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

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.

More than 250 personnel are associated with PSFC research activities. They include 27 affiliated faculty and senior academic staff and 55 graduate students, with participating faculty and students from Aeronautics and Astronautics, Chemistry, Mechanical Engineering, Nuclear Science and Engineering, and Physics; 92 research scientists, engineers, postdoctoral associates/fellows, and technical staff; 45 visiting scientists, engineers, and research affiliates; six visiting students; 19 technical support personnel (technicians and designers); and 21 administrative and support staff.

Center-wide, funding has been relatively stable at nearly $34 million. The past year was the first full year of funding for the SPARC (Soonest/Smallest Privately Funded Affordable Robust Compact) program, which is supported by private industry. The PSFC has historically received the majority of its support from the US Department of Energy (DOE) Office of Fusion Energy Sciences. With the first full year of the SPARC program and the cessation of the DOE-supported Alcator program in 2017, industry is now the single largest provider of PSFC support, at 47%. DOE's Office of Fusion Energy Sciences accounts for about 28% of the total, other DOE offices account for 10%, and the National Institutes of Health (NIH) accounts for about 11%.

Magnetic Fusion Experiments Division

The Magnetic Fusion Experiments (MFE) Division, 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. The division head, Earl Marmar, is a senior research scientist at PSFC and the Department of Physics.

Unique among the divisions at PSFC, MFE has two sub-divisions that report to the division head: Collaborations and SPARC. Over the past year, the Collaborations sub-division has been led by Nuclear Science and Engineering (NSE) professor Anne White, who coordinates on-campus elements of collaborations with large tokamak and stellarator facilities around the world. Collaborations are critical to maintaining scientific and educational excellence in magnetic fusion experiments. The SPARC sub-division is led by NSE professor Zach Hartwig, and work in that sub-division focuses on (1) research on 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. SPARC research is mainly funded by a private company, Commonwealth Fusion Systems, through the MIT Energy Initiative (MITEI).

The MFE team consists of about 115 full-time-equivalent (FTE) 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 $15 million. This includes funding under the umbrella of the five-year MFE cooperative agreement with 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 DIII-D, the Wendelstein 7-X, the ASDEX Upgrade (AUG), EAST, KSTAR, the Joint European Torus (JET), and WEST. Many of the experiments are in direct support of urgent International Thermonuclear Experimental Reactor (ITER) research needs. Most of these efforts directly support the PhD research of graduate students in multiple MIT academic departments.

Remote Control Room

An important new upgrade to the PSFC facilities was completed during the last year: the remote control room in Building NW17. Funded through a combination of a dedicated grant from the DOE Office of Fusion Energy Sciences and the five-year MFE cooperative agreement, the room provides a focal space for collaborative activities, including video, audio, and data links to off-site facilities.

Figure 1. PSFC's remote control room, which provides a space for connections with collaborators at off-site facilities.

SPARC

The SPARC project is a unique, joint collaboration between the MIT Plasma Science and Fusion Center and Commonwealth Fusion Systems (CFS), a private company seeking to commercialize fusion energy. CFS is the sponsor of the research as well as a close participant with PSFC science and engineering staff in research and development (R&D) activities. The primary objective is the design, construction, and operation of the SPARC tokamak by 2025, which will be the first demonstration of net fusion energy production in a controlled manner relevant to electricity generation. The present focus of the collaboration is on a three-year time period between June 1, 2018, and June 1, 2021, with the first year of successful R&D having recently been concluded. The principal goals of this first three-year period are as follows:

- Develop and demonstrate a breakthrough magnet technology based on a new generation of high-temperature superconductors that will provide unprecedented performance of a magnetically confined plasma in a compact device
- Complete a comprehensive and integrated conceptual design of the SPARC tokamak, associated support systems, and necessary facilities
- Identify, qualify, and permit a site for the location of the SPARC tokamak

The first year of R&D focused almost exclusively on taking the first major technical steps toward the demonstration of the high field magnet technology. Key results from this period include:

- The design, fabrication, testing, and analysis of major small- and medium-scale superconducting experiments utilizing high-temperature superconducting (HTS) materials, with world-leading success achieved in the engineering performance of the magnet technology. Experiments were conducted both in house at the PSFC and at international magnet engineering test facilities in Switzerland and Japan. The ultimate finding of the experiments was that significantly high-performance conductors and coils (in terms of electrical current carrying capability and ability to produce a magnet field) can be fabricated to be robust against the enormous electromechanical forces occurring in magnets in a fusion device and safe against a wide array of potential off-normal events; in addition, they can be made with processes that are scalable. Importantly, the technologies that were demonstrated have the potential to transform not only the fusion energy sector but other parts of the economy where magnet technology could play a role, including medicine, energy storage, transportation, science, and industry.
- The conversion of Building NW21, one of the biggest spaces in Cambridge for large-scale engineering research, into an R&D facility supporting and enabling HTS magnet research. Major upgrades to existing facilities (fabrication, test, analysis, office space) were completed to help support the growing project.
- The growth of the combined PSFC/CFS SPARC team to well over 100 individuals and the organization of this team into structured groups optimized to carry out the necessary SPARC R&D. Important technical and support staff hires were made for the project, including research scientists, research engineers, professional engineers, and procurement and administrative staff.

- Establishment of a clear technological path forward for the final two years of magnet-focused R&D. The first year of research has put the SPARC team in position to build the SPARC Toroidal Field Model Coil, which will be the first large-scale HTS coil ever constructed and tested for fusion application. The coil will be designed and fabricated over the next two years, with testing completed by June 2021. The successful demonstration of this coil is the key gating item for the construction of the full SPARC toroidal field magnet, which is one of the largest and most important components of the SPARC tokamak.

International Collaborations

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

The Wendelstein 7-X stellarator (W7-X) 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 turbulence 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 for dealing with plasma heat and particle exhaust. In W7-X, the exhaust is directed onto material target plates using a novel three-dimensional (3D) configuration. Understanding this exhaust scenario 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 Department of Energy funding of $891,000 for the three-year period August 2018 to August 2021. This funding period is a continuation of the project that began in August 2015. The project supports NSE graduate student Sean Ballinger and research scientist S.G. Baek (0.5 FTE). Olaf Grulke and Adrian von Stechow are the project's scientific contacts at W7-X.

Since 2017, the project team has routinely operated a camera-based system for ultra-fast imaging of visible light emitted from the W7-X device, and this system has yielded significant new insights about the plasma boundary in W7-X. At the same time, the project has made significant progress toward providing W7-X with a major diagnostic system to measure turbulence and instabilities in the plasma boundary and divertor regions, a so-called gas-puff imaging (GPI) diagnostic. Providing a design for this diagnostic was the primary goal of the project during the 2015–2018 funding period, and the diagnostic passed a major design review in April 2019. During the 2018–2020 time period, we are building and testing the GPI diagnostic so that it can be installed before the end of 2020 and operated during the next W7-X run campaign, scheduled to begin in 2021. This project is an example of the strong and productive US-German collaboration effort on stellarator research.

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 the PSFC, the State University of New York at Cortland, and the Max Planck Institut für Plasmaphysik (IPP) in Greifswald. 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 continued collecting data during the second phase of the experiments, which commenced in July 2018 and continued through October 2018. Professor Eric Edlund returned to Greifswald for the period of June 1 to August 20, 2018, to participate in the experiments, while Professor Miklos Porkolab attended the last week of operations in September 2018. In addition, MIT postdoctoral associate Zhouji Huang actively participated on site in the PCI experiments together with our German colleagues, including Professor Olaf Grulke (turbulence experiments director), Adrian von Stechow (postdoctoral associate), and Lukas-Georg Böttger (graduate student), as well as technical support staff. In November 2018, the W7-X facility began a two-year shutdown period to accommodate major upgrades such as 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 late 2020.

The magnetic field geometry of the W7-X stellarator has been optimized to minimize neoclassical transport; consequently, turbulent transport is expected to play a significant but unknown role. PCI measurements indicate that the amplitude of broadband turbulent density fluctuations scales with bulk plasma density in conditions of constant electron cyclotron heating (ECH) power without perturbations. When the energy confinement time changes due to variations in heating power or external perturbations, the normalized density fluctuations react accordingly. A similar correspondence of fluctuation amplitude and transport time is observed in impurity transport, wherein the anomalous transport fraction is dominant relative to neoclassical transport predictions. These results indicate that turbulent transport plays an important role in energy and particle confinement in W7-X plasmas. Especially in the pellet injection improved confinement regime, there are multiple phase velocities in the wavenumber spectra of the density fluctuations along with the changes in amplitude. In addition to turbulent spectra, coherent Alfvén waves have been commonly observed in relatively low-density ECH plasmas without the presence of energetic ions. This is a somewhat unusual phenomenon, and further studies are under way to more closely determine the driving mechanisms. It is expected that similar waves can play an important role in the confinement of energetic ions. Hence there is significant interest in understanding their characteristics. A comparison of these results with gyrokinetic modeling by IPP theorists has begun.

Collaboration on the Alfvén Eigenmode Active Diagnostic on JET

Professor Porkolab leads this project from MIT, with active on-site (at JET) participation by Valentin Aslanyan (from March 2016 through March 2018) and Nicolas Fil (starting in March 2018 and continuing on through fall 2019). Work related to the project is performed at JET, the world's largest tokamak, located at the Culham Centre for Fusion Energy in the United Kingdom. The project includes a collaboration among the PSFC, the Swiss Plasma Center, and EUROFUSION/Culham Laboratory scientists. The experimental program is centered around studying the stability of Alfvén eigenmodes by measuring the damping rates of the modes, excited by six phase-controlled antennas installed in the vacuum vessel at JET. The antennas are driven by six transmitters (in excess of 4 kW each) that resonantly excite damped Alfvén eigenmodes in the tokamak plasma. The response is detected by external pick-up Mirnov coils. The drive frequency of the diagnostic is swept by a field programmable gate array module 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.

Regarding physics research, much of last year was spent on analyzing data from JET plasmas to study the interaction of Alfvén waves with energetic particles and compare experiments with theory. 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 mechanisms that control the driving and damping of modes. The main results to date were obtained on JET pulse 92416, from which AEAD measurements showed good agreement with gyrokinetic theory in terms of both the frequency and damping rate of toroidal Alfvén eigenmodes.

I-Mode Research at the ASDEX Upgrade

Collaborative research at the ASDEX Upgrade has also grown more active in the past year. In particular, experimental research on the I-mode regime, a quiescent regime without edge localized modes (ELMs) pioneered at C-Mod, has focused on AUG.

PSFC principal research scientist Amanda Hubbard is leading this effort along with her PhD student William McCarthy. Theresa Wilks has also been involved. She is engaged in experiments on the complementary quiescent H-mode (QH) regime, which is mainly investigated at DIII-D. The team participated in experiments on I-mode detachment and the QH-mode in March, and in June they returned to lead a physics experiment that compared the profiles of radial electric fields, thought to be a parameter of importance for transport barriers, with different field directions and at L-H, L-I, and I-H transitions. Collaborations on boundary physics in the I-mode have also begun.

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 the TCV tokamak. 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 has been used for divertor physics experiments. A 10-channel upgrade to this system was built in collaboration with scientists from the Dutch Institute for Fundamental Energy Research. Initial experiments with the system have yielded detailed images of helium, carbon, and hydrogen emissions from the edge and scrape-off layer of TCV.

We have also started a collaboration with Oliver Schmitz of the University of Wisconsin on the atomic physics modeling for these experiments. The results and analysis are forming the basis of the PhD research of an MIT Physics Department graduate student. A gas-puff imaging diagnostic has been refurbished and installed at TCV. Initial results have focused on comparisons of edge/scrape-off-layer turbulence in positive and negative triangularity plasmas. These experiments are forming the basis of the PhD research of a second Physics Department graduate student.

Collaborations in the United States

Overview of Experimental Research at DIII-D

Progress in Hardware Initiatives

A major MIT hardware initiative is to install and operate a lower hybrid current drive (LHCD) system launching from the high field side (HFS) of DIII-D. Simulations of existing discharges show an optimal launch location on the inner wall of DIII-D, just below the midplane. This location allows for single pass absorption and good wave penetration. HFS LHCD simulations show that efficient off-axis currents at ρ levels of approximately 0.6 to 0.8 with peak current densities of approximately 0.4 MA/m^2 are achievable and sufficient for current profile control. The HFS poloidal launch position was selected to balance the effects of toroidicity and poloidal field down/up shift to improve wave penetration and allow single pass absorption. To assess the impact of a small inner gap and a metallic launcher on plasma performance, discharges with a variety of inner gaps and limited discharges with up to 10 MW injected power were investigated using a mock-up coupler. Experiments showed that the small inner gap had a negligible impact on plasma performance and that core molybdenum contamination was subtle to nonexistent.

The conceptual design of the HFS LHCD system has moved toward completion. The coupler design has been optimized for maximum directivity, a minimum reverse spectrum, and equipartition of power while staying below voltage handling limits. The coupler design effort is summarized in a paper ("A High Field Side Multijunction Launcher with Aperture Impedance Matching for Lower Hybrid Current Drive in DIII-D Advanced Tokamak Plasmas") by Andrew Seltzman accepted for publication in *Nuclear Fusion*. Seltzman also gave an invited talk ("A Novel 3D Printed High Power LHCD Launcher for High Field Side Launch on DIII-D") at the 23rd Topical Conference on Radio Frequency Power in Plasmas.

MIT maintains a laser blow-off (LBO) instrument at DIII-D that consists of both a 50 Hz Nd:YAG laser sited in the Thomson scattering lab and a vacuum interface with an optical box on the DIII-D 105 R+1 port. In 2018 we completed installation of the LBO system and the first experiments were done. During the experimental campaign, about 180 successful LBO injections were performed in three mainline and several piggyback experiments for impurity transport and spectroscopic studies with better than 90% reliability. The accuracy and reliability of the impurity injections were improved by the installation of a new camera holder more distant from the machine, and the range of possible ablation spot sizes was extended by installing a new remotely controlled linear translation stage.

MIT is partnering with the Princeton Plasma Physics Laboratory (PPPL) to develop diagnostics useful for inferring the main chamber neutral deuterium density in DIII-D. The first phase of this effort will employ 1D (i.e., non-imaging) pinhole cameras filtered for the transition in atomic D (Lyman alpha). Two views have been developed in the lower portion of the vessel, one on the low field side and one on the high field side. Aaron Rosenthal, an MIT PhD student, led the conceptual design review for the diagnostic in August 2018 and the final design review in October.

The final design was approved in January 2019, and the diagnostic was named LLAMA (Lyman Alpha Measurement Apparatus). The assembly and alignment of LLAMA were completed within three months, and the finished assembly was installed on DIII-D in April 2019. The LLAMA system has been commissioned, and initial data have included observations of confinement mode transitions, edge localized instabilities, and effects due to pellet fueling, nitrogen puffing, and plasma disruptions. The physics output from the diagnostic will form the experimental core of the PhD thesis research of an MIT Physics Department graduate student.

Physics

MIT has strengthened leadership in disruption prediction using machine learning. During FY2018, the Disruption Prediction via Random Forests (DPRF) algorithm was successfully installed on the DIII-D plasma control system (PCS). It has run in real time and provided data on the probability of impending disruptions throughout the campaign. This successful integration has furthered progress toward subsequent improvements of the algorithm. A 2.0 version is currently under development, and it will be ready for PCS testing and use with the off normal fault response system in FY2020. Several modifications will be made, including real-time calculations of indicators of disruption precursors based on temperature, density, and radiation profiles (i.e., peaking factors). This will enhance interpretability and the capability to detect further in advance the chain of events with respect to disruption precursors. Improved feature engineering (i.e., simplification), combined with the feature contribution analysis used to interpret the DPRF disruptivity output and understand which signals contribute to triggering an alarm of an impending disruption, has the potential to identify and discriminate among different types of disruptions to provide timely information to the PCS regarding avoidance strategies.

Regarding peaking factor engineering, there exists a growing need for uniform physics-based indicators across devices to enable transfer learning and domain adaptation. Given that 0D information has limited informative content, inclusion of 1D profile information could enable identification of earlier precursors in the disruptive chain of events. It is important to acknowledge that profile diagnostics need to be mapped onto flux surfaces or onto specific core/edge/divertor regions in order to allow comparisons of disruption prediction algorithms across different tokamaks. Preliminary analysis of DIII-D data shows how profiles can be mapped from 1D to 0D to reduce feature dimensionality and enhance the interpretability of data-driven disruption prediction algorithms. By adopting a dimensionality reduction approach, we gain straightforward real-time implementation and integration with legacy PCS architectures.

Efforts to maintain the consistency of physics-based indicators among machines despite different diagnostics, design parameters, and time scales will facilitate the development of a machine-independent predictor. Our team is actively collaborating with EPFL (École polytechnique fédérale de Lausanne) to extend this framework and analysis to DIII-D and make robust comparisons with JET, the Alcator C-Mod, EAST, the ASDEX Upgrade, and TCV.

A set of DIII-D discharges with varied power levels, heating mixes (ECH and neutral beam injection NBI), and radial depositions of ECH have demonstrated marked differences in impurity transport coefficients. The diffusive and convective transport are interpreted from signatures of aluminum and tungsten impurities injected with the MIT laser blow-off system and measured via soft x-ray arrays and charge-exchange recombination. We are working to understand these transport changes through both the gyrofluid code TGLF and the gyrokinetic code CGYRO. Long-wavelength (ion-scale turbulence) simulations utilizing high physics fidelity have been found to match measured levels of ion heat flux, aluminum impurity diffusion, and aluminum peaking at mid-radius within experimental uncertainties. Although much of the modeling work to date has focused on Al impurities, ongoing work is extending the CGYRO comparisons to multiple radial locations and to the study of LBO-introduced tungsten impurities.

During the past year, MIT PhD student Pablo Rodriguez Fernandez successfully defended thesis work based partially on DIII-D data. Using perturbative impurity injections in ohmic DIII-D plasmas, Rodriguez Fernandez presented compelling new evidence that local transport models can capture the full dynamics of cold pulses at both high and low collisionality. Experiments were designed using a predict-first approach with predictive TRANSP, and the TGLF SAT1 model was employed for profile predictions. Experimental measurements of electron densities obtained using fast profile reflectometers confirm the existence of density pulses in the low-density branch, which stabilizes transport driven by trapped electron modes (TEMs) and leads to a core temperature increase in response to an edge decrease. The results of this work were presented at the 2018 American Physical Society (APS) meeting in Portland, OR, and are outlined in a paper ("Predict-First Experiments and Modeling of Perturbative Cold Pulses in the DIII-D Tokamak") recently accepted for publication in *Physics of Plasmas*.

An experiment led by Darin Ernst measured the intrinsic torque in the wide pedestal QH-mode using beam torque modulation. Ongoing analysis has revealed that the energy confinement time increases by 60% with 32% ECH power, after which a threshold in Te/Ti appears to be crossed (as indicated by a Fourier analysis of the Te response to modulated ECH). Another experiment led by Ernst demonstrated sustainment of the low torque, wide pedestal QH-mode with 77% ECH power and without confinement degradation, retaining the wide pedestal and the same or higher pedestal pressure.

A key objective of pedestal research within the PSFC is the development of high-performance regimes that are naturally ELM suppressed. At DIII-D, the team has made key contributions to the QH-mode and the wide pedestal QH-mode in terms of physics understanding and extension toward ITER-like parameters.

A recent study in collaboration with colleagues at the University of California, San Diego, shows that access to the QH-mode requires a critical E × B shearing rate. In a series of discharges using torque ramps as an actuator in DIII-D, local access conditions for the QH-mode were explored through measurements of the critical edge rotational shear necessary for the transition from a QH-mode with a coherent edge harmonic oscillation (EHO) to a typical ELMy H-mode. The critical E × B shear and EHO frequency were predicted by a nonlinear phase-dynamics model relating the pressure and velocity perturbations in the edge pedestal region. The reduced theoretical model predicted a linear relationship between the critical shearing rate and $c_s/\sqrt{L_P \Delta x}$, where c_s is the ion acoustic velocity, L_p is the pressure gradient-scale length, and Δx is the radial width of the mode. This scaling of the critical shearing rate agrees with the experimental trend, although the absolute magnitude of the shearing rate threshold is over-predicted by the model. Through normalized predicted scaling, the model demonstrates the dynamic transition into and out of the QH-mode qualitatively, within a single plasma discharge. The experimental comparison lends insight into improving the theoretical model by including more accurate geometry and toroidal mode number physics to produce more accurate quantitative predictions.

The wide pedestal QH-mode is a new stationary ELM-free regime obtained in the DIII-D tokamak. The new regime exhibits a transport-limited pedestal regulated by broadband turbulence, with improved confinement relative to the QH-mode under the same conditions. The QH-mode has been extended to zero net injected NBI torque throughout, as well as low torque conditions with dominant electron heating (77%). Unlike other H-mode regimes at ITER-relevant collisionalities, both pedestal and core confinements were shown to improve with electron heating, in some cases dramatically, as described above. With respect to compatibility with burning plasma conditions, the need for unbalanced neutral beam torque injected to initiate and sustain the wide pedestal QH-mode was eliminated in a demonstration with zero injected NBI torque. Another experiment measured the intrinsic torque in these conditions using beam torque modulation, and the findings showed that the intrinsic torque density profile approximately balances the beam orbit loss torque density in the edge, resulting in very low toroidal rotation across the profile. These results support continued investigation of the wide pedestal QH-mode regime as a viable solution to avoid ELMs and associated divertor damage in a zero-torque high-confinement, electron-heated scenario at ITER collisionality.

Novel piggyback experiments used dynamic shaping variations to transition low-torque wide pedestal QH-modes from double null configurations to single null ITER-like shapes. Relative to the traditional double null shape, the ITER-like shape was shown to have (1) a narrower pedestal width, (2) higher-frequency limit cycle oscillations and larger-amplitude density fluctuations, and (3) shifted E × B shear peaking toward the separatrix. In the peeling-ballooning stability space, the ITER-like shape operates far from the kink/peeling boundary, possibly due to a lower bootstrap current, suggesting that much higher power and potentially wider pedestal operations can be achieved in future experiments.

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

The phase contrast imaging program at DIII-D continued in FY2019. The DIII-D tokamak at General Atomics was in a yearlong period of maintenance and upgrades, and thus the PCI program focused on analysis of data and preparation for the upcoming experimental run, including hardware development for the two projects listed below.

Plasmas with a negative triangularity shape were produced on DIII-D, exhibiting the core confinement typical of high-performance plasmas while the plasma edge was relatively benign, as is typical of low-performance plasmas. In addition, PCI diagnostic measurements were compared with instability growth rates calculated via linear gyrokinetic simulations with CGYRO, and these comparisons suggested that the improved performance resulted from reductions in unstable growth of trapped electron mode turbulence across all fluctuation wavelengths.

A report on the recent upgrade of the PCI system to include absolutely calibrated detection of long-wavelength modes demonstrated a novel design combining existing measurement techniques to produce a system with improved capabilities. The improved system has been used for measurements of long-wavelength eigenmodes as well as turbulent transport measurements simultaneously covering the entire range of interest, from ion-scale to electron-scale modes.

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

The goal of this project is to develop a technique for quantitative, spatially resolved measurements of RF waves and implement the technique at the DIII-D tokamak. A novel modification of the PCI 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 at tens of megahertz and eventually the 476 MHz helicon wave, a heating system to be installed at DIII-D in early FY2020.

A new grant proposal was submitted to DOE in the past year, and we were notified that the proposal will be funded for another three years.

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

This initiative, funded by DOE as a two-year high-risk exploratory project, was recently extended for a third year. The aim of the project is to extend PCI operations to detect higher frequencies and shorter wavelengths with adequate signal to noise while reducing the overall costs for fabrication and maintenance of the system. This is achieved by switching from a 10.6-μm laser wavelength to 1.55 μm, requiring new fabrication techniques for the custom optical component (the phase plate) but allowing the use of modern low-noise, high-bandwidth detectors. A prototype PCI demonstrating spatial detection of soundwaves in air has been implemented, and complete quantification of the effects of optical aberrations and noise due to the reduced wavelength will be completed in the upcoming year. If successful, the system will be capable of measuring not only electron-scale turbulence but also RF waves and will be proposed for implementation at DIII-D and possibly elsewhere.

Professor Anne White (Nuclear Science and Engineering)

Professor Anne White leads the Magnetic Fusion Experiments Collaborations subdivision, coordinating on-campus collaborations with tokamak and stellarator experiments in the United States and abroad. Since January 1, 2019, Professor White has also served as the PSFC associate director for education and outreach. Professor White's research group focuses on the study of turbulent transport in fusion plasmas with the goal of controlling transport and improving the performance of tokamaks. The group's research includes diagnostic developments that will enable new heat, particle, and momentum transport experiments, as well as investigations of "non-diffusive" transport in fusion plasmas. Integrated modeling using reduced transport models plays a key role in developing novel validation tools, some employing machine learning, for the design of future fusion devices such as ITER and ARC (affordable, robust, compact) devices.

Her group is engaged in research at four major tokamaks where the experimental team leads experiments, develops diagnostics, and leads validation projects using advanced turbulence simulation codes. Professor White's graduate student Juan Ruiz Ruiz (NSE) collaborated with PPPL scientist Walter Guttenfelder to compare electron scale density fluctuation measurements from NSTX directly with theory and simulation. Ruiz Ruiz successfully defended his thesis in the spring and is now pursuing a postdoctoral degree at Oxford. In addition, White's graduate student Pablo Rodriguez Fernandez (NSE) collaborated with PPPL scientist Brian Grierson on understanding the propagation of "cold pulses." Rodriguez Fernandez (now a postdoc at PSFC) successfully defended his thesis this spring, in which he showed that modeling of C-Mod and DIII-D experiments with local turbulent transport models can reproduce both steady state and perturbed heat transport in tokamak plasmas.

Graduate student Alex Creely published an article on cross-machine validation of reduced turbulent transport models using data from C-Mod and AUG. He successfully defended his thesis in the fall and is now employed by Commonwealth Fusion Systems. Postdoc Simon Freethy made a successful transition away from the MIT group to a permanent scientist position at the Culham Centre for Fusion Energy in the United Kingdom, where he works on the MAST-U tokamak. Professor White has three students and one new postdoc currently working in the group. NSE student Rachel Bielajew and postdoc Pedro Molina Cabrera continue development and optimization of correlation electron cyclotron emission/nT-phase systems at AUG. NSE student Bodhi Biswas, who is co-advised by Paul Bonoli at PSFC, works on developing reduced models of edge turbulence to study how injected RF waves interact with turbulence in the tokamak. NSE student Xiang Chen is working on a feasibility study for a new diagnostic that would be used to measure electron scale temperature fluctuations.

Professor White is also a member of the PSFC pedestal physics group and the doctoral supervision committee for students working on collaborations at W7-X. In addition, she supervises UROP projects involving the development of small, table-top plasma devices such as "fusors" (electrostatic inertial confinement devices) to aid in classroom teaching at MIT, and she served as an advisor for an undergraduate thesis on this topic in the spring.

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 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. Senior scientist Peter

Catto leads PSFC Theory Grant research in the areas of confinement and transport and boundary physics. PSFC principal research scientist Abhay Ram is the co-PI for the PSFC Theory Grant and leads the group’s efforts in heating, current drive, and nonlinear dynamics. Principal research scientist John Wright and research scientist Syun’ichi Shiraiwa are involved in RF SciDAC and numerical modeling related to SPARC magnet development, and Wright is also involved in 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 and has also worked on the SPARC magnet development project.

New PSFC Parallel Computing Cluster

In 2018 and 2019, usage of the PSFC compute partition on the Engaging Cluster at the Massachusetts Green High Performance Computing Center facility in Holyoke, MA, expanded to include the SPARC tokamak research project. John Wright manages users on the PSFC and NSE nodes and ensures appropriate usage of resources according to funding source.

Plasma Theory, Computation, and Discovery Science

Alpha Particle Transport in Stellarators and Tokamaks

Energetic particle transport in stellarators and tokamaks are among the important unanswered questions in projecting and optimizing the performance of these devices in the reactor regime. Peter Catto has focused on explicitly evaluating alpha particle transport in instances of weak collisions in imperfectly optimized stellarators and tokamaks. Catto has performed analyses revealing that the transport associated with the reversal of the magnetic drift of the alpha particles trapped in the poloidal magnetic well (the so-called super-banana plateau regime) dominates over the transport associated with the barely trapped alphas that spend more time near their turning points. The analytic expressions derived imply that high magnetic field, high density, and lower temperature operation are desirable. These results highlight the importance of optimizing stellarator magnetic fields and improving calculations at the still lower collision frequencies investigated via simulations. The toroidal field coil ripple transport in tokamaks does not appear to be an issue as it is very small on the high field side where the collisional transport occurs.

Current Drive with a Symmetric Spectrum

The steady state current drive power requirement has a significant impact on the net gain of a commercial power plant. The discovery of an additional “free” co-current generated by the heating of a minority species of deuterium in a tritium majority plasma, using balanced antenna phasing, may improve the efficiency of noninductive current drive in the reactor regime. The new current investigated by Catto arises because the drift and flux surfaces of a minority species of heated ions differ due to finite orbit effects. As this new source of driven current is a side effect of minority heating, it comes without any additional economic cost to reactor power balance. The symmetric spectrum current drive for near Maxwellian minorities appears modest. However, as minority heating typically results in strong non-Maxwellian features, it may be possible to drive significantly larger co-currents. Moreover, symmetric spectrum current occurs due to alpha particles in deuterium minority heated plasma with a tritium majority. The low density of the alphas tends to keep this driven current small, but at very high heating levels a significant co-current might be possible.

Multi-scale Gyrokinetic Simulations

Nathan Howard has continued to make progress on multi-scale gyrokinetic simulations using the CGYRO code, focusing on a discharge from the DIII-D tokamak that is representative of an ITER baseline case. The simulations are currently running on the Titan supercomputer and are arguably the most physically comprehensive turbulence simulations performed to date, capturing electromagnetic turbulence that spans the spatial scales of both the electron and ion gyro-radii and including three gyrokinetic species, collisions, and rotation and shearing effects. These simulations display the coexistence of several types of turbulent structures. For example, ion-scale eddies coexist not only with electron-scale streamers but also with electron-scale zonal flows. The persistence of these structures appears to play a potentially important role in the regulation of the turbulence. The coexistence of these phenomena seems to be unique and not to have been observed in any previous gyrokinetic simulations. The results from these multi-scale simulations will be presented as part of Howard's invited talk at the upcoming APS Division of Plasma Physics (DPP) meeting in Ft. Lauderdale, FL.

Tokamak Reactor Studies

Professor J.P. Freidberg, Professor Antoine Cerfon (New York University), and Daniel Segal have continued their studies comparing steady state and pulsed tokamak reactors. The work is nearly complete, and a paper is in preparation. The group found that the recent development of high field, high-temperature REBCO superconducting tapes makes 200 MWe pulsed systems competitive with comparably powered steady state reactors. Before the REBCO tapes were developed, there was consensus in the United States that only steady state systems would be viable. Adding a competitive pulsed system could have an important impact with respect to the follow-on to SPARC.

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. The turbulence in the scrape-off layer spans a broad range of spatial scales and includes blobs and filaments that are elongated along the magnetic field lines. The characteristic properties of the plasma appear as a permittivity tensor in the expression for the current in Ampere's equation. Ram and his group have developed a formalism for expressing spatially non-uniform permittivity using the homogenization technique. This technique has previously been used to express the dielectric properties of composite materials that are spatially inhomogeneous, for example, due to the presence of micro-structures. The present formalism relates to a magnetized plasma and an arbitrary ratio of the wavelength of the radio frequency wave to the spatial scale of the plasma inhomogeneity. Previous formalisms have related to scalar dielectrics and have been limited in their applicability. Ram, along with Professor Hizanidis and his students, has developed the ScaRF code, a full-wave electromagnetic computational code based on the finite difference frequency domain method. The purpose of this code is to study the effects of density turbulence on the propagation characteristics of radio frequency waves.

During the past year, graduate student Samuel Frank, working under the supervision of Paul Bonoli and John Wright, made significant progress in successfully running at scale an electromagnetic field solver for lower hybrid (LH) waves at the National Energy Research Supercomputer Center. Simulations of LH waves at the EAST tokamak in Hefei, China, can now be done routinely on the Edison and Cori computing platforms using approximately 32,000 compute cores. As part of Frank's doctoral research, these "capability computing" simulations will be used to verify regimes of applicability for LH ray tracing calculations in weak damping regimes at EAST.

Fundamental Plasma Theory

Professor Nuno Loureiro continued his research on a broad set of topics ranging from fundamental plasma physics to fusion theory and plasma astrophysics. In particular, he has developed the first theoretical model for turbulence in electron-positron (pair) plasmas (in collaboration with Professor Stanislav Boldyrev from the University of Madison, Wisconsin). Work led by his student Elizabeth Tolman has investigated theoretically and computationally the possible behavior of fusion-born alpha particle populations in high magnetic field tokamaks such as SPARC. Together with Professor Paolo Ricci from EPFL in Switzerland, Loureiro has advised Rogério Jorge (EPFL) in performing the first exact investigation of the effects of collisions on two of the most fundamental plasma oscillations: drift waves and electron plasma waves.

In collaboration with Professors Leonid Levitov (MIT Physics) and Dirk Englund (MIT Electrical Engineering and Computer Science), Professor Loureiro was awarded a Bose grant to perform investigations on electron dynamics in graphene sheets, a topic that resides at the interface of condensed matter and plasma physics.

High-Performance Computing Initiatives

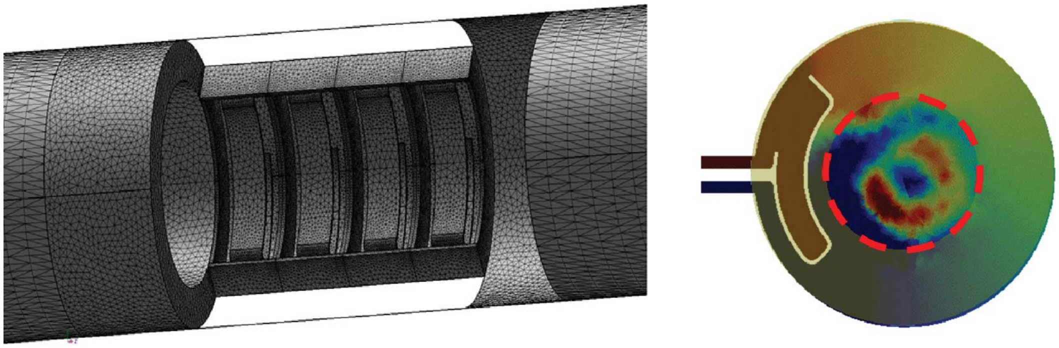
SciDAC Partnership for Integrated Simulation of Fusion Relevant RF Actuators

During 2018–2019, research continued under the SciDAC Partnership for Integrated Simulation of Fusion Relevant RF Actuators. The goal of this multi-institutional partnership is to develop a simulation capability allowing exploration of the self-consistent interaction of power with the short mean free path scrape-off layer (SOL), 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.

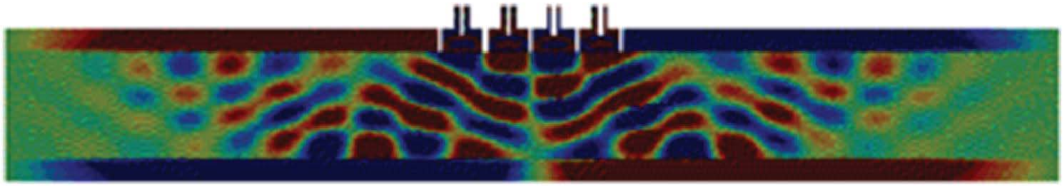
Syun'ichi Shiraiwa made significant progress on the development of the physics equation translator for MFEM (Petra-M) framework, which utilizes the scalable, open-source, modular finite element method library MFEM to carry out detailed simulations of wave scattering and linear wave coupling, including the complicated 3D geometry of the plasma edge and ion cyclotron range of frequency antennas. In collaboration with Professor Mark Shephard at the Rensselaer Polytechnic Institute, Shiraiwa performed the simulations shown in Figures 2(b) and 2(c) using Petra-M. In these simulations, conducted for the high harmonic fast wave antenna in the Large Plasma Device at the University of California, Los Angeles (UCLA), Shiraiwa employed a mesh generated from a computer-aided design drawing of the antenna shown in Figure 2(a).

In addition, graduate student Christina Migliore has been working with John Wright and Mark Stowell of the Lawrence Livermore National Laboratory (LLNL) to develop "Stix," a stand-alone electromagnetic field solver that solves for RF wave fields in the plasma edge based on the MFEM suite of codes. Their goal is to study the implementation of boundary conditions in our field solvers that account for RF-induced sheath potentials at plasma-metal boundaries. Also, graduate student Bodi Biswas, working under the supervision of Professor Anne White and Paul Bonoli, has conducted studies demonstrating that ray tracing techniques can be used to assess the refractive effects on lower hybrid wave propagation of coherent blob-like turbulent structures in the scrape-off layer.

Figure 2. Petra-M simulation of high harmonic fast waves in the Large Plasma Device at UCLA:



(a) physics mesh used for plasma and the antenna generated from computer-aided design drawings (b) RF electric field in the poloidal cross section



(c) RF electric field in the axial direction.

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.

During the past year, Manaure Francisquez joined the group as a postdoctoral associate and is closely involved in the development of the GKEYLL edge gyrokinetic turbulence code at the Princeton Plasma Physics Laboratory. In collaboration with Greg Hammett, Ammar Hakim, and students in the GKEYLL group, he is leading the development and implementation of new multi-species model collision operators in the GKEYLL discontinuous Galerkin framework for use in the collisional tokamak edge plasma region where large, turbulent fluctuations prevail.

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 while accurately capturing important cross-scale interactions. Ernst, Francisquez, and MIT UROP student Jay Lang have developed a one-field multi-scale reduced model with nonlinear interactions of the same form as more comprehensive 5D gyrokinetic codes and have developed and benchmarked the new pseudo-spectral MuSHrooM code for use as a test bed for multi-scale algorithms. They are collaborating with FASTMath SciDAC researchers Dan Reynolds (Southern Methodist University) and Carol Woodward (LLNL) to test new multi-scale time-stepping algorithms in the simplified MuSHrooM code.

Qingjiang Pan (supported by the SciDAC Center for the Study of Plasma Microturbulence) and Ernst have formulated the first gyrokinetic linearized exact (not model) Landau collision operator in conservative form. They have implemented the new multi-species exact collision operator in the GENE gyrokinetic code, numerically conserving particles, momentum, and energy to machine precision independent of resolution. This enables the accuracy of model collision operators to be evaluated in gyrokinetic simulations for the first time. Comparisons with the best available model (Sugama) showed that the operator produces 20% to 25% larger neoclassical ion heat flux and damps zonal flows up to 15% faster.

Navigational Data Management Project

John Wright is also involved in the Navigational Data Management Project along with Martin Greenwald and Joshua and Jason 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 prototype electronic notebook released at the end of 2017 is being tested by experimentalists on the SPARC tokamak project. Based on user feedback, Joshua and Jason Stillerman made updates and improvements to the user interface.

High-Temperature Superconductor Magnets

During the past year, John Wright was a co-PI of the HTS 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 in high field steady state magnets for fusion energy. Wright was responsible for coordinating theory and modeling efforts for the project and comparisons with experimental data. As part of this effort, Syun'ichi Shiraiwa built a time-dependent finite element method simulation model to predict the quench dynamic of the HTS tape-based magnet. The Petra-M framework discussed earlier was used for this work, and the simulation result was compared with our test HTS magnet experimental data. The agreement of the transient response between the experiment and the model prediction during the triggered quench was a key factor in terms of the team's confidence in moving forward with plans to construct a SPARC toroidal field test coil using the HTS tape.

JET Modeling Collaboration

Under the SciDAC Partnership for Simulation of Fusion Relevant RF Actuators, John Wright has 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 future fusion devices such as ITER and SPARC. In 2018–2019, efforts were expanded to include high-fidelity three-dimensional modeling of the radio frequency antennas used on JET. During summer 2019, experiments with deuterium and tritium will begin at JET. Syun'ichi Shiraiwa has joined the JET collaborative effort to participate in this work.

Other Divisional Activities

At the 2018 APS DPP meeting in Portland, OR, Peter Catto gave a tutorial lecture summarizing gyrokinetics in an understandable manner to provide insight into why it is an appropriate description for turbulent transport in tokamaks and is used almost universally to simulate turbulent transport in toroidal magnetic fusion devices. The lecture explained how the gyrokinetic change of variables (first introduced by Catto in 1978) works, applied it to electrostatic turbulence, and generalized it to fully electromagnetic turbulence. It also considered flow modifications, symmetry properties, and stellarator modifications. The tutorial is expected to serve as a valuable and timely resource for the transport and turbulence community.

Abhay Ram was involved in the teaching of 22.061 Fusion Energy, a new undergraduate course being offered by the Department of Nuclear Science and Engineering. Ram was part of a teaching team and gave six lectures on basic plasma physics.

Professor Nuno Loureiro co-organized the Plasma Physics of Neutron Star Mergers workshop, held in New York in October 2018 at the Flatiron Institute's Center for Computational Astrophysics. The meeting, attended by world-renowned experts in plasma physics and astrophysics, aimed to identify the cutting-edge plasma physics topics whose resolution is critical to understanding the electromagnetic component of the observations of neutron star mergers.

High-Energy-Density Physics Division

The High-Energy-Density Physics Division has been awarded a prestigious Center of Excellence grant by the DOE National Nuclear Security Administration (NNSA). The goal is to conduct research, (with MIT's partner institutions) in inertial-confinement fusion (ICF), laboratory astrophysics, and basic plasma properties and to develop new plasma diagnostic instrumentation. In addition to five scientists, one postdoc, eight graduate students, and two undergraduates in HEDP, the Center of Excellence includes scientists and students at four partner institutions working with MIT: the University of Rochester; the University of Iowa; the University of Nevada, Reno; and Virginia Tech. This extraordinary opportunity involves $10 million of support over the next five years, and our selection in a highly competitive process reflects the quality of our team's research and our students. A wide range of important new plasma studies will result.

Over the past year, the division has been characterized by important research, awards, and student achievements. For example, the APS Division of Plasma Physics chose HEDP scientist Maria Gatu Johnson as the 2019 recipient of the Katherine E. Weimer Award for outstanding achievement in plasma science research by a woman physicist in the early years of her career. She was recognized "for significant contributions to Inertial Fusion sciences and pioneering work in Stellar Nucleosynthesis through nuclear measurements" based on her pioneering work with ICF plasmas at the University of Rochester's Laboratory for Laser Energetics (LLE) and LLNL's National Ignition Facility.

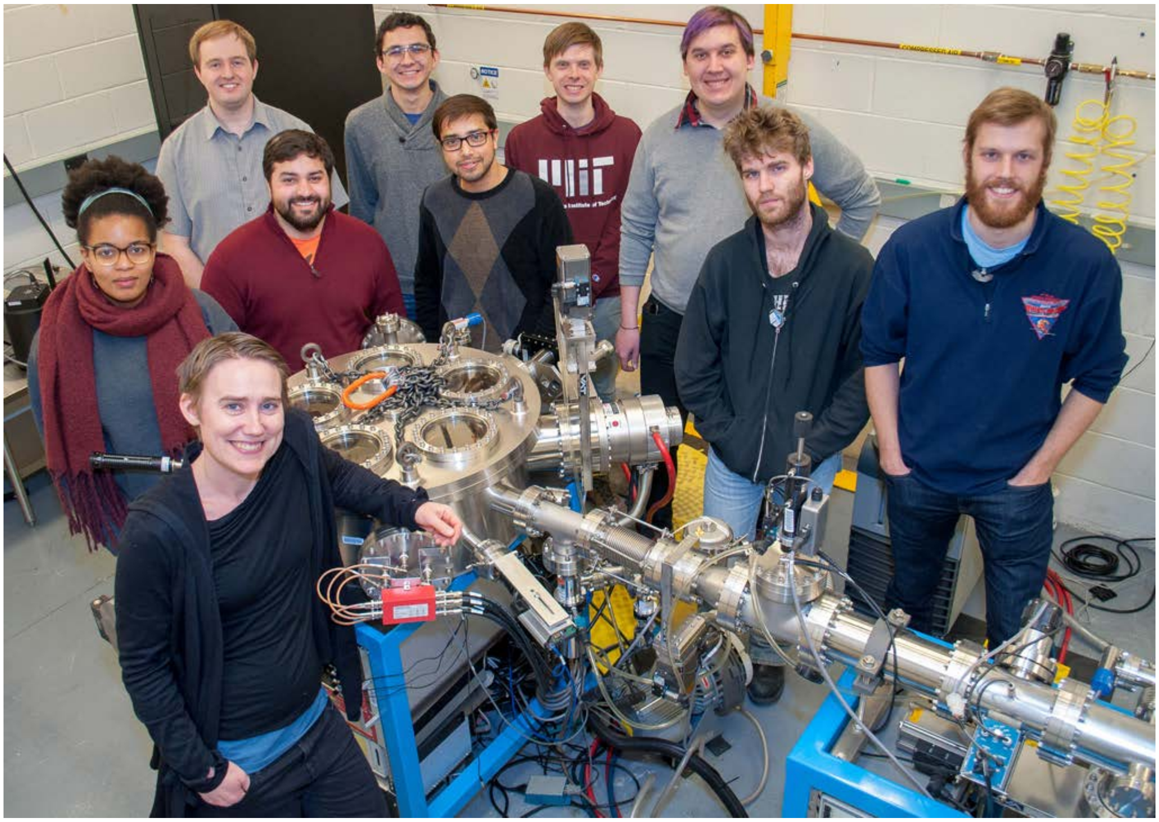


Figure 3. Maria Gatu Johnson (foreground), director of the HEDP accelerator facility, with the division's graduate students and a postdoc. First row, left to right: Raspberry Simpson, Neel Kabadi, Arijit Bose (postdoc), Brandon Lahmann, and Graeme Sutcliffe. Second row, left to right: Patrick Adrian, Jacob Pearcy, Timothy Johnson, and Alexander Sandberg.

Maria Gatu Johnson is shown in Figure 3 along with current division graduate students and a postdoc. Not shown in the photo is Hong Sio, who finished his PhD in late 2018 and recently left for a research position at LLNL, where he was a finalist for the prestigious Lawrence Fellowship. Hong did extraordinarily important research by developing and using diagnostic instrumentation to study the time evolution of ICF implosions and had an article ("Probing Ion Species Separation and Ion Thermal Decoupling in Shock-Driven Implosions Using Multiple Nuclear Reaction Histories") published as an "editor's pick" in the journal *Physics of Plasmas* in 2019. This was his second editor's pick, his first being a paper in *Review of Scientific Instruments*. On the basis of these two editor's picks, a new *Physical Review Letters* publication, and his exemplary thesis work, Sio has been nominated for the 2020 Marshall Rosenbluth Outstanding Thesis Award.

Other student honors include a Stockpile Stewardship Graduate Fellowship awarded by NNSA to Patrick Adrian, following another fellowship awarded last year to Raspberry Simpson. Graeme Sutcliffe received a best poster award at the National Ignition Facility users' group meeting for his work on the Tri-Particle Backlighter, and Neel Kabadi received a second-place award for his poster at LLE's OMEGA Laser Facility users' group meeting. In addition, research this year by Sio, Gatu Johnson, and division scientist Johan Frenje was featured on the LLE web page for its importance to the ICF program at LLE's OMEGA Laser Facility.

An outstanding example of important student contributions is the work of Graeme Sutcliffe, who has been leading the development and implementation of improvements in charged-particle radiography based on the new Tri-Particle Backlighter. Over the last 15 years, the division has developed and utilized the radiography of ICF and other plasma experiments using monoenergetic protons of two different energies (3 MeV and 14.7 MeV). The protons are fusion products created in a laser-driven "backlighter" in the form of a glass capsule filled with D3He gas, and resulting radiographs allow study of the plasma and its electromagnetic fields in various experiments. Importantly, the Tri-Particle Backlighter will add a third monoenergetic particle in the form of 9.5 MeV deuterons resulting from the addition of tritium to the backlighter-capsule fill gas. The subsequent increase in independent images from two to three makes possible a much more uniquely determined reconstruction of the electromagnetic fields in a plasma experiment.

In addition to Gatu Johnson, Johan Frenje, Chikang Li, Richard Petrasso, and Fredrick Seguin have continued to advance plasma science, as well as to advise and inspire students. For example, a paper published by Frenje in *Physical Review Letters* ("Experimental Validation of Low-Z Ion-Stopping Formalisms around the Bragg Peak in High-Energy-Density Plasmas") described the first accurate validation of low-Z ion-stopping formalisms relevant to our understanding of alpha energy deposition and the heating of fuel ions in ICF, which is crucial for the future success of ignition experiments.

Chikang Li and an international array of collaborators published a paper in *Physical Review Letters* ("Collisionless Shocks Driven by Supersonic Plasma Flows with Self-Generated Magnetic Fields") describing the first laboratory study of collisionless shocks, an important phenomenon ubiquitous in the universe as a consequence of supersonic plasma flows sweeping through interstellar and intergalactic media. Although it has been widely speculated that these shocks are the cause of many observed astrophysical phenomena, details of the shocks' structure and behavior have remained controversial because of the lack of ways to study them experimentally. Among other findings, the experiments demonstrated that upstream from the shock is a filamented turbulent region responsible for electron acceleration, a signature of the first-order Fermi process.

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, additive manufacturing, and plasma-material interactions. The division is headed by Richard Temkin, senior scientist in the Department of Physics. Kevin Woller 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, and for enhanced spectroscopy in the NMR research program on biomolecules. These high-power applications require sources operating at frequencies in the range of 100 to 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 2018–2019, we conducted tests of the effect of reflections of power back into the gyrotron on gyrotron operation. Reflectivity values up to 40% have been studied. 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 with very good agreement with theoretical predictions. 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. Testing has been conducted at gradients exceeding 150 MV/m in pulses of several nanoseconds. A semiconductor switch controlled by a 532-nm laser pulse has been used to reduce the gyrotron output power length from 3 microseconds down to as little as 3 ns. A 527 GHz gyrotron that will be used to enhance NMR spectroscopy has been operated at a power level of 9.3 W and is tunable over a 400 MHz frequency range.

Advanced Terahertz Sources

We are building novel high-power vacuum electron 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 2018–2019, we demonstrated a 94 GHz extended interaction klystron with photonic crystal structures in the klystron cavities. Operating at 23.5 kV with 330 mA of current, the klystron provided 26 dB of gain with a saturated output power of 30 W. We have completed designs for extending the operating frequency to 250 GHz.

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 standalone accelerator in the world. In 2018–2019, we completed a unique study of internal dark current in a high-gradient accelerator structure. Using small holes in the structure sidewall, we measured the energy distribution of the electrons that make up the current. Dark current is current emitted by field emission from surfaces of the accelerator wall that may lead to breakdown and cavity heating. The measurements are in good 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

High-power millimeter-wave (MMW) gyrotron sources, originally developed for fusion energy research, are being pursued as an advance drilling technology to enable expansion of geothermal energy as an economic and sustainable energy source. MMW directed energy overcomes the limitations of high temperature, rock hardness, and slow rates of penetration that are problems for current mechanical drilling systems with attempts to apply short wavelength infrared lasers for directed-energy drilling. The feasibility of MMW drilling has been established in the laboratory under the leadership of Paul Woskov.

In FY2019, ARPA-E (Advanced Research Projects Agency–Energy) approved a proposal, pending budget negotiations, for a three-year development effort that would bring the technology to the threshold of commercialization. The partners in this proposal are AltaRock Energy Inc., Geoffrey Garrison (PI 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). A new company, Quasie Inc., has been created to commercialize the project and raise additional private funding. The goals of this three-year effort are to advance the depth to diameter borehole ratio from about 1:1 (achieved in the laboratory) to 10:1 by the end of the first year and then to 100:1 by the third year using the AFRL 100 kW continuous wave gyrotron. A study of future megawatt scale systems is also a goal.

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. In FY2019, Paul Woskov completed a project with Sandia National Laboratories designed to advance additive manufacturing by investigating new in-process analysis methods and technologies. A dual 137 GHz receiver millimeter wave radiometer system developed at PSFC had previously been delivered to Sandia. The device was used to measure the emissivity of 316 stainless steel as it melted and re-solidified, and the significant change in emissivity at the phase transition was documented.

Plasma Material Interactions

Many magnetic confinement experiments today utilize low atomic number elements to condition plasma-facing components and improve device performance. Particularly, lithium has been used at NSTX in Princeton, NJ, and EAST in Hefei, China, among other facilities, with accompanying performance enhancements. Experiments at the MIT DIONISOS facilities have shown that deuterium from the plasma is retained in larger quantities on lithium-coated (relative to uncoated) graphite and molybdenum, two leading plasma-facing component materials for toroidal confinement experiments. The increased retention reduces recycling at the edge in toroidal confinement experiments, which may help explain high-performance plasma operation. However, this same retention may also be detrimental to the tritium economy of future fusion power plants and must be taken into account accordingly. The DIONISOS facilities were enabled to study lithium films deposited in vacuo via a vapor deposition gun developed by postdoctoral research associate Felipe Bedoya, and the work was published in the *Review of Scientific Instruments* in July 2018. Bedoya also performed the measurements and presented the results at the International Atomic Energy Agency Fusion Energy Conference in October 2018 and the International Conference on Plasma Facing Materials and Components in May 2019.

The propensity of lithium in plasma experiments to migrate and condition (or contaminate) remote surfaces is also of interest to the plasma-material interactions research community. Sample coupons exposed in the EAST tokamak without prior lithium exposure were found to have deposits of lithium even with minimal exposures. Additionally, lithium deposits were found on materials exposed in the MAGNUM-PSI linear plasma device several weeks after previous lithium experiments. Undergraduate student Chris Reis, a participant in MIT's Summer Research Program, worked with PhD student Leigh Ann Kesler and research scientist Kevin Woller to study the redeposited lithium layers during the summer of 2018, culminating in a presentation by Reis to program attendees and MIT at large. Woller also presented this work to the fusion engineering community at the Symposium on Fusion Engineering in June 2019.

The erosion and migration of plasma-facing materials is a large uncertainty for component lifetime considerations in future fusion power plants. Novel depth markers have been developed and deployed to measure erosion on bulk plasma-facing materials. In the 2018 EAST experimental campaign, implanted depth markers were used to measure erosion of molybdenum from the inner wall. Leigh Ann Kesler worked on these experiments and successfully defended her doctoral thesis in October 2018. Kevin Woller is continuing the experiments with further refinements of the depth marker analysis and advancements toward in situ measurements. This research has been presented at the International Conference on Plasma Surface Interactions, the International Conference on Ion Beam Modification of Materials, the International Conference on Nuclear Materials, and the International Conference on Plasma Facing Materials and Components.

Liquid walls have been proposed for fusion confinement experiments, with liquid metals currently having the majority research share. However, the unique concept of the molten salt immersion blanket in the ARC fusion pilot plant proposed at MIT represents an opportunity to study molten salts as a first wall material. Additionally, PSFC's newly created Laboratory for Innovation in Fusion Technology offers an opportunity to infuse fusion research with private support. This combination has resulted in a unique project aimed at studying the viability of molten salt surfaces to face the fusion plasma in magnetic confinement devices. Felipe Bedoya performs these experiments with collaborators Kevin Woller and Professor Dennis Whyte. Bedoya gave a presentation on the work at the International Symposium on Fusion Engineering in June 2019.

Magnets and Cryogenics Division

The Magnets and Cryogenics (M&C) Division is headed by Professor John Brisson of the Department of Mechanical Engineering. Professor Brisson also heads the MIT Cryogenic Engineering Laboratory. During the past year, the Cryogenic Engineering Lab has been integrated with M&C.

The M&C Division conducts research on conventional and superconducting magnets for fusion devices and other large-scale power and energy systems. This past year's R&D 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 Benjamin Hamilton has focused his master's thesis research on the study of supercritical helium for cooling HTS magnets. His research has indicated that existing fluid heat transfer correlations do not extend to the extreme range of pressure and mass flow rates needed to extract nuclear heat deposited by neutron irradiation in HTS toroidal field coils. He is designing a new cryogenic flow loop study in order to simulate the desired operating conditions and determine the proper heat transfer correlations experimentally.

Makoto Takayasu of M&C delivered a moderate-length (several meters) high-current REBCO twisted stack tape conductor (TSTC) to the National Institute for Fusion Studies in Gifu Prefecture, Japan. The conductor test was initiated in January 2019, but a failure of the current leads caused all testing to be suspended.

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. This year we also collaborated with Composite Technology Development Inc. of Lafayette, CO, on a Small Business Innovation Research program to develop insulation systems for HTS Twisted Stacked-Tape Cable conductors and joints.

We continued our collaboration with the Laboratory 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 of the PSFC, 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 (DNP) and electron paramagnetic resonance to enhance NMR signal intensities. Three of these areas are discussed here.

Dipolar Recoupling and Spectral Assignments

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 findings from other laboratories 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 SPC-5.

During the past year, we have continued to explore new approaches to recoupling with simulations of proton-assisted recoupling and proton-assisted insensitive nucleus spectra. In addition, we have started to develop new analytical approaches to ^{1}H recoupling during mixing periods. The goal is to develop sequences that operate efficiently at high spinning frequencies and high fields.

Structure of Amyloid Fibrils

Over the past year, we have determined the structure of beta-2-microglobulin (β2m) fibrils, and are near to completing the structure of $A\beta_{1\text{-}40}$. We have also obtained well-resolved ^{1}H detected spectra and low-temperature DNP enhanced spectra of $A\beta_{1\text{-}42}$ showing no decrease in resolution at 90 K.

Dynamic Nuclear Polarization

Dynamic nuclear polarization 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 magic-angle spinning (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 ^{1}H NMR enhancement factors up to 430. However, a major impediment in the implementation of NOVEL at high fields is the requirement for increasingly high electron microwave power to fulfill the on-resonance polarization-transfer matching condition, $\omega_{0I} = \omega_{1S}$,where ω_{0I} and ω_{1S} are the nuclear Larmor and electron Rabi frequencies, respectively.

As indicated above, the efficiency of continuous wave dynamic nuclear polarization 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 a new pulsed experiment that we refer to as time-optimized pulsed DNP. The experiment was tested at 9 and 34 GHz microwave frequencies, and simulations indicate that it should perform well at frequencies up to 527 GHz (800 MHz for ^{1}H). The paper describing this work appeared in *Science Advances.*

In a second investigation, we sought to determine the size of the spin diffusion barrier for trityl radical, a popular DNP polarizing agent, in glassy glycerol-water mixtures. The size was found to be less than 6 Å, much smaller than the proposed barrier of 20 to 40 Å. The analysis that led to this conclusion involved developing a description of the three-spin solid effect, which is very sensitive to distances as well as rudimentary ^{1}H ENDOR spectra. Again, the paper describing this investigation appeared in *Science Advances*.

Mei Hong (Professor of Chemistry)

The Hong group employs advanced solid-state NMR techniques to address fundamental questions in biology, medicine, and materials science. Current focuses are virus membrane proteins, plant cell walls, and amyloid fibrils involved in diseases and explored in pharmaceutical sciences. In 2018–2019, the Hong group made major scientific discoveries in four areas, as described below.

Structure and Dynamics of Influenza Virus M2 Protein

The Hong group developed a yeast expression protocol to enrich cholesterol with ^{13}C and used this ^{13}C-labeled cholesterol to conduct 2D NMR experiments aimed at defining cholesterol’s binding interface with the influenza virus A M2 protein (AM2). This approach is generally applicable for studying cholesterol’s role in membrane protein function.

Structure and Lipid Interactions of Viral Fusion Proteins

The Hong group completed a challenging study of the three-dimensional topology of the HIV gp41 protein, which mediates HIV entry into host cells by merging the virus lipid envelope with the cell membrane. Their NMR data indicate that the protein has a partially formed hairpin structure that may bridge two lipid bilayers. This structural model may represent the hemifusion state of the protein. Intermolecular distance restraints on the nanometer scale are extremely valuable in obtaining information on the three-dimensional structures of membrane protein complexes. The Hong group demonstrated two new ^{19}F distance NMR techniques that measured ^{19}F-^{19}F and ^{19}F-^{1}H distances to 1 to 2 nm under fast MAS in high magnetic fields. These methods will be useful for structure determination of proteins and pharmaceutical compounds.

Amyloid Protein Structure

During the past year, the Hong group published two groundbreaking studies of amyloid fibril structures. In the first study they discovered that the peptide hormone glucagon, at high pharmaceutical concentrations, forms an antiparallel hydrogen-bonded beta-sheet fibril that contains two coexisting molecular conformations. This novel structure suggests how to design glucagon analogs that prevent fibril formation in order to improve the treatment of diabetic hypoglycemia. In the second study, the Hong group investigated the structure and dynamics of the fibrils formed by the tau protein, which are involved in a number of neurodegenerative diseases. Their results revealed a fibril core structure that is unique among all tau isoforms studied so far. This rigid core is surrounded by dynamically heterogeneous segments in the rest of the protein. Moreover, the study identified a biochemical error in the literature that led to polymorphic tau fibrils. This discovery will significantly clarify and positively impact the field of tau research.

Structure and Dynamics of Plant Cell Walls

Plant cell walls expand rapidly under acidic conditions, but the molecular mechanism for this acid growth has been elusive. By measuring the NMR spectra of intact cell walls at neutral and acidic pH levels, the Hong group determined that acidic pH weakens the interactions between pectins and cellulose microfibrils, leading to polysaccharide slippage and the consequent wall loosening. To facilitate cell wall structural studies, the Hong group developed fast MAS ^{1}H-detected 2D and 3D solid-state NMR techniques that not only increase the sensitivity of NMR analysis but also enhance the resolution of polysaccharide signals in multidimensional correlation spectra. This ^{1}H-detected solid-state NMR approach will facilitate future studies of plant cell walls.

Yukikazu Iwasa (Senior Research Scientist)

During the period July 1, 2018, through June 30, 2019, 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 (1.3G) program, supported by the National Institute of General Medical Sciences, began on September 1, 2015; its end date will be no-cost extended to a new date of August 31, 2019. This project seeks to design a very high magnetic field NMR magnet (30.5 T) using high-temperature REBCO superconductors.

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

Supported by the National Institute of Biomedical Imaging and Bioengineering (NIBIB) and begun on April 1, 2017, this project has two specific aims. The first is to complete a tabletop liquid-helium-free, persistent-mode, solid nitrogen (SN2) cooled superconducting (MgB2) MRI magnet prototype for phalangeal scanning in osteoporosis research. The second aim is to demonstrate the benefits of MgB2/SN2 technology for magnetic resonance magnets in the context of a compact, affordable scanner. In this experiment, Jerome Ackerman of the Martinos Center for Biomedical Imaging at

Massachusetts General Hospital will measure the distal phalanx of left-hand true 3D bone mineral density, 3D bone matrix density, and trabecular microstructure. We have decided to purchase MgB2 wire for the magnet from the Hitachi Research Laboratory, with which we are collaborating on this project. MgB2 joints made with and model coils wound with Hitachi MgB2 wire are being developed and built.

Tabletop Liquid-Helium-Free Microcoil NMR Magnet

This two-year NIBIB-supported project, initiated in July 2018 and led by Dongkeun Park, has four specific aims: (1) designing and constructing a prototype single-coil all-REBCO 23.5 T/Ø20-mm cold-bore magnet and achieving a field of 23.5 T at 10 K in a volume of SN2, (2) validating a screening-current-inducing field reduction method for enhancing field quality, (3) applying an iron yoke design to reduce a 5-gauss fringe field radius, and (4) designing a shielded tabletop LHe-free 23.5 T/Ø25-mm high-resolution NMR magnet incorporating the field-shimming techniques developed for our 1.3 GHz high-resolution NMR magnet. This prototype magnet is composed of a single stack of 12 no-insulation double-pancake coils. We have already purchased REBCO tape from the Shanghai Superconductor Technology Corporation. Currently, we are practice-winding double-pancake coils.

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 fermions, superconducting spintronics, molecular spintronics), with funding from the Army Research Office (ARO), 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 University, Howard University, and the Boston Museum of Science. Based on its excellent success during the past five years, this program has been renewed until 2023. Three research proposals have been submitted to the Department of Defense and are under preparation. The new ARO-sponsored project, which began in December 2018, is progressing successfully. Under this new ARO project, a guest postdoctoral fellow was placed at 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 such as Oak Ridge and 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’s group and his collaborators published several articles in journals such as *Science*, *Physical Review Letters*, and *Applied Physics Letters*. 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 international conferences in Germany, Spain, Hong Kong, the United Kingdom, and India.

The group's biggest breakthrough during the past year was the discovery of Majorana bound states pair in solid state. This is something that has been sought for many decades by top groups in the world. The implication is that this breakthrough has a high potential to lead to topological qubits that could form the backbone of quantum computers. A provisional patent application has been submitted based on this work.

Moodera's 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 low power spin-based communication and storage technologies. If these technologies can be exploited, they may 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.

Moodera's research group seeks to use state-of-the-art molecular beam epitaxy systems to understand the quantum state exhibited by many novel materials. One of the major projects is an investigation of Majorana bound states in nanostructures and their entanglement properties. This highly versatile and sensitive equipment should lead to new discoveries and collaborations.

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 one woman), a female visiting scientist from Brazil, undergraduates from the California Institute of Technology and China, and two high school students have taken part in Moodera's research. One of the postdocs received a prestigious Marie Curie Fellowship. Another Swiss-funded postdoc has been closely collaborating with the group over the past two years and will continue for another year. An undergraduate from Caltech is completing a three-month summer internship at MIT. The participating high school students have won several science competitions, and some have joined the MIT undergraduate program. The group has also welcomed visiting scientists from the UK, China, Denmark, and Germany.

Educational Outreach

The Plasma Science and Fusion Center's educational outreach program is planned and organized under the direction of Paul Rivenberg, PSFC education and outreach administrator. This year Anne White replaced senior research scientist Richard Temkin in overseeing the DOE Office of Fusion Energy Sciences grant that funds a portion of the program.

The program conveys the excitement of advances in plasma physics and fusion energy research to the general public, the national and international scientific communities, and the MIT community. A particular focus of the program is heightening the interest of 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 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, the Plasma Science and Fusion Center offered 65 tours to a variety of groups. For example, groups from middle- and high schools, US and international educational institutions, and MIT classes, offices, and organizations all visited the center, along with Cambridge Science Festival participants. Overall, the PSFC hosted close to a thousand people on site.

The PSFC continues 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. This year, members of Commonwealth Fusion Systems joined PSFC staff and graduate students to explain the latest directions in MIT fusion research.

Jointly with CFS, we also participated in April's MIT Energy Conference and Tech Showcase. During this event, held at the Boston Marriott Cambridge in Kendall Square, a number of demonstrations helped illustrate the science and technology behind current PSFC research.

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 in Portland, OR, 23 exhibitors representing laboratories and schools across the US and 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 fusion projects with a video game that encourages participants to work cooperatively to confine a fusion plasma in a tokamak vacuum chamber. Research scientist Ted Golfinopoulos and students oversaw a series of magnet experiments at the booth, and Philip Michael provided a demonstration in which the ultraviolet protection of sunglasses and various grades of sunscreen was tested.

Senior research scientist John Rice oversees the PSFC seminar series, weekly plasma science talks aimed at the MIT community, with the assistance of Darin Ernst, Johan Frenje, Seung Gyou Baek, 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 and associate director Anne White helped organize the center's annual Independent Activities Period (IAP) open house seminars and tours. This year, for the first time, Cristina Rea and Ted Golfinopoulos led a weekend-long hackathon competition in which 11 participants from the MIT community tried applying machine learning algorithms to fusion databases to see who could save the plasma from collapse before it was too late. In fusion research, MIT scientists are using machine learning to predict the sudden and catastrophic collapse of fusion plasmas. Avoiding such transient events is critical for the development of an electricity-generating device such as an ARC device. PSFC will attempt to expand this event for the January 2020 IAP.

Professor Nuno Loureiro co-organized the 2019 School of Plasma Physics program, held at the École de Physique de Les Houches in France. This two-week program seeks to educate around 50 students on a broad set of topics in plasma physics and related disciplines.

The PSFC also continues to be involved with educational efforts sponsored by the Coalition for Plasma Science, an organization formed by members of universities and national laboratories to promote understanding of the field of plasma science.

Honors and Awards

Thach (Cody) Can PhD '17, a former member of Professor Robert Griffin's research group, has been selected as the winner of the 2019 Raymond Andrew Prize. The prize is awarded annually by the Groupement AMPERE (Atomes et Molécules Par Études Radio-Électriques) to young scientists for outstanding PhD theses in magnetic resonance. Can was awarded the prize in recognition of his thesis "New Methods for Dynamic Nuclear Polarization in Insulating Solids: The Overhauser Effect and Time Domain Techniques."

Nuno Loureiro, associate professor of nuclear science and engineering, has received a Professor Amar G. Bose Research Grant. In collaboration with professors in the fields of quantum physics and quantum mechanics, he will explore graphene, an anatomically thin carbon sheet with properties of interest for applications in electronics.

Appointments

- PSFC headquarters: Kwokin Ou and Tesha Myers were appointed fiscal officers.
- Magnetic Fusion Experiments Division: Vincent Fry was appointed mechanical engineer associate; Leigh Ann Kesler, Andrew Seltzman, Pablo Rodriguez Fernandez, and Pedro Molina Cabrea were appointed postdoctoral associates; Camilo Calzas Rodriguez was appointed procurement and contract specialist; Ryan Sweeney was appointed postdoctoral fellow; Fernando Santoro and Stephen Lane were appointed software developers; Yu Tang was appointed research engineer; and William Kalb was appointed mechanical engineer.
- Plasma Theory and Computation Division: Manaure Francisquez Rodriguez and Muhammad Mohebujjaman were appointed postdoctoral associates.
- High-Energy-Density Physics Division: Hong Sio was appointed postdoctoral associate.
- Plasma Science and Technology Division: Samuel Schaub was appointed postdoctoral associate.
- Magnetic Resonance Division: Hang Chi was appointed postdoctoral fellow, and Hao Chang and Wooseung Lee were appointed postdoctoral associates.

Promotions

Several staff from the Magnetic Fusion Experiments Division were promoted. Theresa Wilks and Christina Rea were promoted to research scientists, Anastasia Alexandridis was promoted to sponsor relations manager, and Joshua Stillerman was promoted to research engineer. In addition, Syun'ichi Shiraiwa was promoted to leader of RF and HTS magnet computational development, and Rui Vieira was promoted to deputy head of MFE engineering.

Graduate Degrees

- Nuclear Science and Engineering: Alexander Creely, PhD; Leigh Ann Kesler, PhD; Adam Qing Yang Kuang, PhD; Pablo Rodriquez Fernandez, PhD; Juan Ruiz Ruiz, PhD; Dan Joseph Segal, MS
- Physics: Roy Alexander Tinguely, PhD; Hong Weng Sio, PhD; Xueying Lu, PhD; Samuel Schaub, PhD
- Chemistry: Myungwoon Lee, PhD

Dennis Whyte
Director
Hitachi American Professor of Engineering