoveries and collaborations and open up many technological possibilities.

Based on the group's work related to superconducting spin memory, a patent application has been filed and another one is under way. The group's past research in the structure of quantum materials has been further developed by various companies such as IBM, Motorola, Seagate, TDK, and Fujitsu for application in digital storage. These companies have introduced into the market mini- and micro-disc drives with unprecedented capacity and read head sensors based on magnetic tunnel junctions. Another important area of application involves nonvolatile magnetic random access memory elements and reprogrammable logic circuits. These innovations will potentially have a significant and highly profitable impact on memory technology and are being developed by major companies including IBM. There is now the possibility of low-dissipation superconducting spintronics for quantum electronics.

Six postdoctoral scholars (including two women), a female visiting scientist from Brazil, (and current graduate student), and five high school students have taken part in Moodera's research. One of the postdocs won the prestigious Marie Curie Fellowship. An undergraduate from the California Institute of Technology is carrying out three months of summer internship work. A female MIT undergraduate also participated in research during the past academic year.

Moodera continues as a visiting professor at Eindhoven Technical University, and 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 "Superspins" program at the University of Cambridge, and he was invited to be part of an international review board to set scientific orientations and objectives for nanosciences at the frontiers of nanoelectronics.

Educational Outreach

The Plasma Science and Fusion Center's educational outreach program is planned and organized under the direction of Paul Rivenberg, PSFC communications and outreach administrator. The program 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 K–12 students in scientific and technical subjects by bringing them together with scientists, engineers, and graduate students in laboratory and research environments. This kind of interaction is aimed at encouraging young people to consider science and engineering careers, and feedback has always been extremely positive. Efforts are made to reach populations that are underrepresented in the sciences, including girls and minorities. Tours of our facilities are also available for the general public.

Outreach days are held twice a year, encouraging high school and middle school students from around Massachusetts to visit the PSFC for hands-on demonstrations and tours. PSFC graduate students who volunteer to assist are key to the success of our tour programs. The experience helps them develop the skill of communicating complex scientific principles to those who do not have advanced science backgrounds. This year, more than 1,000 people visited the PSFC.

The PSFC continued to receive attention from lawmakers this year, facilitated by MIT alumnus Reiner Beeuwkes '67. These included visits by Senators Tammy Baldwin (Wisconsin), Chris Van Holland (Maryland), Joe Donnelly (Indiana), and Jeff Merkley (Oregon); Representatives Jim Langevin (Rhode Island), Elizabeth Esty (Connecticut), and Jacklyn Rosen (Nevada); and Massachusetts state senator Maria Cantwell. All were guided around the Alcator C-Mod control room and experimental cell to learn more about the benefits of fusion energy.

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 Weekend, was attended by hundreds of MIT students and their families, who learned about the latest directions in plasma and fusion research.

This year the PSFC collaborated with the Department of Nuclear Science and Engineering, the Media Laboratory, and the Program in Art, Culture and Technology (ACT) on the installation of the Resynthesizer in the PSFC's Alcator C-Mod cell. Created by MIT professor Joe Paradiso, the project used dramatic data from one of the final experiments performed on the Alcator C-Mod as the basis for a synthesized soundscape. Graduate students from the PSFC and the Media Lab provided weekly late-afternoon tours for six weeks.

The PSFC continues to collaborate with other national laboratories on educational events. The annual Teachers Day (to educate middle school and high school teachers about plasmas) and Plasma Sciences Expo (to which teachers can bring their students) are traditions at each year's American Physical Society–Division of Plasma Physics meeting. Paul Rivenberg continues to organize the Plasma Sciences Expo. This year, 16 exhibitors representing laboratories and schools around the United States provided hands-on plasma and physics demonstrations for local students as well as the general public. The PSFC booth, staffed by Rivenberg, NSE administrator Valerie Censabella, and PSFC graduate students, introduced students to MIT's Alcator C-Mod fusion project with a video game that encourages participants to work cooperatively to confine a fusion plasma in a tokamak vacuum chamber. Research scientist Ted Golfinopoulos oversaw a series of magnet experiments at the booth, and Philip Michael participated as well, with a demonstration in which the ultraviolet protection of sunglasses and various grades of sunscreen was tested.

In April, the PSFC participated in the USA Science and Engineering Festival in Washington, DC. Paul Rivenberg, Ted Golfinopoulos, Valerie Censabella, and graduate student Lucio Milanese spent three days introducing thousands of the 370,000 attendees to the physical properties of magnets and plasma that are critical for fusion research.

Richard Temkin oversees the PSFC seminar series, weekly plasma science talks aimed at the MIT community, with the assistance of Abhay Ram, John Rice, and Paul Rivenberg. Graduate students also hold their own weekly seminar series, where they take turns presenting their latest research in a relaxed environment. PSFC deputy director Martin Greenwald has helped organize the center's annual Independent Activities Period (IAP) open house seminars as well as special visits from alumni and dignitaries, including US and Massachusetts lawmakers.

The PSFC also continues to be involved with educational efforts sponsored by the Coalition for Plasma Science (CPS), an organization formed by members of universities and national laboratories to promote understanding of the field of plasma science. PSFC associate director 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. Temkin and Rivenberg are members of the CPS steering committee. Rivenberg works with CPS on new initiatives and is editor of the coalition's *Plasma Page*, which summarizes CPS news and accomplishments of interest to members and the media. He also heads a subcommittee that created and maintains a website to help teachers bring the topic of plasma into their classrooms. This year, he concluded work overseeing a significant upgrade of the CPS website. He also works with the coalition's technical materials subcommittee to develop materials that introduce the public to different aspects of plasma science.

Honors and Awards

A number of PSFC staff members were recognized for their achievements this past year.

Only July 2 Professor Robert Guy Griffin, head of the Magnetic Resonance Division, received 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 euros, was awarded to Griffin at the European Magnetic Resonance conference (EUROMAR) in Warsaw, Poland. The prize is widely considered to be the second most prestigious award in the magnetic resonance community after the Laukien Prize, which Griffin received in 2007. Griffin was also appointed to the Arthur Amos Noyes Professorship.

Three members of the High-Energy-Density Physics Division received 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 (HED) plasmas."

Mechanical design and fabrication specialist Rick Leccacorvi was honored with a 2018 Infinite Mile Award at a ceremony held on May 23. His work designing an experimental apparatus for physicists and students at the Plasma Science and Fusion Center has received continued enthusiastic appreciation from his peers. Although he has recently focused on a collaboration with the DIII-D tokamak in San Diego, most of Leccacorvi's career has been spent supporting the center's own fusion experiment, the Alcator C-Mod tokamak.

Systems programmer and analyst Tom Fredian was recognized by the Institute of Electrical and Electronics Engineers (IEEE) Nuclear and Plasma Science Society with the Computer Applications in Nuclear and Plasma Sciences Award. This prestigious award, which is given out every other year, honors those who have made major contributions in the field of real-time computing in nuclear and plasma physics. Fredian is credited with creating a fundamental data software system for fusion research.

Three members of the PSFC custodial staff were recognized for their continued efforts to keep the center's buildings clean. Audilia Fernandez, Emily Scoppettuolo, and Manny Costa received the MIT Excellence Award at a ceremony held in June.

Division Appointments

- Magnetic Fusion Experiments: Tomas Odstrcil and Carlos Bedoya Arroyave were appointed postdoctoral associates.
- Plasma Theory and Computation: Qingjiang Pan, Evan Davis, Nicolas Fil, Zhouji Huang, and Silvia Espinosa-Gutiez were appointed postdoctoral associates.
- High-Energy-Density Physics: Arijit Bose was appointed postdoctoral associate.
- Magnets and Cryogenics: Joseph Minervini was appointed research scientist.
- Magnetic Resonance: Yi Li, Yoonhyuck Choi, Debaleena Nandi, Mirko Rocci, and Dhavala Suri were appointed postdoctoral associates.

Promotions

- Magnetic Fusion Experiments Division: Jerry Hughes was promoted to principal research scientist.
- Plasma Theory and Computation Division: John Wright was promoted to principal research scientist.

- High-Energy-Density Physics Division: Johan Frenje was promoted to senior research scientist.
- Plasma Science and Technology Division: Jacob Stephens was promoted to research scientist.

Graduate Degrees

- Nuclear Science and Engineering: Silvia Espinosa-Gutiez, PhD; Brandon Sorbom, PhD; Chuteng Zhou, PhD; Christopher Willmott, SM; Hannah Hoffmann, SM
- Chemistry: Qing Zhe Ni, PhD; Jonathan Williams, PhD; Byungsu Kwon, PhD
- Mechanical Engineering: Julien Victor Barber, SM
- Physics: Evan Davis, PhD
- Electrical Engineering and Computer Science: Alexander Soane, PhD

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