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.

The center's research focuses on the following: 1) the science of magnetically confined plasmas in the development of fusion energy; 2) general plasma science, including plasma-surface interactions, development of novel high-temperature plasma diagnostics, and theoretical and computational plasma physics; 3) the physics of high energy density plasmas; 4) the physics of waves and beams (gyrotron and high-gradient accelerator research, beam theory development, non-neutral plasmas, and coherent wave generation); 5) development of high field superconductors and superconducting magnet systems; 6) research in magnetic resonance, including NMR, electron paramagnetic resonance (EPR), and magnetic resonance imaging (MRI); 7) NMR and MRI magnet development; and 8) nanoscience condensed matter physics (quantum coherent behavior charge and spin transport).

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

More than 200 personnel are associated with PSFC research activities. They include 25 affiliated faculty and senior academic staff and 50 graduate students, with participating faculty and students from the Departments of Aeronautics and Astronautics, Chemistry, Mechanical Engineering, Nuclear Science and Engineering (NSE), and Physics. The PSFC also includes 108 research scientists, engineers, postdoctoral associates/fellows, and technical staff; 74 visiting scientists, engineers, and research affiliates; two visiting students; 20 technical support personnel (technicians and designers); and 23 administrative and support staff.

Center-wide, funding has grown to $40 million. The past year was the second year of funding for the SPARC (Soonest/Smallest Privately Funded Affordable Robust Compact) program, which is supported by private industry. With the cessation in 2017 of the Alcator program supported by the US Department of Energy (DOE), 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 accounts for about 11%.

Magnetic Fusion Experiments Division

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 participating closely with PSFC science and engineering staff in research and development (R&D)

activities. The overall PSFC-CFS objective is the design, construction, and operation of the SPARC tokamak by the mid-2020s, which will be the first demonstration of net fusion energy production in a controlled manner relevant to electricity generation. The collaboration is presently in the midst of its third year of a three-year (June 2018 to June 2021) MIT-CFS research agreement. The goals of this phase of the project 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 second year of SPARC R&D focused on two principal activities: the building of the Toroidal Field Model Coil (TFMC) and the design of the SPARC tokamak.

The TFMC involves a two-year, roughly 60-person effort to design, build, and test the world's highest performance superconducting fusion magnet using a high-temperature superconductor. The project also encompasses a substantial phase of research and development in superconducting magnets and in fabrication processes, as well as building out magnet test facilities at the PSFC. The following were accomplished over the past year:

- The design of the TFMC magnet, fabrication facility, and test facility
- Complementary hardware R&D on TFMC design and fabrication processes
- Identification and qualification of all TFMC vendors
- Establishment of the TFMC fabrication facility and test facility at the PSFC

The SPARC device saw impressive growth in the maturity and integration of the design as well as an increase in the size of the design team to include upwards of 100 people. Physics baselines for SPARC design and operation have been established and integrated design and engineering to support the SPARC mission are well under way, as is hiring of key personnel with expertise in fusion physics and engineering.

A rigorous site selection process was established and executed. A final site for the SPARC device has been selected, and preparations to acquire and prepare the site are under way.

International Collaborations

Gas-Puff Imaging for Study of Physics in the Wendelstein 7-X Stellarator

The Wendelstein 7-X stellarator (W7-X), an experimental research facility located at the Max Planck Institut für Plasmaphysik (IPP) in Greifswald, Germany, is the world's most advanced nuclear fusion device in the "stellarator" magnetic configuration. The long-term aim of our collaborative project with W7-X is a detailed study of boundary and scrape-off-layer physics and turbulent transport in the facility. A major component of our work is providing a gas-puff imaging (GPI) diagnostic system for this experimental device. The GPI system is scheduled for commissioning and operation on W7-X for the device's next operational campaign beginning in 2022. In addition to designing, procuring, and installing this sophisticated diagnostic, we provided and operated a fast-framing camera system that viewed the W7-X boundary plasma during that device's last run campaign. The 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.

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. 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 MIT Plasma Science and Fusion Center, the State University of New York (SUNY) at Cortland, and the Max Planck Institut für Plasmaphysik. The US side of the project is funded by the DOE Office of Fusion Energy Sciences. Additional funding for on-site support is provided by IPP. The project began in August 2015 and concluded its first three-year phase in August 2018. A renewal proposal was submitted by Professor Miklos Porkolab (PI) and Eric Edlund (co-PI; SUNY at Cortland) in fall 2017. The proposal was approved in spring 2018, with a stated award amount of $900,000 over three years (August 2018 to August 2021). In February 2018, Zhouji Huang joined PSFC as a postdoctoral associate for the PCI project on site in Greifswald. On June 1, 2020, Søren Kjer Hansen joined the project as an MIT postdoctoral fellow supported by a Carlsberg Foundation Fellowship, with the goal of developing a synthetic PCI diagnostic for W7-X. A new three-year grant proposal will be submitted by Professor Porkolab in early 2021.

I-Mode Research

Research into the I-mode regime, pioneered on Alcator C-Mod and featuring the beneficial properties of high energy confinement and no impurity accumulation, no large transients, and low particle confinement, has continued to be a focus. Graduate student William McCarthy has been studying the characteristics and role of a coherent low (approximately 10 kKz) oscillation and has found interesting trends in frequency. He has also identified the mode on AUG diagnostics. AUG has again been the primary focus of experimental collaborations. Despite travel restrictions, MIT researchers were able to remotely conduct several experiments in June 2020 that explored differences in radial electric fields with magnetic configurations, thought to be key to transition physics, and revealed impacts of resonant magnetic perturbations on I-mode thresholds. A postdoctoral researcher from the Max Planck Institut für Plasmaphysik in Garching has in turn begun a collaboration (initially remotely) to study the occasional small transients seen in C-Mod I-modes and compare them with AUG observations. A proposal to establish I-mode on the new WEST tokamak has been accepted, and experiments are expected in the coming year. MIT scientists were active in a EUROfusion ad hoc working group on edge localized mode (ELM)–free regimes and a US–European Union technical workshop that highlighted this topic as important for increased collaboration in coming years.

Edge Turbulence Measurements on TCV

The PSFC ran a series of experiments on the Tokamak à Configuration Variable (TCV) device at École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland. This research, part of a collaboration with EPFL's Swiss Plasma Center, combined equipment designed and built by MIT and EPFL. The diagnostic shown in Figure 1, which utilizes a technique employed at MIT's own Alcator C-Mod tokamak, allows high-speed imaging of plasma turbulence in the outer boundary region of the plasma (Figure 2). The experiments carried out in the past year provide the first high-quality imaging of edge turbulence in a tokamak plasma with "negative triangularity," wherein the plasma shape is turned inside out from its standard geometric orientation, a configuration that shows promise in offering high performance with favorable operating conditions. This work supports the doctoral thesis research of two graduate students, one at MIT and one at EPFL, and has been presented at the annual American Physical Society (APS) Division of Plasma Physics (DPP) conference.

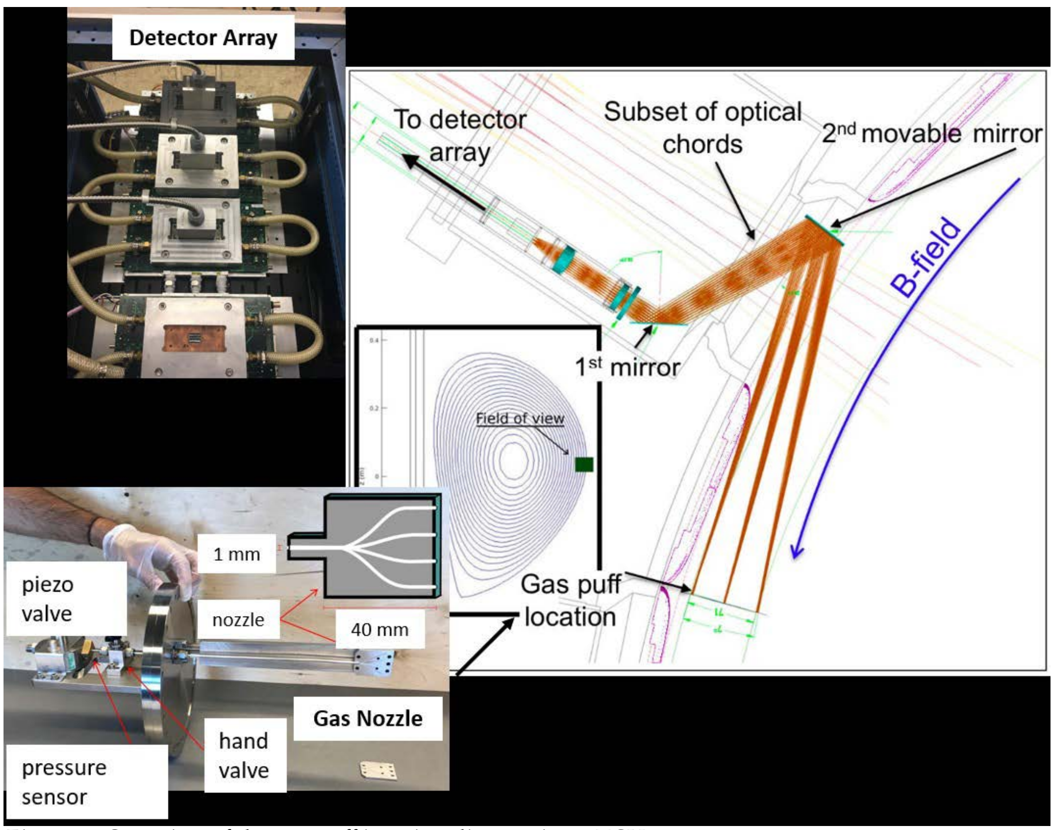

Figure 1. Overview of the gas-puff imaging diagnostic on TCV.

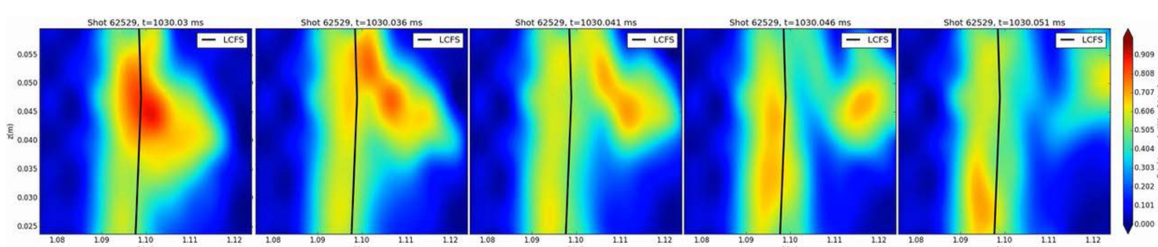

Figure 2. Several frames captured from the GPI array on TCV showing the propagation of a plasma filament, or "blob," in the edge region of the TCV plasma. Each consecutive frame is delayed by 5 milliseconds from the previous frame; the sampling time of the device is 0.5 milliseconds.

Collaborations in the United States

High Field Side Lower Hybrid Current Drive on DIII-D

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. The guiding physics criterion is off-axis current drive with peak current density approaching 0.4 MA/m^2 in advanced tokamak discharges. The HFS launch position was selected to improve wave penetration and allow for single-pass absorption and off-axis deposition. In existing advanced tokamak discharges, good wave penetration is achieved because the poloidal upshift balances the toroidal downshift as the wave penetrates into the plasma. Near the damping location, the wavenumber upshifts quickly, resulting in localized absorption and current drive. The technical challenges involved in implementing an HFS LHCD coupler in DIII-D are substantial. The coupler and waveguides enter on the low field side and follow the vacuum vessel contour up to the center post near the mid-plane. The expected disruption loads, 400°C bake, and detailed radio frequency (RF) structures compel the use of an additive manufactured (AM) high-temperature copper alloy, GRCop-84. Furthermore, the waveguide utilizes two compact vacuum-RF flanges tested to withstand more than two years of accumulated bake time and five years of thermal cycling. The adaptation of AM GRCop-84 has led to a number of publications regarding manufacturing techniques and mechanical and RF properties.

In the past year, this project has moved from conceptual designs to final designs for the in-vessel LHCD coupler and waveguide system. Final design reviews were completed for the external waveguide network and klystrons. We have delivered the klystrons, carts, and high-voltage power supply. Figure 3 shows the high-voltage power supply installed at the DIII-D facility. We have also overcome the challenge of manufacturing the coupler with the AM alloy, allowing for an integrated RF matching network within the waveguides. This should allow the launcher to couple power over a wide range of plasma densities.

Figure 3. DIII-D high-voltage power supply.

Turbulence Transport Studies

Professor Anne 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 development 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 the International Thermonuclear Experimental Reactor (ITER) and the ARC (affordable, robust, compact) reactor. White and her group are engaged in research at four major tokamaks (Alcator C-Mod, AUG, DIII-D, National Spherical Torus Experiment [NSTX]/NSTX upgrade) where they lead experiments, develop diagnostics, and lead validation projects using advanced turbulence simulation codes. Four students and two postdocs currently work in Professor White's group. Postdoc Pablo Rodriguez Fernandez performs predictive modeling for SPARC, develops new optimization tools at AUG, and leads a new collaboration with the Joint European Torus (JET) tokamak on integrated modeling. He also supports students in the group working on tokamaks. NSE students Rachel Bielajew and Christian Yoo and postdoc Pedro Molina Cabrera continue development and optimization of CECE (correlation electron cyclotron emission)/nT-phase systems at AUG. Molina Cabrera is focused on the physics of isotope scaling, Bielajew is studying edge turbulence in ELM-free high-performance plasmas, and Yoo is exploring the use of machine learning (ML) and artificial intelligence applied to understanding scaling of turbulence and transport across a wide range of engineering and plasma parameters. Undergraduate Research Opportunities Program (UROP) student Calvin Cummings has joined the group for summer 2020; he will work on new control room visualization tools for CECE access 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 a 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.

Impurity Transport Studies on DIII-D

In fusion reactors, the accumulation of impurity ions can lead to fuel dilution, decreased energy confinement, and a reduction in reactor performance. MIT's collaboration at the DIII-D tokamak in San Diego has made significant progress in providing a physics-based understanding of how impurities are transported in and out of the fusion core and has helped identify mechanisms that can be harnessed to expel impurities and therefore improve the performance of future fusion devices. Cutting-edge turbulence modeling was validated against dedicated experimental measurements of impurity transport in the tokamak. Qualitative trends in the measured impurity transport were well reproduced through modeling, and quantitative agreement was found in many of the conditions analyzed. Measurement of turbulent fluctuations in the plasma, combined with computer modeling, demonstrated that application of electron heating in the core of the plasma excites trapped electron mode (TEM) turbulence, leading to an increase in impurity diffusion by up to an order of magnitude. This increase in impurity diffusion resulted in dramatically lower impurity confinement and confirmed that electron heating can help reduce impurity accumulation in future fusion devices. The results of this work were presented as an invited talk at the APS DPP meeting in November 2019. To better quantify the ability of turbulence models to reproduce impurity transport, a database of DIII-D carbon profiles has been analyzed and compared with linear and nonlinear modeling. This database spans the DIII-D tokamak operational space and reveals clear discrepancies between modeling and experiments when certain types of plasma turbulence are present. These discrepancies point to potential missing physics in current impurity transport modeling, and the current work represents an integral contribution to the Department of Energy's fusion Joint Research Target for 2020.

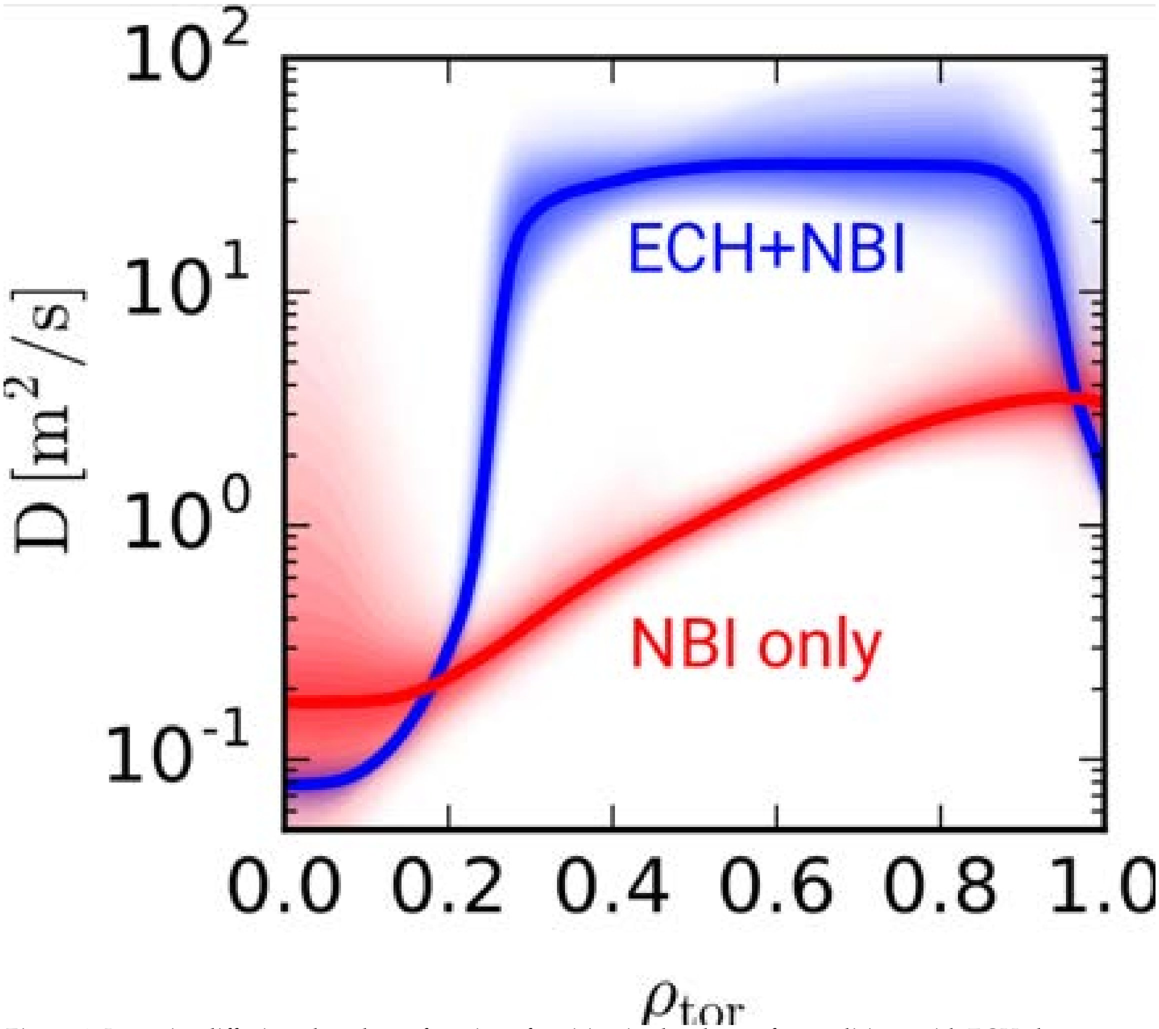

Figure 4. Impurity diffusion plotted as a function of position in the plasma for conditions with ECH electron heating and with neutral-beam injection (NBI) heating only.

Wide Pedestal Quiescent H-Mode on DIII-D

The high-confinement wide pedestal quiescent H-mode (QH) regime, obtained in the DIII-D tokamak, is promising for steady-burning plasma operation without ELMs and associated divertor damage at ITER collisionalities, with nearly equal ion and electron temperatures and no net torque injected. Future burning plasmas will not have significant neutral beam torque, and, unlike neutral-beam injection (NBI), fusion reactions heat mainly electrons. Our recent DIII-D experiments, in contrast to those conducted in other low-collisionality H-mode operating regimes, show that confinement improves when electron cyclotron heating (ECH) replaces neutral beam power, which is promising for burning plasma operation. As shown in Figure 5, we have sustained wide pedestal QH-mode discharges for several confinement times with up to 77% ECH power (23% NBI); these discharges exhibit very high central electron temperatures ($T_{e0} > 12$ keV). A Fourier analysis of the measured transverse electric field (Te) response to modulated ECH separates diffusion and convection in the electron power balance, revealing an inward core electron thermal pinch. The pinch leads to formation of an internal transport barrier in the electron thermal channel as the ECH is moved on-axis. The physics of the pinch is being explored using GENE simulations (wherein we have implemented the first exact gyrokinetic collision operator). In the plasma core, TEM turbulence dominates, driving significant magnetic flutter transport. Even without the internal transport barrier, ion channel confinement improves in the core and pedestal as the fraction of off-axis electron heating increases. The pedestal radial electric field well broadens and deepens, while the intensities of low and intermediate wavenumber density fluctuations respond oppositely. The wide pedestal QH-mode has been separately demonstrated with zero net injected NBI torque throughout. We have measured the effective "intrinsic" torque profile (the effective torque giving rise to intrinsic rotation that is not externally driven) as a function of ECH power fraction while simultaneously measuring electron thermal transport. The intrinsic torque density profile approximately balances that from edge beam orbit loss to produce near-zero total torque density across the profile. As the fraction of ECH power increases, the edge beam orbit loss torque diminishes along with beam power, yet confinement significantly improves. This improved confinement allows for a more stable path to net positive fusion power. Our projections indicate that the ITER equivalent Q = 10 goal could be attained in this regime on DIII-D at a lower, more stable plasma current than is required in regimes with lower confinement. The wide pedestal QH-mode has been recently initiated with the plasma current in the normal direction, which together with its high electron temperature makes it an ideal candidate for current profile modification using the MIT lower hybrid (LH) system to be installed in DIII-D. The additional 1 MW of electron heating from the LH system may also make it possible to sustain the regime without NBI.

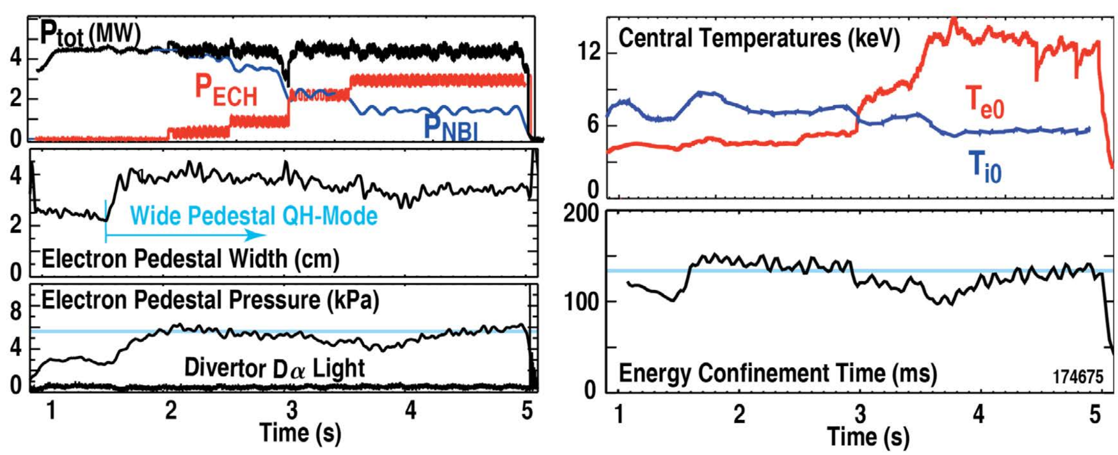

Figure 5. Sustaining the wide pedestal QH-mode regime in the DIII-D tokamak as neutral beam power (P_{NBI}) is exchanged for electron cyclotron heating (P_{ECH}), showing formation of an electron temperature internal transport barrier with central electron temperatures (T_{e0}s) exceeding 12 keV. Unlike other H-mode regimes at low collisionality, the energy confinement time in the wide pedestal QH-mode does not decrease and often improves markedly with electron heating. Here the regime was sustained with 77% of external heating power from ECH, limited only by the available ECH power.

Development of Super H Mode on DIII-D

MIT is collaborating with General Atomics in the development of a regime called the super H-mode (SH), which aims to close key gaps such as integrating a high-performance fusion core with realistic exhaust solutions. The SH regime is a promising scenario for future devices due to the high pedestal pressures obtained through decoupling dominant physics processes typically seen in plasma H-mode pedestals. By leveraging peeling-type instabilities as opposed to ballooning instabilities (or a strongly coupled mix between the two), the SH pedestal can access high densities at low collisionalities because the temperature pedestal is maintained. The SH pedestal top can be maintained with high separatrix and scrape-off layer densities, which are more compatible with detached conditions.

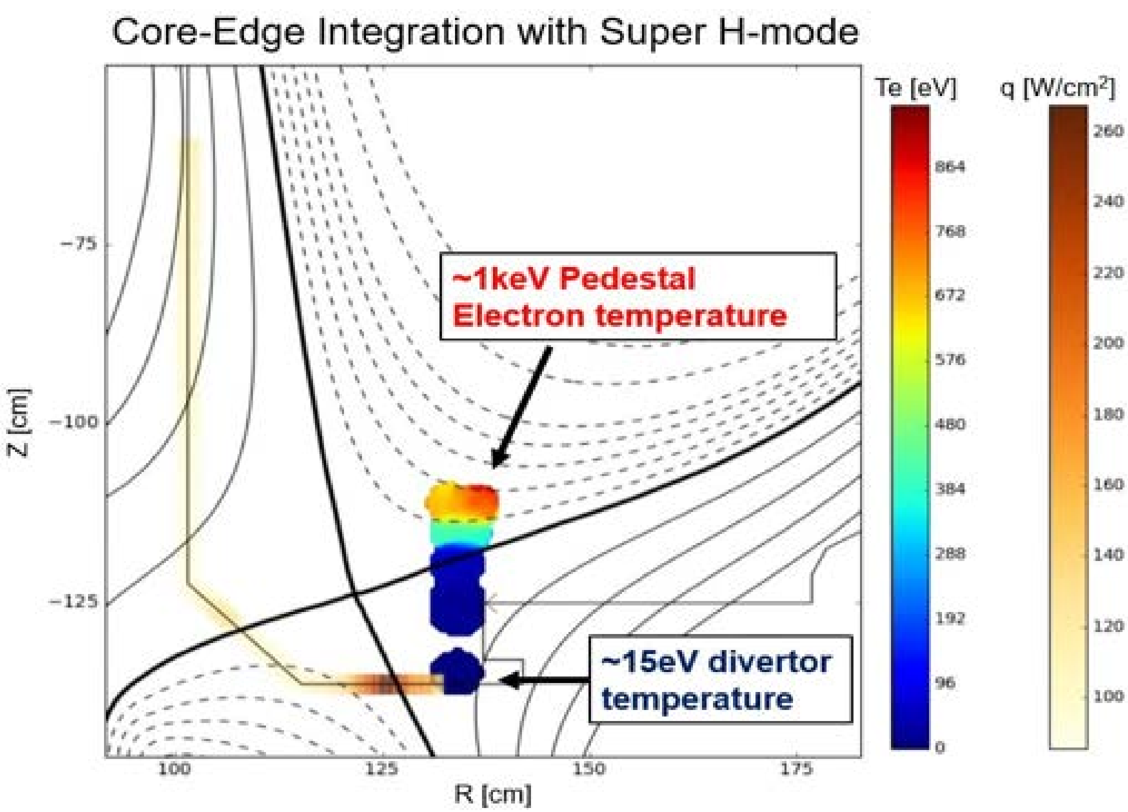

Figure 6. Cross section of a DIII-D plasma using the super H-mode for core-edge integration studies. Nitrogen seeding reduces heat flux and temperature while maintaining a 1 keV electron temperature pedestal.

Edge Neutral Measurements on DIII-D

MIT continues to partner with the Princeton Plasma Physics Laboratory to develop diagnostics useful for inferring the main chamber neutral deuterium density in DIII-D. The first instrument deployed was a diagnostic called LLAMA, which measures radial profiles of Lyman alpha brightness in the tokamak edge, both inboard and outboard. MIT PhD student Aaron Rosenthal led the design and fabrication of LLAMA in-vacuum components, including optics, detector mounting, water cooling, and temperature monitoring. During the past year, an improved version of this instrument was delivered to DIII-D and calibrated in preparation for installation on the machine. In November 2019, in a DIII-D session led by Rosenthal in support of his thesis work, the instrument was used for the first time to collect data for a physics experiment.

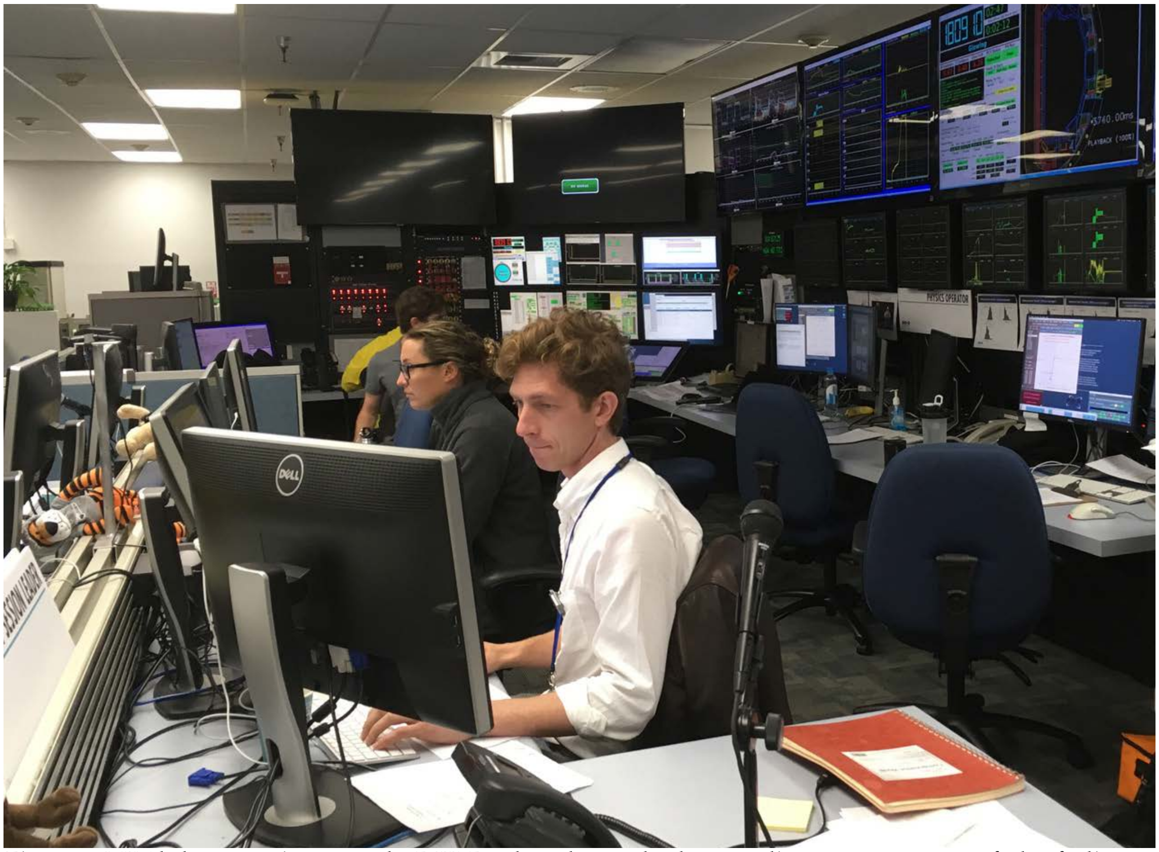

Figure 7. MIT led an experiment on the DIII-D tokamak to make the most direct measurements of edge fueling sources on the device to date. The experiment was led by PhD candidate Aaron Rosenthal (foreground). Theresa Wilks, an MIT scientist sited at DIII-D in San Diego, sits at his right and supports the experiment with auxiliary power programming.

Projects at WEST

The PSFC/WEST collaboration involves two areas: I-mode studies and assistance with the WEST X-ray imaging diagnostic.

I-Mode

I-mode is an enhanced confinement regime, extensively studied on C-Mod, that features a strong heat transport barrier at the plasma edge without the usual concomitant impurity accumulation and destructive energy bursts of other regimes. I-mode experiments will be conducted during WEST's upcoming run campaign to determine the device size scaling of the energy confinement time for extrapolation to operation on future devices and to verify the magnetic field dependence observed on C-Mod.

X-Ray Imaging Crystal Spectroscopy System

The WEST X-ray imaging crystal spectroscopy system will be the only means of determining the ion temperature and plasma rotation in the tokamak's plasmas, so routine operation is essential. Two problems that have been encountered are double images of emission lines and the appearance of unknown transitions in spectra. The double images are due to the use of two crystals that are not properly aligned. The "mystery" lines are from tungsten (the device wall material), determined from a comparison of C-Mod X-ray spectra that had deliberate tungsten injections.

Phase Contrast Imaging for Multiscale Measurements of Turbulence and Helicon Waves in DIII–D

The Phase Contrast Imaging program at DIII-D continued through FY2020, advancing previous lines of research and promoting Helicon detection development to a major component of the research program. The COVID-19 pandemic halted most laboratory work and delayed operation of the DIII-D tokamak, thereby eliminating new data collection in the latter part of the year, so the focus was successfully shifted to plasma modeling projects and further analysis of previously acquired data.

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

The aim of this high-risk exploratory project is to extend the PCI measurements to plasma fluctuations with higher frequencies and shorter wavelengths by orders of magnitude while maintaining excellent signal-to-noise ratios and reducing the overall cost for fabrication and maintenance of the system. This is achieved by switching from a 10.6-μm laser wavelength to 1.55 μm, which requires new fabrication techniques but allows the use of modern low-noise, high-bandwidth detectors. A prototype PCI system and fabrication of the custom optical component (the phase plate) have been completed. An improved fabrication technique developed at Pennsylvania State University's plasma etching laboratory has provided improved performance. Advances with the prototype have reduced optical distortions and improved detection signal to noise. If successful, the system will be capable of measuring not only electron-scale turbulence but also RF waves and will be proposed for implementation on DIII-D and possibly elsewhere.

Plasma Theory and Computation Division

New Parallel Computing Cluster

In 2019–2020, we initiated procurement of a test cluster for graphics processing unit (GPU) acceleration of physics modeling using a small set of six compute nodes with a total of 12 GPU cards. Acquisition of these GPU nodes follows the trend of the PSFC having local compute resources for training and preparation for use in larger facilities. This set of GPU resources will serve several purposes for thevPSFC.

The GPU cards are a mixture of two types. One type is optimized for machine learning algorithms and the second for computations, although it also can be applied to ML. These cards, which will be immediately useful to ML researchers at PSFC, are of sufficient size to significantly accelerate deep learning workflows for disruption prediction and regression models for lower hybrid actuators. The second set of GPU cards has full precision and is of the type being considered for the next National Energy Research Supercomputer Center (NERSC) system, Perlmutter. Our GPU system will serve as a development platform for members of PSFC to prepare their codes and workflows for the Perlmutter system, which is expected to come online in two phases in 2020 and 2021. Finally, this system will help inform possible expansions into a larger GPU cluster to continue to provide the dual platforms the PSFC has used for local and NERSC resources.

Plasma Theory, Computation, and Discovery Science

Analytic Tokamak Equilibria

Professor J. P. Freidberg and Professor Luca Guazzotto (University of Auburn) have initiated studies of exact analytic tokamak equilibria. These equilibria are simple, general, realistic, robust, analytic solutions to the well-known Grad-Shafranov equation. What is meant by all of these adjectives? "Simple" refers to the fact that the equilibria contain only a few terms that are intuitively simple to visualize. "General" indicates that the equilibria are valid for a wide range of configurations, including smooth surfaces, double null surfaces, single null surfaces, and finite and inverse triangularity. "Realistic" implies that the profiles are continuous and monotonic, with the pressure, pressure gradient, and toroidal current density smoothly vanishing at the plasma edge. Finite edge pedestals in pressure and toroidal current density are also allowed if desired. "Robust" refers to the fact that only five input parameters are required to obtain a solution (three geometrical and two simple physically intuitive parameters). The model leads to well-behaved solutions every time, with no delicate choosing of parameters. Lastly, "analytic" indicates that the solutions are exact solutions to the Grad-Shafranov equation, expressed in terms of known functions. Simple analytic expressions for the flux function and, importantly, its first and second derivatives have been derived.

Current and Flow in Imperfectly Optimized Stellarators

Stellarators are three-dimensional (3D) toroidal magnetic field configurations used to confine magnetic fusion–relevant plasmas. To avoid unacceptably large particle and heat flux losses, the magnetic field geometry must be optimized. Strict optimization is possible only at a single radial location; thus, while stellarators can be designed to have good symmetry properties, they are always imperfect. In addition, the confined plasma always possesses radial gradients in the confined plasma density and temperature. These radial variations give rise to flows and currents. The gradient-induced current is referred to as the bootstrap current. There are substantial disagreements between analytic and numerical evaluations of this current even though the radial particle and heat transport are in good agreement. Peter Catto and Professor Per Helander (stellarator theory head, Max Planck Institut) have been able to generalize the analytic treatment to include lower collision frequencies. The technique employed makes it clear that spurious numerical results are obtained at low collisionalities in part because radial magnetic drifts are not properly accounted for and, perhaps, because the imperfect fields considered are too far from optimization.

Multi-scale Gyrokinetic Simulations

Nathan Howard used the CGYRO code to complete a set of multi-scale gyrokinetic simulations of a DIII-D tokamak that are representative of the conditions expected in ITER's baseline scenario. Two simulation conditions were completed. One utilized the mean values from all experimental input profiles, and one used a one-standard-deviation increase in the high-k turbulence driving gradient. These two simulations 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 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 in the discharge simulated. In this work, it was demonstrated that a single-scale (ion or electron scale alone) simulation was unable to reproduce experimental heat flux levels. In contrast, multi-scale simulation appears able to resolve the discrepancy between simulated and experimental heat flux levels. Extending beyond heat fluxes, comparisons were made between turbulent density fluctuations measured with the beam emission spectroscopy diagnostic and both single-scale and multi-scale simulations. Using a synthetic diagnostic to model the beam emission spectroscopy measurement in the simulation, it was shown that neither simulation type was able to quantitatively match the measured fluctuation level, but the shape of the frequency spectrum was well reproduced by multi-scale simulation. Analyses of the origin of this discrepancy and comparisons of measured intermediate-k density fluctuations with multi-scale simulations are still under way. This work was presented as part of an invited talk at the 2019 APS DPP meeting in Ft. Lauderdale, FL.

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 studies on the effects of edge turbulence on the propagation of radio frequency waves in fusion plasmas. Previous studies by this group have focused on stationary representations of the density fluctuation in the edge region. These are valid representations as the transit time for electromagnetic waves through the edge plasma is much shorter than the evolution time for the fluctuations. In order to understand experimental observations, it is necessary to include the temporal evolution of the fluctuations. Computationally and theoretically, this is a formidable task because of time scales that span several orders of magnitude and spatial scales that range from the short wavelengths of the waves to the total extent of the edge region. In order to simplify analyses of disparate spatio-temporal scales, the group has been looking at statistical techniques for quantifying physical parameters appropriate for understanding the scattering of radio frequency waves. The first stage of the research has involved modeling the fluctuating plasma through an appropriately relevant permittivity tensor. Toward this end, the group has developed an effective medium approximation using the homogenization formalism for spatially non-uniform permittivity. This permittivity is being included in simulation codes for scattering of radio frequency waves. The second stage involves quantifying the variation in the wave power that is being reflected and transmitted through the turbulent plasma and the modifications to the power spectrum of the waves. For these studies, the method of polynomial chaos expansion is being developed. Polynomial chaos expansion is a non-sampling-based method that determines the evolution of uncertainty in a dynamical system having a probabilistic uncertainty in the system parameters. For radio frequency wave scattering, the system is the edge region composed of turbulent plasma and the "dynamical" properties are those pertaining to the waves, in particular the power spectrum.

Collisional Effects on Resonant Particles during Radio Frequency Heating and Current Drive

Magnetic fusion–relevant plasmas must be heated to fusion temperatures by external heating sources such as radio frequency waves. In addition, to obtain steady-state operation, a toroidal current must be driven in a tokamak by RF waves. Treatment of these wave processes relies on understanding how the charged particles are accelerated during what are referred to as resonant wave-particle interactions. The resonant and nearly resonant particles are particularly sensitive to weak collisions that scatter them out of and into resonance. As a result, the resonant particle-wave interactions occur in the center of a narrow collisional boundary. Peter Catto has shown that the diffusive nature of the collisions combined with the wave-particle resonance condition substantially enhances collision frequency. The usual delta functions of existing models are thereby replaced by collisional resonant functions, and these physical quantities preserve the entropy production principle associated with wave-particle descriptions. In addition, the limitations of the collisional boundary layer treatment are also estimated and indicate that substantial departures from a Maxwellian equilibrium are not permitted.

Fundamental Plasma Theory

Over the past year, Professor Nuno Loureiro and his group focused on several aspects of nonlinear plasma dynamics with applications ranging from magnetically confined fusion to space and astrophysical plasmas. Highlights include the continuation of earlier work in collaboration with Professor Stas Boldyrev (University of Wisconsin) on the role of magnetic reconnection in strong plasma turbulence and, in work led by graduate student Muni Zhou, an investigation of the conditions for the inverse transfer of magnetic energy in magnetohydrodynamics plasmas. These efforts have led to several publications and invited talks at international conferences.

High-Performance Computing Initiatives

SciDAC Partnership for Integrated Simulation of Fusion Relevant RF Actuators

During 2019–2020, research continued under the SciDAC (Scientific Discovery Through Advanced Computing) 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 RF power with the short mean free path scrape-off layer, including the effects of large RF-induced sheath potentials, ponderomotive forces near an antenna, and turbulence and transport. MIT graduate student Christina Migliore has been working with John Wright and Mark Stowell at the Lawrence Livermore National Laboratory to develop “Stix,” a standalone electromagnetic field solver that solves for RF wave fields in the plasma edge using the scalable, open-source, modular finite element method library MFEM. 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. Graduate student Bodhi Biswas, working under the supervision of Anne White and Paul Bonoli, has used ray tracing techniques to demonstrate that coherent blob-like turbulent structures in the scrape-off layer can have significant effects on lower hybrid wave propagation and absorption via refraction.

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. The focus over the past year has been on antenna modeling. An analysis of the JET ITER antenna was performed using the finite element–based Petra-M (Physics Equation Translator for MFEM) framework, developed by Syun'ichi Shiraiwa during his time at MIT (he is now at Princeton University). A rigorous benchmarking exercise was also done with an established antenna modeling code from Torino University. This work continues in collaboration with Princeton and Torino.

As JET enters its deuterium/tritium (the fuels needed for fusion energy production) experimental phase, we are modeling possible fuel mixtures and heating scenarios to maximize performance. Over the past few months, we have begun an optimization exercise with other Euratom JET researchers, in particular physicists at the Barcelona Polytechnic University of Cataluna.

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 magnetic fusion plasma turbulence. Ernst also leads experiments on the DIIID tokamak as part of the PSFC/DIIID domestic collaboration. In addition to his theoretical and numerical work on collision operators, multiscale turbulence, and trapped electron mode turbulence, this dual role allows him to leverage large-scale gyrokinetic simulations to interpret and explain these experiments and to use the experiments to validate models and simulations. Work supported by the ongoing SciDAC MGK and the SciDAC Center for the Study of Plasma Microturbulence (with Ernst as PI), which concluded during this reporting period, is described below.

Implementation of Exact Gyrokinetic Collision Operator and Comparison with Models

During the past year, Qingjiang Pan (supported by the SciDAC Center for the Study of Plasma Microturbulence) and Darin Ernst (within the SciDAC MGK) have implemented the gyrokinetic exact linearized collision operator in a widely used gyrokinetic code (GENE) for the first time and compared it with the recent Sugama model in calculations of trapped electron modes and zonal flow damping. This work was presented as an invited talk at the 2019 APS DPP meeting and was published recently in *Physics of Plasmas*. Prior to this, gyrokinetic simulations have used approximate collision operators in which the accuracy of model linearized field-particle terms is unknown or collisional finite Larmor radius (FLR) effects are neglected. The present implementation is based on a finite-volume method recently employed to discretize the Sugama model in GENE, allowing a direct comparison between the two operators. The new exact operator makes it possible to assess the accuracy of widely used model collision operators for the first time. When compared with the Sugama model, the exact operator yields up to 20% weaker zonal flow damping at finite wave numbers. For density-gradient-driven TEMs, the Sugama model captures the linear growth rate spectrum and its reduction by collisional FLR effects as wavenumbers increase. However, when electron temperature gradient drive is included (in addition to density gradient drive) and collisionality increases, the Sugama model becomes less accurate for TEMs. The new exact gyrokinetic collision operator shows significant increases in TEM growth rates and, thus far, up to a 68% increase in electron heat flux. Furthermore, almost all of the corrections to the linear growth rates and nonlinear fluxes can be attributed to the exact field-particle terms in the collision operator without FLR effects. This leads us to propose a new model operator consisting of gyrokinetic test-particle terms with FLR effects and drift-kinetic field-particle terms without FLR effects. This form of the operator alleviates many of the computational challenges associated with the full exact operator without significantly compromising accuracy.

Reduced Model for Multiscale Turbulence Simulations as an Algorithmic Test Bed

Studying cross-scale interactions and developing more efficient ways to simulate multiscale turbulence are central efforts in the Partnership for Multiscale Gyrokinetic Turbulence. As described in last year's report, Darin Ernst and Manaure Francisquez are collaborating with the FASTMath SciDAC Institute to test multi-rate and multiscale algorithms to speed up coupled ion-electron simulations. The new 2D pseudo-spectral turbulence code developed by Francisquez facilitates this collaboration by serving as an efficient test bed for new algorithms. Over the past year, Ernst and Francisquez have formulated a new four-equation fluid model that describes simultaneous ion temperature gradient–driven and electron temperature gradient–driven turbulence in the toroidal limit. The new multiscale reduced model has Poisson bracket nonlinear terms closely resembling those in large gyrokinetic codes such as GENE and includes Bessel functions to capture finite gyro-radius effects as well as closure terms. The ability to conduct direct multiscale turbulence simulations will also allow us to assess the accuracy and speed of the new multi-rate and multiscale algorithms before implementing them in larger gyrokinetic codes.

Joint International Collaboration: Plasma Theory/Computation and Magnetic Fusion Energy Divisions

Long Pulse High Performance Scenarios and Control in EAST

Paul Bonoli serves as the MIT PI for this multi-institutional international collaboration, which involves the Plasma Theory and Computation Division and MFE and is led by General Atomics (San Diego, CA). The high-level goals of the project are to adapt high-performance scenarios from the DIII-D tokamak to the Experimental Advanced Superconducting Tokamak (EAST) in Hefei, China; to develop control physics understanding and solutions to enable this adaptation; and to pioneer reactor-specific scenario and control solutions. As part of this collaboration, Bonoli, Seung Gyou Baek, Syun'ichi Shiraiwa, and Gregory Wallace work with the Institute for Physical Sciences at the Chinese Academy of Sciences in Hefei to carry out experiments and extensive simulations of lower hybrid current drive in the EAST device. During the past year, Baek led a series of dedicated experiments on EAST that showed that lithium wall conditioning extends LH current drive and heating with the injection of both 2.45 GHz and 4.6 GHz power, up to the densities needed to access high-performance plasmas in EAST. Wallace has carried out extensive ray tracing/Fokker simulations of LHCD for the proposed China Fusion Engineering Test Reactor showing that promising current density profiles for control of the plasma can be generated by coupling LH waves from the high field side of the reactor. Baek has also worked on the development of a reduced model for LH wave scattering from edge turbulence that will be used to construct a control level algorithm for LHCD that can be used in time-dependent transport simulations. Finally, Baek and Wallace have worked closely with graduate student Yunfei Wang at EAST on the interpretation of RF probe results for the detection of LH waves in EAST. Research in the RF area of this collaboration has resulted in publications in major journals and an invited talk at the 23rd Topical Conference on Radiofrequency Power in Plasmas. In November 2019, three team members working in the RF area traveled to Hefei. Due to the Covid-19 pandemic, no new trips are currently planned for the near future.

High-Energy-Density Physics Division

The High-Energy-Density Physics Division is in its second year as a DOE-designated Center of Excellence (CoE) for research in inertial-confinement fusion (ICF), laboratory astrophysics, and basic plasma properties and for development of new plasma diagnostic and analysis methods. Within the center, MIT's scientists are joined by scientists and academics from four outside partner institutions (University of Rochester; University of Iowa; University of Nevada, Reno; and Virginia Tech) for collaboration in research, recruitment, and education of the best students and young scientists for the future of plasma physics. This year, scientists and students performed plasma physics experiments at the National Ignition Facility, the Lawrence Livermore National Laboratory, the OMEGA Laser Facility at the University of Rochester Laboratory for Laser Energetics, and the Sandia National Laboratory. Students (PhD and undergraduate) and postdoctoral researchers play major roles in all of the center's research.

The CoE research projects go hand in hand with the center's development of plasma diagnostics, with major contributions by the students. Almost all of the MIT-designed diagnostics are tested and calibrated in the division's linear accelerator laboratory, which is used as a source of charged particles and neutrons. This accelerator was completely designed and constructed by several generations of PhD students, and current students update and run the accelerator for their diagnostic development work. Many of the MIT-developed diagnostics utilize CR-39 solid-state detectors, which record information about charged particles and neutrons and are used in spectrometers and imaging devices. Since these diagnostics are used at the Lawrence Livermore National Laboratory, the Laboratory for Laser Energetics, and the Sandia National Laboratory in addition to MIT, special lab facilities have been designed by MIT and installed at all four facilities for chemical treatment of CR-39 and for computer-controlled readouts and storage of CR-39 data on the positions and energies of charged particles.

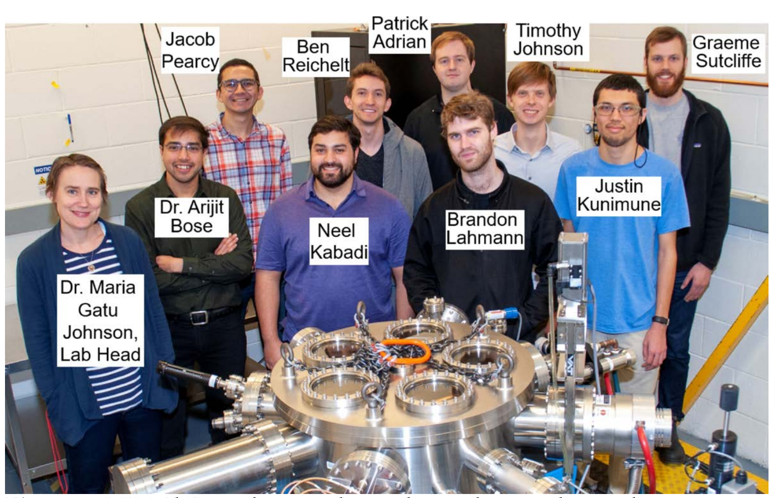

Figure 8. MIT PhD students and postdoctoral researcher at the target chamber of the division's linear accelerator with MIT scientist Maria Gatu Johnson, who directs activities at the accelerator.

One of the important diagnostic methods employing CR-39 is charged-particle radiography, which is used for imaging the spatial structure of electromagnetic fields in and around various laser-generated plasmas. During the past year, student Graeme Sutcliffe has been developing and optimizing a special new configuration of our radiography system that uses monoenergetic charged particles of three different types to simultaneously record three different kinds of images (Figure 9). Sutcliffe is radiographing ICF experiments with fuel capsules directly driven by lasers (at OMEGA) and indirectly driven by lasers that heat up the inside surfaces of a gold cylinder(“hohlraum”), generating X-rays that drive the fuel capsule (at the National Ignition Facility). Charged-particle radiography is also being used in laboratory astrophysics experiments involving magnetic reconnection, instabilities, plasma jets, plasma shocks, and other phenomena in laser-driven plasmas designed by Chikang Li (see Figure 10 for an example of collisionless shocks). Student Timothy Johnson is in the process of designing related experiments, and another student, Jacob Pearcy, has developed an important new tool for many of these studies: a procedure for using charged-particle radiographs to reconstruct the distribution of the electric and magnet fields present in many laser-generated plasmas. These methods have been so successful that MIT, as part of the mandate of the CoE, supports a wide selection of research with radiography at different universities and national labs. A list of experiments supported by MIT during calendar years 2019 and 2020 is shown in Table 1. Many experiments were completed in spite of the fact that the COVID-19 pandemic this year resulted in prolonged delays during which no experiments could be done.

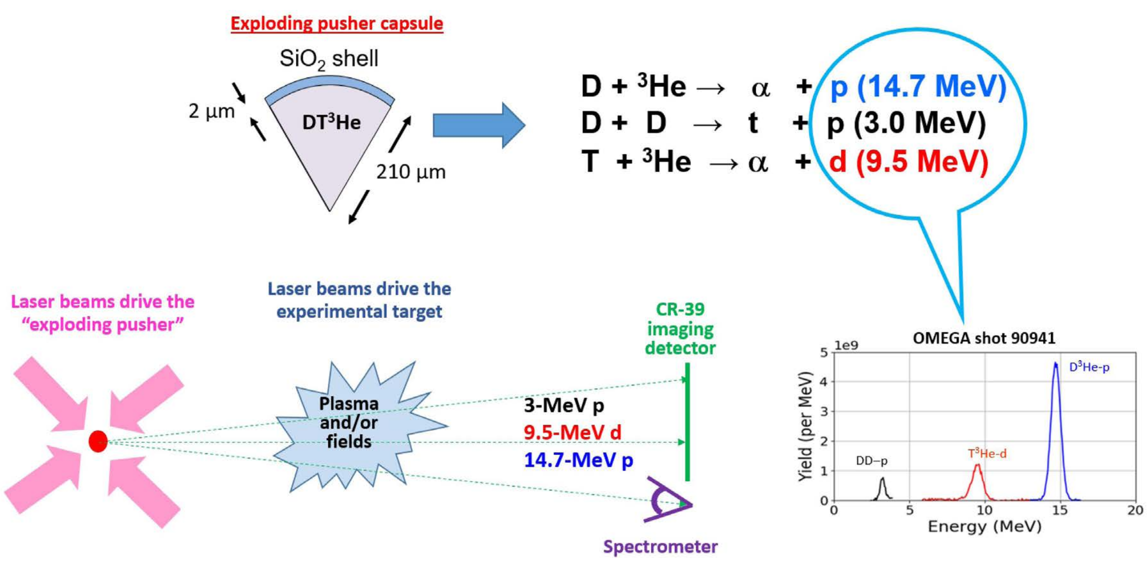

Figure 9. Illustration of the setup for “tri-particle” radiographs of a laser-driven plasma experiment. The 9.5 MeV deuteron, coming from the new addition of tritium to the backlighter fuel, is more penetrating and easier to detect than the 3 MeV proton. Some experiments can use only one of the particles of the D^3He backlighter because of the disparate scales on which the particles deflect; these experiments are improved by the intermediate electric-field and stopping/scattering scaling of the T^3He deuterons.

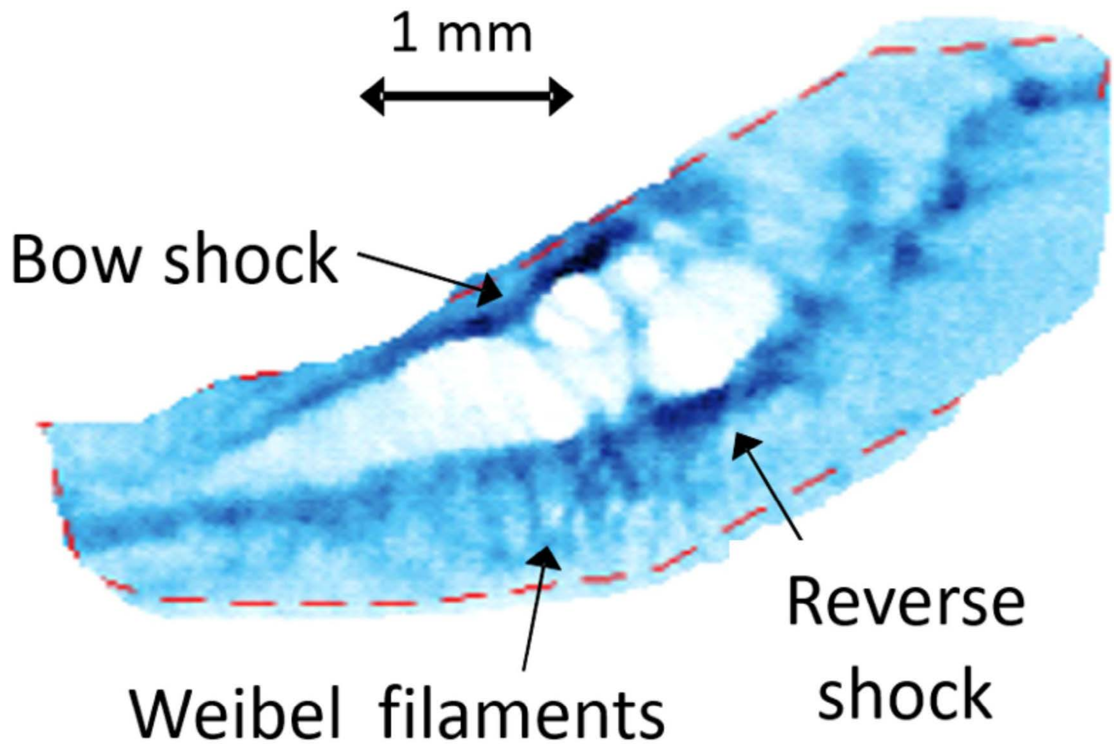

Figure 10. A radiograph made with D^3He fusion protons (14.7 MeV) showing that the interaction of two counter-streaming plasma flows generates a bow shock and a reverse shock along with Weibel instabilities.

Plasma Science and Technology Division

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 800 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 2019–2020, we completed a series of tests of the effect of reflections of power back into the gyrotron on gyrotron operation. Reflectivity values up to 40% were studied. The results showed a new state of operation of the gyrotron in which the gyrotron spontaneously pulsed on and off at a 30 MHz repetition rate. This may be useful for applications. Interpretation of these results presents a challenge to present-day gyrotron theory. In collaboration with the accelerator research group at the SLAC National Accelerator Laboratory, we have studied high gradient acceleration and breakdown in copper accelerator structures built at the laboratory. Very high surface electric field strengths, up to 500 MV/m, have been seen in testing with nanosecond pulses from the megawatt gyrotron at 110 GHz. 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. The gyrotron was successfully installed at the 800 MHz NMR spectrometer with a low-loss eight-meter transmission line.

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 2019–2020, we completed our demonstration of 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 the fabrication and begun the testing of a backward wave oscillator operating at a frequency of 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. The long-term emphasis has been on research conducted using the Haimson Research Corporation/MIT 25 MeV, 17 GHz electron accelerator. In 2019–2020, after more than 25 years of operation, the accelerator was shut down and placed in storage to allow additional space for another major experiment. The focus of our program has now shifted to research conducted in our gyrotron lab in collaboration with SLAC (as noted above) and research conducted at the Argonne National Laboratory (ANL). Our research with ANL uses their unique wakefield accelerator facility, which provides a train of electron bunches of high charge at an energy level of 65 MeV. In earlier tests, up to 80 MW of power at 11.4 GHz was generated in 2-ns pulses. In tests during 2019–2020, a power level of 380 MW was produced in a 10-ns pulse. These results are very promising for the design of future electron-positron linear colliders.

Magnetic Resonance Division

Robert G. Griffin (Professor of Chemistry)

The Griffin group is working to determine the structures of amyloid fibrils of Aβ1-42, the toxic species in Alzheimer’s disease. About two years ago we published the initial atomic resolution structure of Aβ1-42, which had been unknown since the discovery of the disease approximately 110 years ago. This is accepted as the “thermodynamically stable” structure, and we are now working on structures seeded with fibrils from Alzheimer’s patients.

We are also determining the structure of ΔN6-β2m, the fibrils associated with dialysis-related amyloidosis, a disease that occurs when kidney dialysis fails and fibrils began to accumulate in patients.

A third area of research is focused on the development of new methods for performing nuclear magnetic resonance. In particular, we are developing methods using high-frequency microwave radiation (150–600 GHz) to transfer high-electron polarization in stable paramagnets to nuclear spins. This allows us to enhance sensitivity in NMR experiments by two to three orders of magnitude.

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 areas of focus include virus membrane proteins, amyloid proteins, and plant cell walls. In 2019–2020, the Hong group made three important scientific discoveries.

Influenza B Virus M2 Protein Structure

We determined the first atomic-resolution structures of the influenza B virus M2 (BM2) proton channel in its closed and open states (Figure 11). Prior to this study, to our knowledge, the best comparative channel structures were solved by cryo–electron microscopy at 3.5 Å resolution. The solid-state NMR structures of BM2 revealed that BM2 activates at low pH through a scissor-like motion that differs from the transporter-type motion of the related influenza AM2 protein. These closed and open structures should stimulate drug designs to inhibit influenza B infections, which have become more dominant in recent flu seasons.

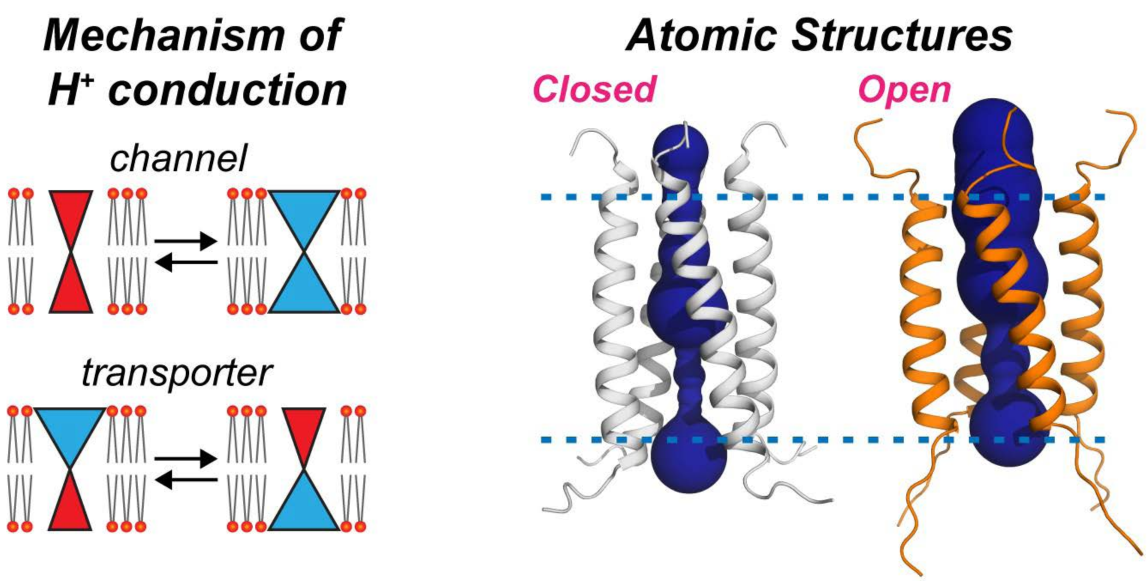

Figure 11. Illustration of the Mechanism of H+ conduction of channel and transporter (left) and illustration of the Atomic Structure in the closed and open states (right).

HIV Viral Fusion Protein

We conducted two studies to understand the structure and lipid interactions of gp41, the HIV-1 virus fusion protein, which merges the lipid membranes of the virus and cell to allow virus entry. In one study, we investigated how the two hydrophobic termini of gp41 associate with each other in lipid membranes. The results showed that the N-terminal fusion peptide domain has sparse sub-nanometer contacts with the C-terminal domain, implying that the protein forms a hemifusion-like intermediate. In a second study, we investigated whether cholesterol binds the C-terminal portion of gp41 to address the question of whether the protein uses cholesterol to facilitate membrane curvature induction. Using ^{19}F NMR and molecular dynamics simulations, we showed that the trimeric protein binds three cholesterol molecules in close proximity (within a nanometer), and binding depends not on a putative cholesterol-binding sequence motif but on the helix-turn-helix fold of the protein. This result suggests that gp41 can be recruited to the boundary of cholesterol-rich and cholesterol-poor regions of the lipid bilayer to incur membrane curvature.

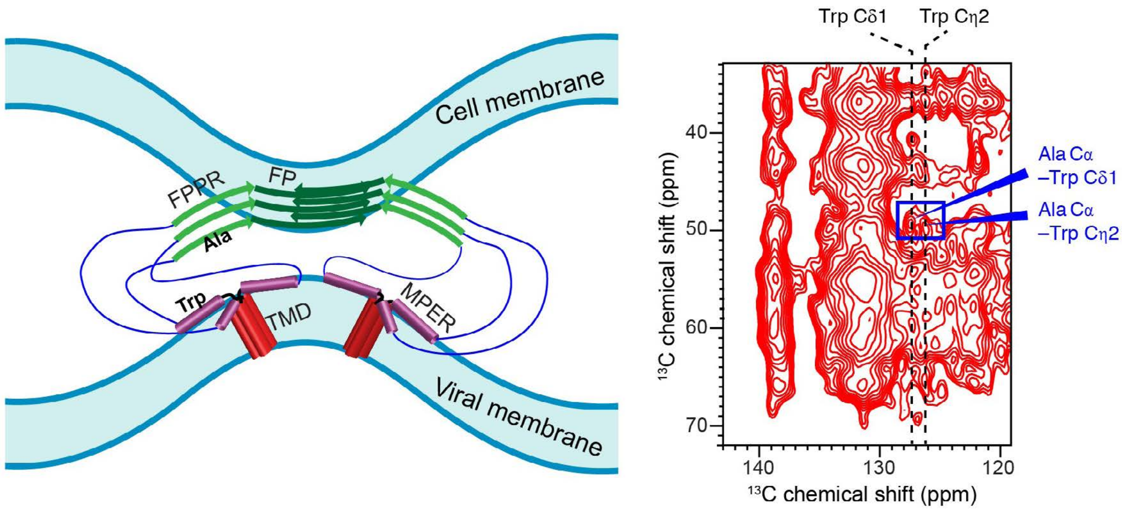

Figure 12. Illustration of membrane curvature as a result of interactions between gp41 and the HIV-1 virus fusion protein.

Amyloid Tau Protein

We investigated the hydration of the amyloid fibrils formed by the tau protein. Using water-edited solid-state NMR experiments, we measured the water accessibilities of β-sheet residues. The data revealed that most of the β-sheet core is poorly hydrated, thus it is surrounded by the dynamic, fuzzy coat domains of the protein. However, two serine residues, S285 and S316, showed enhanced hydration, suggesting that there is a small water channel inside the β-hairpin formed by the second and third microtubule-binding domains of the protein. These results suggest potential sites for inhibitor binding to disassemble these amyloid fibrils to slow disease progression, in addition to offering fundamental insight into the three-dimensional fold of this dynamically heterogeneous protein.

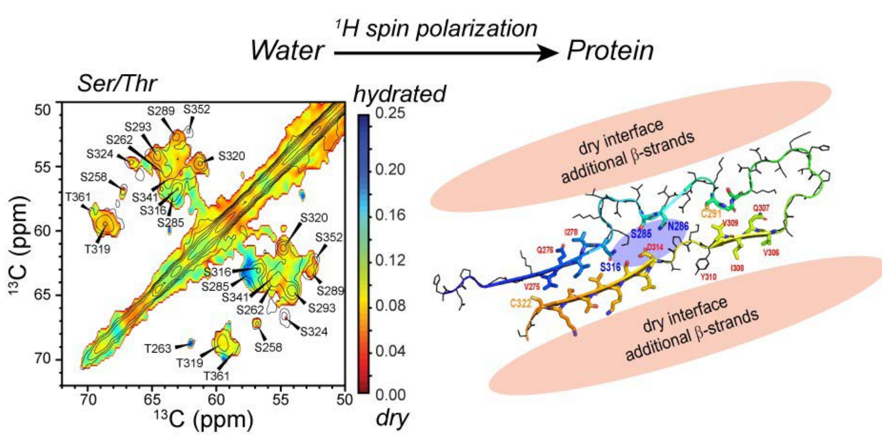

Figure 13. Illustration of ^{1}H spin polarization from water to protein.

Yukikazu Iwasa (Senior Research Scientist)

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 whom 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 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 liquid-helium-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)

The Moodera group's biggest breakthrough during the past year was the discovery that Majorana bound states pair in solid state. This is something that has been sought for over many decades and by top groups in the world. The implication of this breakthrough is that it has the potential to lead to topological qubits that could form the backbone of quantum computers. A patent application has been submitted based on this work, which has already appeared in more than a dozen websites all over the world. This might lead to a bigger NSF program on quantum networking with the potential for a start-up company.

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 can be expected to have a transformational influence on data storage and communication. Thus, in research on nanoscience condensed matter physics, the group continues to make significant contributions in both fundamental and applied sciences.

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 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.

Moodera's group and his collaborators published several articles in journals such as *Physical Review Letters*, the *Proceedings of the National Academy of Sciences*, *Nature Materials*, *Physical Review*, and the *Journal of Applied Physics.* Research results have been disseminated at international conferences. Moodera is a member of the organizing committees of international scientific workshops, and he delivered invited talks at universities and international conferences in Germany, Spain, the United Kingdom, and India.

Geothermal Energy

High-power millimeter-wave (MMW) gyrotrons, originally developed for fusion energy research, are being applied to advance the art of deep drilling to enable increased accessibility to geothermal energy. Current mechanical drilling technology is severely limited by high temperatures, rock hardness, and slow rates of penetration to reach deep heat in crystalline basement rock. Directed energy drilling converts drilling from the current mechanical grinding process to an energy-to-material interaction that overcomes these limitations. MMW gyrotrons are ideally suited in terms of the physics and available technology for this application. The feasibility of MMW drilling has been established in the laboratory in past years under the leadership of Paul Woskov.

About midway through FY2020, budget negotiations were finally completed and the ARPA-E (Advanced Research Projects Agency–Energy) contract and subcontract to MIT were awarded. The partners in the project are AltaRock Energy Inc., Geoffrey Garrison (PI); Quasie Inc., a company primarily created by AltaRock to lead the development of the program and raise more funding; MIT (with Paul Woskov at the Plasma Science and Fusion Center and Professor Herbert Einstein at the MIT Rock Mechanics Laboratory); Ken Oglesby of Impact Technologies LLC; and Tim Bigelow at the Oak Ridge National Laboratory (ORNL). The replacement of the Air Force Research Laboratory (AFRL) by ORNL this past year was necessitated by problems with the gyrotron system at AFRL that could take over a year to fix. The goals of the planed three-year effort are the same as before: 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 one of ORNL's 100+ kW continuous wave gyrotrons. In the second half of this past year, progress was made in transitioning plans from the original 95 GHz AFRL gyrotron to the 28 GHz ORNL gyrotron.

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 Nuno Loureiro assumed responsibility for overseeing the DOE Office of Fusion Energy Sciences grant that funds a portion of the program. He replaced Anne White, whose duties as the new head of the Department of Nuclear Science and Engineering have focused her energies in other areas. The grant, scheduled through September 2020, has been renewed for a three-year period.

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. Tours of our facilities are also available for the general public.

Concern about the outbreak of Covid-19 curtailed outreach activities at the PSFC as early as February. With in-person tours and outreach eliminated for the near future, the PSFC is evaluating ways to reach K–12 students virtually as well as through one-on-one mentoring programs.

Outreach days are held twice a year, encouraging high school and middle school students from around Massachusetts to visit the PSFC for hands-on demonstrations and tours. PSFC graduate students who volunteer to assist are key to the success of our tour programs. The experience helps them develop the skill of communicating complex scientific principles to those who do not have advanced science backgrounds. While the fall program for high school students was able to take place as planned, the spring event for middle schoolers had to be canceled, along with all other spring education activities, due to health concerns.

This year the PSFC offered 26 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 visited the center, along with Cambridge Science Festival participants. Overall, the PSFC hosted 575 people on site. Because we were not able to provide tours during the spring, typically our busiest time, we hosted approximately half our normal number of visitors. Among our tours, we were pleased to be able to offer a full day of outreach to the Minority Introduction to Engineering and Science Program group in summer 2019, beginning with a morning talk with Anne White about fusion and the exciting potential of this field of research and concluding with an afternoon of magnet demonstrations and facility tours.

The PSFC hosted the first Computational Physics School for Fusion Research in August 2019. Traditional physics classes do not often focus on teaching the computational tools that can help young scientists speed their research. The PSFC hopes to fill this knowledge gap. Sponsored by the Department of Energy Office of Science, the summer school program provided instruction in such topics as high-performance computing, parallel programming, computational statistics, and machine learning. The instructors were a selected pool of experts from MIT, General Atomics, Intel, Julia Computing, the Lawrence Berkeley National Laboratory, the University of Texas, New York University, and IBM. The course attracted graduate students and postdocs from many institutions across the United States as well as some from Australia, Germany, Norway, Brazil, and the United Kingdom. The school's organizing committee consisted of Paul Bonoli, Christina Rea (research scientist), Francesco Sciortino (graduate student), Jessica Coco (administrator), and Paul Rivenberg.

The PSFC continued its educational collaboration with the MIT Energy Club, bringing a variety of interactive plasma demonstrations to MIT Energy Night in October. This event, held on Family Weekend, was attended by hundreds of MIT students and their families. This year members of Commonwealth Fusion Systems joined PSFC staff and graduate students to explain the latest directions in MIT fusion 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) is a tradition at each year's APS DPP meeting. Paul Rivenberg continues to organize the Plasma Sciences Expo. In fall 2019 in Fort Lauderdale, FL, 28 exhibitors representing laboratories and schools across the US 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

Senior Research Scientist John Rice oversees the PSFC seminar series. These are weekly plasma science talks aimed at the MIT community. Graduate students also hold their own weekly seminar series where they take turns presenting their latest research in a relaxed environment. In March, the series had to be canceled and none of the speakers were able to arrange to give their seminar virtually.

During MIT's Independent Activities Period, the PSFC focused on introducing and promoting the makerspace available in Building NW21. Research Engineer William Burke offered a participatory course titled Build Your Own Fusor. The course, spread over three weeks, attracted 25 students. Paul Rivenberg attended the class to see if it might become the basis for a special outreach event for high school students. In addition, Rivenberg, who has received training in administering online classes related to an NSE course on nuclear energy, was able to assist in editing and maintaining edX content for spring 2020.

USA Science and Engineering Festival (USASEF): The PSFC had anticipated participating in the USA Science and Engineering Festival (USASEF) in spring 2020 before it was canceled due to health concerns. The event, which is typically held every other year, is expected to be scheduled next for some time in 2021. In the meantime, USASEF is creating a virtual event to be held in mid-September 2020. Paul Rivenberg will oversee the creation of a virtual MIT booth about plasma and fusion science.

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.

In spring 2020, the PSFC began discussions with the MIT Museum regarding the creation of an exhibit about the history of fusion research at MIT, to be available when the museum opens at its new site in Kendall Square.

Honors and Awards

Pablo Rodriquez Fernandez (PhD '19) received the Del Favero Thesis Prize, awarded annually to a PhD graduate in nuclear science and engineering whose thesis is judged to have made the most innovative contribution to the field.

Research Scientist Maria Gatu Johnson, who plays a key role in inertial confinement fusion and discovery science campaigns at the National Ignition Facility, was presented the Katherine E. Weimer Award, which recognizes outstanding plasma science research by a woman physicist in the early stages of her career.

Research scientist Nathan Howard won the 2019 Nuclear Fusion Award for a paper explaining heat losses due to turbulence in the core of magnetically confined fusion plasmas.

Anne White was named an American Physical Society Fellow for 2019. Nominated by the APS Division of Plasma Physics, White was cited for her "outstanding contributions and leadership in understanding turbulent electron heat transport in magnetically confined fusion plasmas via diagnostic development, novel experimentation, and validation of nonlinear gyrokinetic codes."

Appointments

- PSFC headquarters: David Parker was appointed administrative officer.
- Magnetic Fusion Experiments Division: Alexander Tinguely, Owais Waseem, Adam Kuang, David Fischer, Ethan Peterson, and Michael Wigram were appointed postdoctoral associates; Darren Garnier was appointed research scientist; William Baumgartner was appointed RF engineer; Mohamad Mohamed was appointed RF engineering specialist; Amelia Watterson was appointed mechanical engineer; Dhananjay Kandadai Ravikumar was appointed cryogenic research engineer; Ivan Garcia was appointed electrical systems specialist; and Nouf AlMousa was appointed postdoctoral fellow.

- Plasma Theory and Computation Division: Severin Denk was appointed postdoctoral associate and Soren Hansen was appointed postdoctoral fellow.
- Plasma Science and Technology Division: Jeremy Genoud was appointed postdoctoral associate and Paul Woskov was appointed research scientist.

Promotions

Andrew Pfeiffer was promoted to operation coordinator; Jerry Hughes was promoted to deputy head, MFE off-campus collaborations; Samuel Pierson was promoted to West Cell engineering coordinator; and Ryan Sweeney was promoted to research scientist.

In the Plasma Science and Technology Division, Guy Rosenzweig was promoted to research scientist.

Graduate Degrees

- Nuclear Science and Engineering: Alexander Sandberg, MS; Norman Cao, PhD
- Chemistry: Chloe Anne Morgan, MS; Matthew Elkins, PhD; Pyae Phyo, PhD

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