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 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, which includes nuclear magnetic resonance (NMR), electron paramagnetic resonance (EPR), and magnetic resonance imaging (MRI); NMR and MRI magnet development; and nanoscience condensed matter physics (quantum coherent behavior charge and spin transport).

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.

There are approximately 250 personnel associated with PSFC research activities. These include: 25 affiliated faculty and senior academic staff; 54 graduate students, with participating faculty and students from Departments of Aeronautics and Astronautics, Chemistry, Mechanical Engineering, Nuclear Science and Engineering (NSE), and Physics; 85 research scientists, engineers, postdoctoral associates/fellows and technical staff; 44 visiting scientists, engineers, and research affiliates; 18 technical support personnel (technicians, designers); and 24 administrative and support staff.

Center wide, funding has grown to over $40 million. This past year was the third year of funding for the private industry funded Soonest/Smallest Privately Funded Affordable Robust Compact (SPARC) program. With the cessation of the US Department of Energy (DOE)-supported Alcator program in 2017, industry support is now the single largest portion of PSFC support, at 47%. DOE's Office of Fusion Energy Sciences (OFES) account for about 28% of the total, other DOE offices account for 10%, and National Institute of Health (NIH) accounts for about 11%.

Magnetic Fusion Experiments Division

The Magnetic Fusion Experiments (MFE) division at the PSFC, created in 2016, 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. Earl Marmar, a senior research scientist in the MIT Department of Physics and PSFC, is the division head. Unique among the divisions at PSFC, the MFE division has two subdivisions which report to Marmar: Collaborations and the SPARC project. For 2020–2021, the Collaborations subdivision is led by Jerry Hughes, who coordinates elements of multiple off-campus collaborations with large tokamak and stellarator facilities around the world. Collaborations are critical to maintaining scientific and educational excellence in magnetic fusion experiments at the PSFC. The SPARC project subdivision is led by Zach Hartwig, assistant professor of NSE, and its work focuses on: a) research on, and development of, advanced superconducting magnets for application to burning plasma experiments and fusion pilot plant designs; b) design, and ultimately construction, of a new high-field tokamak, aimed at being the world's first net energy magnetic confinement fusion facility. The collaborations research is primarily funded through a combination of a five-year cooperative agreement and multiple smaller grants with the DOE, Office of Science, Fusion Energy Sciences. Funding for the cooperative agreement runs through August 31, 2021. A renewal proposal, to continue and extend the research under the agreement through 2026, was submitted in the spring of 2021, was successfully reviewed, and has been approved for funding beginning in September 2021. The SPARC research at MIT is mainly funded by a private company, Commonwealth Fusion Systems, through the MIT Energy Initiative.

Magnetic Fusion Experiments Division, Off-campus Collaborations Subdivision

Research in the Collaborations subdivision during the past year has focused on exploring the foundational science behind high-performance plasma confinement. This research exploits groundbreaking experimental work at off-campus facilities including DIII-D, W7-X, ASDEX Upgrade, EAST, KSTAR, JET, NSTX-U and WEST. Many of the experiments are in direct support of urgent ITER research needs, and contribute to a broader physics basis for burning plasma experiments including SPARC. Most of these efforts directly support the PhD research of graduate students in multiple MIT academic departments.

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, with first commissioning expected in 2023. The guiding physics criterion is to drive off axis current drive, r/a~0.6-0.8, with peak current density approaching 0.4 MA/m^2 in advanced tokamak discharges. The HFS launch position was selected to improve wave penetration, allow for single pass absorption and off-axis deposition. The HFS-LHCD project moved fully into the fabrication stage following final design reviews for in-vessel components and instrumentation required for system operation. Fabrication of in-vessel components was undertaken, using a significant amount of additive manufacturing with a novel copper alloy, GRCop-84. Examples are shown in the figure below. A second phase of fabrication needed to improve the surface finish of the 3D printed parts. It underwent a round of optimization and ultimately proved successful. The majority of system sub-components have been fabricated and await welding into larger modules. In-vessel installation of HFS-LHCD waveguide and launcher has been deferred to 2022. Ex-vessel work is proceeding now, with low power and interlock testing of the RF system planned for the fall of 2021.

3D printed waveguide structures for the Lower Hybrid system.

Disruption Science and Machine Learning Activities

The Plasma Science and Fusion Center continues to play a leadership role in Disruption Science and Prediction by adopting state-of-the-art Machine Learning (ML) methodologies and crafting new applications. In academic year 2021 (AY2021), the Disruption Prediction via Random Forest algorithm was successfully installed on the real-time Plasma Control Systems of the DIII-D tokamak, hosted by General Atomics, and of the EAST superconducting tokamak in China. Successful experiments were conducted on both devices to mitigate and avoid the occurrence of disruptive events during routine plasma operations. Our team continues to develop ML algorithms using historical experimental data from multiple tokamaks to design a successful strategy to predict disruptions from scratch on new experimental devices, such as ITER and SPARC.

Edge Neutral Measurements on DIII-D

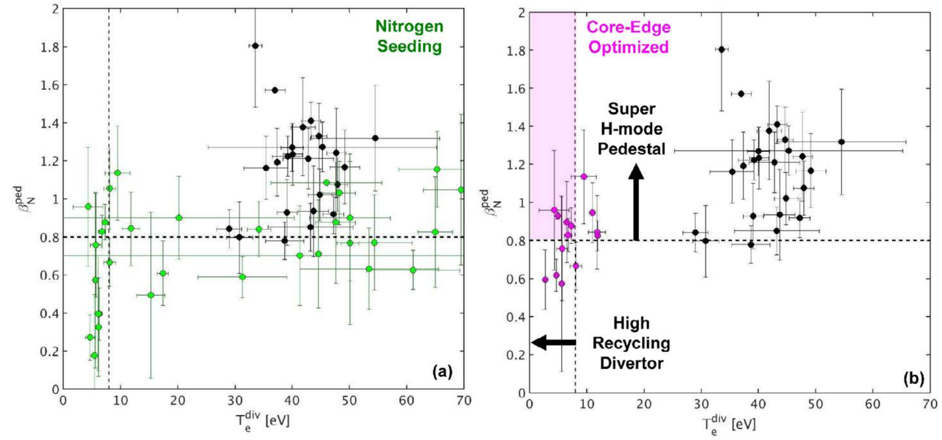
MIT PhD student Aaron Rosenthal continued his research into the edge fueling of plasmas on the DIII-D tokamak, executing experiments on DIII-D that take advantage of the LLAMA diagnostic, which measures radial profiles of Lyman alpha (121nm) brightness in the tokamak edge, both inboard and outboard. Rosenthal described this innovative diagnostic in an invited talk at the High Temperature Plasma Diagnostics conference in December 2020 and in a subsequent paper in *Review of Scientific Instruments*. The diagnostic is now providing measurements on request to DIII-D experimentalists, and Rosenthal has completed his own experimental sessions intended to quantify particle sources and transport coefficients in the tokamak boundary. The development and operation of LLAMA are done in partnership with Princeton Plasma Physic Laboratory.

Super H-Mode Studies on DIII-D

An optimized pedestal regime called the Super-H Mode (SH-mode) is being developed and leveraged to couple a fusion relevant core plasma with a high density scrape-off layer appropriate for realistic reactor power exhaust solutions. DIII-D experiments led by MIT have expanded understanding and the operating space of the SH regime using advanced control algorithms. Simultaneous real-time control of the pedestal density and radiated power with in-vessel coils and nitrogen seeding enable coupled high performance divertor and pedestal conditions. Several scenarios for optimization of core, pedestal, and divertor performance are being pursued with emphasis on leveraging physics that is relevant in future devices. Theresa Wilks presented these new findings in a talk at the International Atomic Energy Agency (IAEA) Fusion Energy Conference in May 2021.

Development of Edge Localized Modes-Suppressed Scenarios

The large heat pulses from Edge Localized Modes (ELMs) could damage future tokamaks. We are developing high-performance regimes that are naturally ELM-suppressed, extending operation toward ITER and SPARC-like parameters. An invited talk at the 2020 American Physical Society (APS) Division of Plasma Physics Annual Meeting entitled, “Favorable Core and Pedestal Transport Properties of the Wide Pedestal QH-Mode Regime” by Darin Ernst detailed recent progress. In further DIII-D experiments by Ernst et al., (1) real time injection of boron, lithium, and nitrogen greatly reduced problematic carbon content in this regime, and (2) profile-matched hydrogen and deuterium ELMy H-Mode plasmas were used to determine the isotope effect on intrinsic rotation.



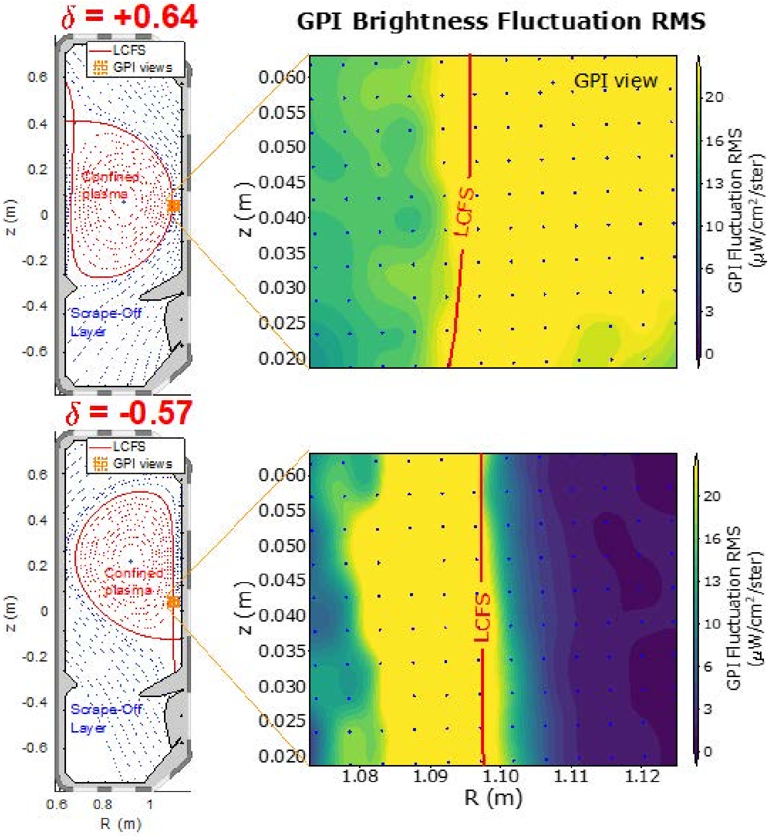
Normalized beta in the pedestal versus electron temperature in the divertor for Super H-mode plasmas with no seeding (black) compared to: a) the full dataset with nitrogen seeding (green); and b) a subset of the seeding data points representing maximized core-edge integration (pink).

Particle Transport Studies

Significant progress has been made by the MIT team working on impurity transport research on DIII-D. Utilizing a large database of carbon profiles from DIII-D, the peaking of low-Z impurities was measured and compared with simulation in a wide range of ELMy H-mode plasmas. These results, a key element of the PhD thesis of MIT graduate student Francesco Sciortino, reveal a negligible role of roto-diffusion and demonstrate a systematic discrepancy between simulation and experiment in Ion Teperature Gradient (ITG)-dominated plasmas. The new impurity transport code, AURORA was used to infer the impurity transport from laser blow-off (LBO) injected impurities in negative triangularity plasmas. The inferred transport was found to be in reasonably good agreement with combined neoclassical and gyro-fluid modeling over much of the plasma radius. Analysis of a wide range of impurities that were injected via LBO as part of a recent US DOE Joint Research Target is in progress. Extensive gyrokinetic modeling has been performed revealing a clear scaling of impurity diffusion with impurity charge. This scaling will be compared with experimentally inferred values in future work.

Studies of Edge Turbulence on Tokama à Configuration Variable

Core plasma shapes with negative triangularity exhibit a substantial increase in energy confinement compared to plasmas with positive triangularity. Negative triangularity plasma shapes also show reductions in the fluctuation levels of the core electron temperature and density. This by itself makes negative triangularity plasmas promising candidates for a future fusion power reactor. Gas puff imaging studies on Tokama à Configuration Variable, led by MIT graduate student Harry Han, show that the sign and degree of triangularity also have a large effect on plasma edge dynamics and power and particle exhaust properties. These experiments revealed a strong reduction of boundary-plasma fluctuations and plasma interaction with the facing wall for sufficiently negative triangularity values. The effects are observed across a wide range of densities in both inner-wall-limited and diverted plasmas. This strong reduction in plasma-wall interaction at sufficiently negative triangularity strengthens the prospects of negative triangularity plasmas as a potential reactor solution.



Poloidal cross sections of the flux surfaces of plasmas on the Tokama à Configuration Variable with positive (top) and negative (bottom) triangularities and the corresponding fluctuation levels in the boundary of the plasma.

The "donut-hole" of the full donut shape is to the left of both cross-sections. The nominal "edge" of the plasma is shown by the red line.

Zachary Hartwig

Professor Hartwig leads multiple efforts in NSE and at PSFC, where he holds a co-appointment. These efforts are principally focused on accelerating the deployment of commercial fusion energy through the advancement of fusion science, engineering, and technology.

Hartwig's principal role during this period has been as the principal investigator (PI) and project head of the SPARC Toroidal Field Model Coil (TFMC) Project. The TFMC project is a 2-year collaborative effort between PSFC and Commonwealth Fusion Systems (CFS), a private company spun out from MIT to focus on fusion energy commercialization. The primary objective of the TFMC project is to design, build, and test the world's highest performance, large-scale superconducting magnet as well as to develop and construct the technology and test facility required to properly test the magnet. If successful, the TFMC will provide a full-scale demonstration of the MIT-CFS high-field magnet technology, opening a pathway to a high-field fusion device called SPARC that seeks energy break even in the mid-2020's as well as application of the magnet technology in other areas of research and industry. At the time of this writing, the TFMC Test Facility has been successfully constructed and commissioned at full performance and the TFMC has been completed and is ready for installation within the test facility. The initial full performance tests are expected to take place in August 2021, when the TFMC will be cooled and energized to attain over 20 T peak magnetic field-on-coil.

Hartwig has also been the PI on several fusion science and engineering research projects in addition to his work on the TFMC Project:

- The development and initial validation of a new experimental technique called Intermediate Energy Proton Irradiation (IEPI) with PhD student Steve Jepeal, who successfully defended his PhD in May 2021. The techniques uses proton beams in the 10–30 MeV range (roughly a factor of 3–10x higher than present techniques) to achieve uniform radiation damage in bulk material specimens suitable for macroscopic engineering testing, which enables the direct extraction of material property evolution as a function of radiation damage Additional advantages of the technique include much higher fidelity in terms of the material response to a fusion energy relevant neutron spectrum, high radiation damage rates (up to approximately 5 displacement per atom per day), transmutation of elements to emulate hydrogen and helium gas accumulation or radiation induced precipitates, and lower activation of the material compared to traditionally radiation techniques.

- The exploration of the effect of magnetic fields on heat transfer in molten salts with PhD student Caroline Sorensen, who successfully defended her PhD in May 2021. Molten salts are proposed as an attractive liquid material for use in fusion blankets, a component that must convent neutron kinetic energy into heat, breed tritium through nuclear reactions induced by neutrons, and shield the rest of the device from the neutron and gamma flux coming from the fusion core; however, as a conductive material, molten salt's material properties and thermal hydraulic performance will be impacted by operation within magnetic fields, particularly the high magnetic fields of >20 tesla found in fusion devices. Characterization of heat transfer suppression was made in magnetic fields up to 2 tesla, providing significant physical insight and model validation. The next step experiment will increase the magnetic field magnitude.

Fast Particle Wave Interaction an Alfvèn Eigenmodes in the JET Tokamak Plasma

Research personel included Miklos Porkolab, PI, and Alex Tinguely, postdoctoral associate and staff.

The Alfven Eigenmode Active Diagnostic (AEAD) on the Joint European Torus (JET) is a collaboration among the MIT PSFC, the Swiss Plasma Center, and the Culham Centre for Fusion Energy, and the EUROfusion organization. Over the past year, our team mostly operated the AEAD remotely because of COVID restrictions. The JET Deuterium campaign resumed in July 2020, Hydrogen campaign in October 2020, and Tritium campaign in January 2021. During hundreds of JET plasma discharges, the AEAD actively resonated with thousands of stable Alfven Eigenmodes (AEs), a type of magnetohydrodynamic wave. A database of measured resonant frequencies, net damping rates, and mode structures was assembled [RA Tinguely, M. Porkolab, *et al*. 2020 *Plasma Physics and Controlled Fusion*] from which various drive/damping mechanisms were assessed. Of particular interest will be to assess alpha particle drive during the upcoming JET Deuterium campaign (fall 2021). A dedicated study of plasma-AEAD coupling was performed to optimize AEAD operation in future experiments [RA Tinguely, *et al*. 2021 *Nuclear Fusion* 61 026003]. Other novel measurements include simultaneous unstable and stable AEs, an edge-localized Ellipticity-induced AE [IAEA Fusion Energy Conference 2021], and H-D-T isotope effects on damping [EPS Conference on Plasma Physics 2021].

Phase Contrast Imaging for Multiscale Measurements of Turbulence and Helicon Waves in DIII–D (Measurement of Helicons and Parametric Decay Waves in DIII-D with Phase Contrast Imaging)

Research personel include Miklos Porkolab, PI; Chris Rost and Alessandro Marinoni, research staff; and Severin Denk, postdoctoral associate.

The Phase Contrast Imaging (PCI) program at DIII-D focused on continuing the development of a novel technique to allow imaging the perturbation in plasma density resulting from instabilities as well as radio frequency (RF) waves across the range of 5 to 500 MHz by modulation of the laser beam using Electro Optical modulators (EOM) and optical mixing. A report covering the previous three-year grant period of this project was recently published. In the first stage of the new three-year grant period, a tunable frequency EOM covering 10 to 50 MHz, to be used to study Ion Cyclotron Emission (ICE), is undergoing refinement to ensure proper low-noise performance prior to installation on DIII-D. Meanwhile, a high frequency EOM driver at 475 MHz has been designed with goal of measuring the waves launched by the new Helicon RF heating system that has been recently installed on DIII-D. Measurement of the Helicon waves in the plasma core is necessary to understand the efficiency of coupling and propagation of the waves in the plasma with the aim of efficient current drive.

Modeling of the Helicon wave in 3D with the hot plasma, full wave code All-ORders Spectral Algorithm (AORSA) and a synthetic PCI diagnostic are being used to assess the efficiency of wave coupling with the antenna. In benchmarking tests, a cold plasma finite element model accurately predicted the expected electric field amplitudes at reduced computational cost while confirming that hot plasma effects are needed to accurately predict the density perturbations. This is sufficient to guide the ongoing hot plasma code development that maximizes the signal-to-noise ratio of the PCI diagnostic.

Non-DIII-D Project. Development of an Ultrahigh-bandwidth Phase Contrast Imaging System for detection of Electron scale turbulence and Gigahertz Radiofrequency Waves

This project to extend the PCI spatio-temporal response while maintaining the excellent signal-to-noise ratio has recently been completed. A prototype PCI using a probe laser at 1.55 µm (compared to the typical 10.6 µm) demonstrated good short-wavelength measurements, with the expected increased noise and distortion held within acceptable limits. Robust techniques for accurate fabrication of the needed custom optical components were developed. These results allow a full-scale implementation on a large plasma device to be designed, providing unique low-noise fluctuation imaging at short wavelength and high frequency.

Phase Contrast Imaging for W7-X

Research personel include Miklos Porkolab, PI; Zhouji Huang, postdoctoral associate; Soren Hansen, postdoctoral fellow; and Eric Edlund, subaward investigator, SUNY Cortland.

In fiscal year 2021 (FY2021), W7-X did not operate owing to its upgrading to long pulse, high power operation by adding water cooling pipes and new tiles to protect the inner walls against the expected high heat load. At the same time from MIT, a new proposal—*Phase Contrast Imaging (PCI) for Wendelstein 7-X*, Award Number DE-SC0014229—was prepared and submitted to the DOE to renew and extend our present grant for another three-year period. The proposal was favorably reviewed and extended through calendar year 2024. During this next phase, numerous upgrades to the MIT PCI diagnostic system will be completed, allowing turbulence measurements during the long-pulse, high heating power—Electron Cyclotron Resonance Heating (ECRH), Neutral-beam injection, and ion cyclotron range of frequencies—machine operation. During the past year the PCI diagnostic was also upgraded by procuring a new laser, and a number of optics components. Meanwhile, a new numerical synthetic diagnostic was also developed, based on the Gyrokinetic Electromagnetic Numerical Experiment code which will allow a quantitative interpretation of the density fluctuation data collected by the PCI diagnostic, which otherwise gives a line integrated data that is difficult to compare with theoretical predictions. One of the outstanding goals of the Wendelstein 7-X scientific mission is to determine the role of turbulence in controlling particle and energy transport in optimized stellarators, such as W7-X. The MIT PCI diagnostic is especially suited to contribute to this task through its ability to measure electron density fluctuations over a range of scales, including ITG and trapped electron mode fluctuations. Onsite support in Greifswald has been aided by strong collaboration with Institute of Particle Physics scientists. as well as German graduate student (Jan Peter Bahner) whose thesis work includes a study of turbulence during ECRH in W-7X using the PCI diagnostic. Three refereed papers have been published during this period, covering the design of the upgraded PCI system (Z. Huang et al. *J. Instrum.* 16, P01014 [2021], turbulence measurements during ECRH of W7-X (J. P. Baehner et al, *J. Plasma Physics* [2021]) and assessing ECRH damage in W7-X (S.Hansen et al, *Plasma Physics & Controlled Fusion* 63, 095002 [2021]).

Turbulent Transport Studies

The research group of Anne White—head of the Department of Nuclear Science and Engineering (NSE) and the MIT School of Engineering Distinguished Professor of Engineering—focuses on the study of turbulent transport in fusion plasmas, with the goal of controlling the transport and improving 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 ITER and ARC. Her group is engaged in experimental research at three major tokamaks (ASDEX Upgrade, DIII-D, and NSTX/NSTX-U) where the experimental team leads experiments and develops diagnostics and leads validation projects using advanced turbulence simulation codes. White has four students and a research scientist currently working in the group. Research Scientist Pablo Rodriguez Fernandez performs predictive modeling for SPARC, develops new optimization tools at ASDEX Upgrade (AUG), and leads collaboration with the JET tokamak on integrated modeling, with a focus this year on the upcoming D-T campaign. He also supports students working on several tokamaks in the group. NSE students Rachel Bielajew and Christian Yoo continue development and optimization of Correlation Electron Cyclotron Emission (CECE)/nT-phase systems at AUG. Bielajew is studying edge turbulence in ELM-free high-performance plasmas, and Yoo is exploring the use of ML/AI applied to understanding scaling of turbulence and transport across a wide range of engineering and plasma parameters. Undergraduate Research Opportunity Program Calvin Cummings joined the group summer 2020, working on new control room visualization tools for CECE access at AUG, and has expanded his work in 2021 to develop a bench-top test of the optics set-up at AUG to better characterize the spatial resolution of the instruments via direct tests in the laboratory at MIT. NSE student Bodhi Biswas, who is co-advised with Paul Bonoli at the PSFC, works on developing reduced models of edge turbulence to study how injected RF waves interact with turbulence in the tokamak. Biswas gave an invited talk in November 2020, "Study of turbulence-induced refraction of Lower Hybrid waves using synthetic SOL blobs," at the 62nd Annual Meeting of the APS Division of Plasma Physics. He also published two papers in 2020 in AIP Conference Proceedings and in *Physics of Plasmas* on his research. NSE student Xiang Chen completed a feasibility study for a new soft x-ray based diagnostic that could be used to measure electron temperature fluctuations in NSTX-U, and his work was published in *Review of Scientific Instruments*. White is also involved as a member of the doctoral supervision committee for students working in the area of High-Energy Density Physics at Lawrence Livermore National Laboratory (LLNL), on collaborations with the SPARC tokamak, at the stellarator, W7-X located in Germany, and in the pedestal physics and boundary physics groups at PSFC.

Plasma Theory and Computation Division

The mission of the Plasma Theory and Computation Division is to conduct basic and applied plasma theory and simulation in support of domestic and international toroidal confinement devices. The division head is Paul Bonoli, senior research scientist, and the assistant head is Nuno Loureiro, associate professor of NSE.

Plasma Theory, Computation, and Discovery Science

Analytic Tokamak Equilibria

Exact tokamak equilibria have been derived which are are valid for a wide range of configurations, including smooth surfaces, double null surfaces, single null surfaces, finite aspect ratio including spherical tokamaks, finite elongation, finite and inverse triangularity, and small, medium, large beta.

Tokamak Reactor Studies

Studies have been been completed that indicate 250 MWe pulsed reactors are competitive with steady state reactors. High magnetic field is a potential game changer for improving performance on virtually all fronts.

Multi-scale Gyrokinetic Simulations

Nathan Howard has continued to make progress on multi-scale CGYRO simulations, comparing the existing multi-scale CGYRO simulations with measured Doppler Backscattering measurements in a DIII-D ITER baseline scenario discharge. This work is in collaboration with scientists at both University of California, Los Angeles and Oxford University. Investigations have been limited to linear gyrokinetic simulations spanning ion and electron-scale and ion-scale nonlinear simulations at rho = 0.8 but will soon be expanded to electron-scale simulations at near edge locations.

Heating, Current Drive, and Nonlinear Dynamics

Abhay Ram in collaboration with Professor Kyriakos Hizanidis (National Technical University of Athens, Greece) and Professor Ioannis Tigelis (National and Kapodistrian University of Athens, Greece) have continued their studies on the effect of edge turbulence on the propagation of radio frequency waves in fusion plasmas, recently developing a numerical code for comprehensive simulations of scattering.

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

Resonant interactions of charges moving in phase with electromagnetic waves can lead to deleterious loss, or advantageous heating or current drive in a fusion plasma. Peter Catto collaborated with Libby Tolman on Alfven wave instabilities in a tokamak that demonstrated these interactions are collisional in narrow velocity space boundary layers. Recent work examined the combined effects of toroidal geometry and narrow collisional boundary layers on radio frequency heating and current drive.

Coupled Full-wave / Fokker Planck Simulations of Lower Hybrid Current Drive

Graduate student Samuel Frank, working with Paul Bonoli and John Wright, has most recently been investigating the effects of plasma inhomogeneity on the plasma dielectric in the TorLH lower hybrid field solver.

Quantum Information Science

Under a new grant, Abhay Ram together with Professor George Vahala (College of William and Mary), Professor Linda Vahala (Old Dominion University), and Professor Min Soe (Rogers State University) have been developing quantum lattice algorithms for Maxwell equations to study electromagnetic pulse propagation in scalar dielectrics.

Fundamental Plasma Theory

Nuno Loureiro's group focus is on theory and simulations of nonlinear plasma dynamics. Over this reporting period, work has continued on turbulence, magnetic reconnection and the interplay between the two phenomena. Particularly noteworthy has been work by graduate student Lucio Milanese on uncovering the (novel) mechanism of dynamic phase alignment in turbulence in both plasmas and neutral fluids (Milanese, Loureiro, Daschner, and Boldyrev, *Phys. Rev. Lett.* 125, 265101 (2020); Milanese, Loureiro and Boldyrev, arXiv:2104.13518), which underlies the joint direct cascade of energy and helicity in turbulence.

A parallel research direction has been the derivation of efficient quantum algorithms for the potential quantum simulation of nonlinear plasma problems. In collaboration with researchers at the University of Maryland, we have proposed a novel algorithm based on a mathematical technique known as Carleman linearization (J. P. Liu et al, arXiv:2011.03185). This work was featured on *Quanta* magazine.

High Performance Computing Initiatives

SciDAC Partnership for Integrated Simulation of Fusion Relevant RF Actuators

Graduate student Christina Migliore, under the supervision of John Wright and Mark Stowell (LLNL), successfully implemented boundary conditions in the Stix electromagnetic field solver that account for RF induced sheath potentials.. Graduate student Bodhi Biswas, working under the supervision of Anne White, Abhay Ram, and Paul Bonoli, 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.

SciDAC Partnership for Multiscale Gyrokinetic Turbulence

Postdoctoral associate Mana Francisquez and Darin Ernst implemented their first-of-kind multiscale 2D gyrofluid model, describing simultaneous toroidal ITG–driven and toroidal electron temperature gradient driven turbulence, in their pseudospectral code MuSHrooM. The new code demonstrated 2D multiscale simulations in far less time than required by gyrokinetic 5D simulations. Comparisons with the GENE code show close agreement in ITG nonlinear fluxes and linear growth rates as the ion temperature gradient drive is varied over a wide range.

Radio-frequency Machine Learning SciDAC and ARPA-E BETHE Projects

John C. Wright leads the Radio-frequency (RF) Machine Learning project and the Advanced Research Projects Agency-Energy (ARPA-E) RF Project. During this reporting year, machine learning artificial tools have been developed that can greatly speed up calculations of electric currents produced by RF waves to the point that they may be used in realtime control of experiments. Also, an RF antenna is being designed for the Wisconsin HTS Axisymmetric Mirror ARPA-E RF experiment in Madison, WI.

International Collaboration: Plasma Theory and Computation Division and Magnetic Fusion Energy Division

Long Pulse High Performance Scenarios and Control in EAST

Paul Bonoli serves as the MIT PI of this multi-institutional international collaboration. During the past year, Seung Gyou Baek working with Greg Wallace led a series of dedicated experiments on the EAST Tokamak in Hefei, China to investigate the absorption efficiency of 2.45 GHz and 4.6 GHz power, up to the densities needed to access high performance plasmas in EAST.

Robert Granetz and Cristina Rea, and MIT graduate students Kevin Montes ’21 and Jinxiang Zhu collaborate with the EAST Team on the training, testing, and evaluation of disruption prediction algorithms based on random forest and advanced recurrent neural network architectures, as well as continued development of the EAST disruption database.

WEST Tokamak RF Project

John Wright is the institutional PI on the WEST French Tokamak RF project where measurement techniques for RF waves have been designed by graduate student Raymond Diab.

High Energy Density Physics Division

The High Energy Density Physics (HEDP) Division is now in its third year as a Department-of-Energy-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. This moment in time, July 2021, turns out to have particular historical significance. Richard Petrasso, the head of the HEDP Division who founded the division four decades ago and has led its expansion and rise in importance, has now announced his retirement, just as the division and its CoE is reaching its peak size, level of accomplishment, and importance.

MIT has built the CoE by combining its own scientists and students with scientists and students from four outside partner institutions: the University of Nevada, Reno; Virginia Polytechnic Institute (Virginia Tech); the University of Michigan; and the University of Rochester. MIT and all partner institutions contribute special skills and experience to the CoE’s work, collaborating in research and the recruitment and education of the best students and young scientists. The result is a strong collaboration that is more productive as a whole than the sum of what the partners would be without the collaboration.

The CoE brings MIT's wide range of diagnostic techniques, and MIT's wide range of physics expertise and analysis, to a huge range of experiments with laser-driven plasmas. The diagnostics include spectrometry of charged particles, neutrons, and x rays; radiographic imaging of plasmas and their electromagnetic fields using charged-particle backlighting; penumbral imaging of the spatial distributions of charged-fusion-product production and x-ray production; and time evolution of charged particle and neutron production. The University of Nevada,Reno partners, led by Roberto Mancini, complement MIT well by providing specialized expertise in important types of x-ray measurements. At the University of Michigan (when the CoE was first formed, Scott Baalrud was at the University of Iowa. In 2021, he moved to the University of Michigan), Scott Baalrud's microphysics and transport models will complement and feed into Bhuvana Srinivasan's fluid and kinetic simulations at Virginia Tech for purposes of planning and interpreting MIT's experiments. The expertise of Baalrud's group in strongly-coupled, degenerate plasmas will also be essential for interpreting and understanding Warm Dense Matter plasma-stopping-power data in upcoming experiments. The expertise of Professor Riccardo Betti's group at the University of Rochester will be critical in multiple ways. One way is making possible the generation of strong magnetic fields externally applied to ICF fuel capsules, to study the effects of the fields on ICF performance. Another way is using comprehensive simulations and analytical modeling to support MIT's ongoing program for developing the important magnetic recoil spectrometer (MRSt) diagnostic that will measure the time evolution of the energy spectrum of ICF-generated neutrons.

Now that Petrasso is retiring from MIT, he is passing the HEDP division head title to John Frenje, senior scientist, and the title of CoE PI to Chikang Li, senior scientist. The division and the CoE will reach new heights while all members of the division and partners in the CoE will remember the many magnificent accomplishments of Petrasso that brought us to this point.

Plasma Science and Technology Division

The Plasma Science and Technology Division conducts research on advanced sources of terahertz radiation, high gradient electron acceleration, gyrotron drilling for geothermal energy, and plasma-material interactions. The division is headed by Richard Temkin, senior scientist in the Department of Physics and Kevin Woller, assistant division head. Paul Woskov, senior research engineer, oversees Geothermal Energy Research.

Electron Cyclotron Heating Technology Research

Electron Cyclotron Heating (ECH) technology includes research on gyrotron high power microwave sources and the transmission lines used to transmit gyrotron output power to the plasma. Gyrotrons are under development for ECH of present day and future plasmas and for double resonance spectroscopy in Nuclear Magnetic Resonance (NMR) research on the structure of biomolecules. These applications require gyrotron sources operating in the frequency range of 100–800 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 AY2021, we conducted and published theoretical research to analyze our experimental results on the effect of reflected power on gyrotron operation.

Advanced Terahertz Sources

We are building novel high-frequency, high-power vacuum electron devices that are based on backward wave oscillators and klystrons, at frequencies from the microwave to the THz region. These devices use electromagnetic waves with phase velocity slower than the speed of light, in contrast to fast-wave gyrotron sources. In AY2021, we built and completed the first tests of a backward wave oscillator designed to produce tunable radiation near 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. In AY2021, in collaboration with the accelerator research group at Stanford Linear Accelerator Center, we completed tests of a novel 110 GHz accelerator structure with field strengths in the structure up to 500 MV/m in five nanosecond pulses from a megawatt gyrotron. Preparations are being made for a second structure test. Research was conducted at Argonne National Lab (ANL) at the Argonne Wakefield Accelerator (AWA). A novel metamaterial structure was tested using a train of eight electron bunches of 65 MeV with a total of 280 nanocoulombs of charge. We obtained a record-high output power level of 510 MW in a three nanosecond pulse at 11.7 GHz. These results are very promising for the design of future electron-positron linear colliders.

Geothermal Energy

High-power millimeter-wave (MMW) gyrotrons, that were originally developed for fusion energy research, are being applied to advance the state of the art of drilling to enable accessibility to geothermal energy in deep super-hot rock. 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 a mechanical grinding process to an energy-material interaction that overcomes these limitations. MMW gyrotrons are ideally suited in terms of the physics and available technology for this application over past attempts to using shorter wavelength lasers. The feasibility of MMW drilling has been established in the laboratory in past years under the leadership of Paul Woskov.

During FY2021, the funding for the ARPA-E subcontract to MIT “Millimeter-Wave Technology Demonstration for Geothermal Direct Energy Drilling” became available to start work. The partners in this ARPA-E project are: AltaRock Energy Inc., Geoffrey Garrison, PI; Quasie Inc., Carlos Arque CEO—a company primarily created by AltaRock to lead this development, commercialize the findings, and raise more funding; MIT with Paul Woskov at PSFC, Herbert Einstein at the MIT Rock Mechanics Laboratory, Department of Civil Engineering; Ken Oglesby of Impact Technologies LLC; and Tim Bigelow at Oak Ridge National Laboratory (ORNL). The goals of the planned 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 year three using one of ORNL’s 100+ kW continuous wave gyrotrons.

Progress was made at the PSFC despite the limitations to laboratory access caused by the COVID-19 pandemic. A postdoctoral researcher, Hen Yeung (jimmy) Lee, was hired. The 10 kW, 28 GHz gyrotron system was made operational and about 20 rock melting tests were carried out on two grades of basalt and granite. Making holes in hard crystalline rock on the 1:1 scale with a millimeter-wave beam was reestablished.

In addition, two laboratory advances were made: 1) A pressure sapphire window was installed in the gyrotron transmission line that verified that the pressure increases with temperature in the confined borehole environment. This demonstrated that full-bore directed energy drilling would be a positive pressure process eliminating the need for drilling mud to stabilize borehole drilling. 2) A 95 GHz reflectometer was combined with the 137 GHz radiometer to view the melt surface through a small hole in the finial miter bend in the gyrotron waveguide transmission line to provide both rate of penetration and temperature measurements in real-time, respectively. The reflectometer measurements were found not to be very coherent likely due to molten deformations. However, weak interference fringes could be observed some of the time to indicate relative surface displacement.

Set up of the 10:1 test at ORNL was just beginning at the end of this time period.

Magnets and Cryogenics Division

The Magnets and Cryogenic Division research and development efforts continued into High-Temperature-Superconductor (HTS) Rare-Earth-Barium-Copper-Oxide (REBCO) conductor developments towards very high-field, high-current device applications and their quench protection system developments. Makoto Takayasu has specifically been developing a new REBCO flat-tape cabling method. He has also worked on a unique quench detection development using a micro-electric-sensor array with Tanner Research Inc. and Tufts University on a DOE Small Business Technology Transfer Program. In addition, we have collaborated with Brookhaven Technology Inc. to develop high-performance, low-loss narrow-width REBCO conductors. The division assisted in designing the TF Coils or SPARC, testing of the TFMC pancakes. Over last year jointly with CFS submitted 11 patent applications (first author on eight of them) about various aspects of HTS-based high-field magnets. Presently working on various perspective projects using HTS REBCO tape based magnets for Wind Generators, Electrical Motors, Maglev, SMES, Particle Accelerators, Power Transmission Lines.

Magnetic Resonance Division

Robert G. Griffin

We present the results of an experimental pulsed dynamic nuclear polarization (DNP) study at 1.2 T (33.5 GHz/ 51 MHz electron and ^{1}H Larmor frequencies, respectively). The results include a comparison of constant-amplitude nuclear orientation via electron spin locking (CA-NOVEL), ramped-amplitude NOVEL (RA-NOVEL) and the frequency-swept integrated solid effect (FS-ISE) experiments all of which were performed at the NOVEL matching condition, $\omega_{1S} = \omega_{0I}$, where ω_{1S} is the electron Rabi frequency and ω_{0I} the proton Larmor frequency. To the best of our knowledge, this is the initial pulsed DNP study carried out at field higher than X-band (0.35 T) using the NOVEL condition. A combination of high microwave power (~150 W) and a microwave cavity with a high Q (~500) allowed us to satisfy the NOVEL matching condition. We also observed stretched solid effect (S^{2}E) contributions in the Zeeman field profiles when chirped pulses are applied. Furthermore, the high quality factor of the cavity limits the concentration of the radical to ~5 mM and generate a hysteresis in the FS-ISE experiments. Nevertheless, we observe very high DNP enhancements that are comparable to the results at X-band. These promising outcomes suggest the importance of further studies at even higher fields that delineate the instrumentation and methods required for time domain DNP.

Magic-angle spinning (MAS) nuclear magnetic resonance (NMR) spectroscopy is an ideal tool for studying amyloids at atomic resolution but suffers from low sensitivity, requiring relatively large amounts of samples and extensive signal acquisition periods. Recent advances in ultra-fast MAS ^{1}H-detection and fast-MAS DNP have ushered in a new era for NMR-based structural biology, but their potential has not yet been demonstrated for the structural investigation of complex amyloid assemblies. Here we show resolved and sensitive 2D and 3D correlations obtained on ^{13}C,^{15}N-enriched and fully-protonated samples of M0Ab$_{1\text{-}42}$ fibrils by high-field ^{1}H detected NMR at 23.4 T and 18.8T, and ^{13}C detected DNP MAS NMR at 18.8 T. These spectra enable nearly complete resonance assignment of the core of M$_0$-Ab$_{1\text{-}42}$ (K16-A42) using sub-mg sample quantities, as well as the detection of numerous unambiguous inter-nuclear proximities defining both the structure of the core and the arrangement of the different monomers. Overall, this work demonstrates the possibility of expeditious structural analysis of amyloid fibrils without requiring preparation of large sample amounts, and illuminates the path to the study of unlabeled AD peptides derived from tissue samples available in limited quantities.

Mei Hong

The Hong group develops and applies advanced solid-state NMR spectroscopy to address fundamental questions in biology, medicine, and materials science. Current focuses are viral membrane proteins, amyloid proteins, and plant cell walls.

In FY2021, the Hong group accomplished several highly impactful studies of infectious disease proteins, including a SARS-CoV-2 protein and an antibiotic-resistant protein. These timely studies have been widely reported in the news. They also conducted cutting-edge studies of an amyloid protein that is critical in many neurodegenerative diseases.

1. The Hong group reported the atomic-resolution structure of an essential membrane protein of the SARS-CoV-2 virus , the causative agent of COVID-19. The envelope (E) protein is important for the virus pathogenicity and is targeted by antiviral drugs such as hexamethylene amiloride. In only 6 months, Hong and coworkers rapidly cloned and purified this membrane proteins, and carried out advanced solid-state NMR experiments to solve the structure of the transmembrane domain of the protein in lipid bilayers. The E protein assembles into a tight five-helix bundle with a hydrophobic pore, whose N-terminus forms the drug-binding site. This structure represents one of the only two structures of SARS-CoV-2 membrane proteins known to date, and paves the way for medicinal chemists to design more potent antiviral drugs to treat COVID-19 infections. Since its publication in November 2020, this paper has been accessed 40,000 times and cited 69 times by July 2021, demonstrating the impact of this work for the global effort to combat COVID-19.
2. The Hong group solved a long-standing structural biology problem by reporting the high-resolution structure of a bacterial transporter, EmrE. EmrE is the prototype of the family of small multidrug-resistance proteins, and couples proton import with drug export to cause antibiotic resistance. For more than two decades, the high-resolution structure of this protein has been resistant to crystallography and electron microscopy because of the conformational plasticity of the protein. The Hong group applied their recently invented proton-fluorine distance-measurement NMR technique to determine the structure of EmrE in lipid bilayers. The structure shows that the fluorinated substrate, tetraphenylphosphonium, binds an aromatic-rich pocket of the protein, and is asymmetrically positioned between the two subunits of the dimeric protein. The proximity to one of the two subunits explains the asymmetric protonation of the protein. The spaciousness of the binding pocket explains the promiscuity of substrate binding by this protein.
3. The Hong group investigated the three-dimensional structure of a full-length tau protein, which is involved in many neurodegenerative diseases such as Alzheimer's disease. The tau protein aggregates into β-sheet rich amyloid fibrils in neurons. Understanding the molecular structures of these fibrils is

important for the diagnosis and treatment of neurodegenerative disorders. The Hong group investigated a tau isoform that contains three microtubule-binding repeats. They found that the β-sheet core of the protein has an unprecedented large size, encompassing the C-terminal segment of the protein. This has never been observed before and suggests that the smaller fibril cores obtained from patient brains are more toxic due to the absence of the C-terminus. This study has profound implications, as it suggests that small-molecule drugs that prevent post-translational modifications of the C-terminus may slow or inhibit disease progression by shielding the more toxic microtubule-binding repeats.

Jagadeesh Moodera

Jagadeesh Moodera is a senior research scientist and a group leader at the Department of Physics (Physics), with the research laboratories located in PSFC; his research effort is in nanoscience condensed matter physics with particular focus on emerging phenomena in quantum materials heterostructures (quantum coherent transport in topologically driven nanodevices, investigation of topological superconductivity and Majorana Fermions, superconducting spintronics, molecular spintronics) with funding from Army Research Office (ARO), Office of Naval Research (ONR), and National Science Foundation (NSF) research grants (collaborators Patrick Lee and Liang Fu of Physics). He is also part of the large NSF funded five-year Science and Technology Centers program initiated Center for Integrated Quantum Materials (CIQM) that is between MIT, Harvard University, Howard University, the Museum of Science, and etc. Based on the excellent success during the past years, this CIQM program continues until 2022. Moodera's group acquired a large project funding from NSF Convergent Accelerator program (Phase I) on quantum technology to investigate and develop robust, fault tolerant topological qubits based on Majorana states to build a scalable, economical, and reliable quantum computer. Under Moodera's leadership, with the success of Phase I, a major Phase II multi investigator two-year proposal that includes the top research centers in Switzerland, is under consideration at NSF involving IBM, the industrial leader in quantum computing. We acquired the needed funding to set up two important infrastructure facilities: an ultra-low temperature set up called dilution refrigerator—capable of reaching 10 milliK temperatures and magnetic fields up to 14 Tesla—and a large capacity helium gas recovery and recycling unit—a huge boost enabling low temperature quantum transportand scanning tunnel spectroscopy studies more feasible, efficient, and economical. Two other research proposals are under consideration by ONR and NSF. Under the ongoing ARO project that began in December 2018, a guest postdoctoral fellow from the Army Research Laboratory (ARL) has been placed in MIT under Moodera's supervision to build a strong close collaborative program with ARL. Having this guest postdoctoral fellow has made an enormous difference when we were getting back into operation after the COVID-19 pandemic induced shut down of research activities as well as in the infrastructure facility buildup

Moodera's group collaborates with various universities—in Brazil, Canada, Germany, India, Italy, Spain, Switzerland, the United Kingdom, and the US—and Oak Ridge National Laboratory. The group focuses on both fundamental and applied physics: interface science, quantum technology, coherent and dissipationless transport in topological systems into creating exchange tuned memory device; and investigate the interaction of Majorana bound states and their quantum entanglement, triplet paired superconductors and spintronics (energy efficient memory, sensing, and logic). Another recent noteworthy achievement was the demonstration of three state magnetic memory based on low energy dissipation magnon transport in thin film heterostructures. For these studies the group works at the limit of thin film and nanotechnology in search of novel phenomena.

In the recent past the group has mentored graduate, undergraduate, and high school students by providing research opportunities in his laboratory. Visiting scientists from China, Brazil, Germany, Italy, and Japan took part in his research and for extensive collaborative discussions during 2019–2020 (until the COVID-19 pandemic mandated shut down and curtailed experimental research for nearly one year). The impact was extensive, as the program had to be rebuilt, hiring a new team and training them in the advanced techniques and the science required to conduct the experiments. He continues to help out other faculties and their students from Departments of Electrical Engineering and Computer Science, Materials Science and Engineering, Mechanical Engineering, and Physics.

Moodera's group along with his collaborators published articles in *Physical Review*, *Advanced Materials Electronics*, *Applied Physics Letters*, *Journal of Applied Physics*, *Proceedings of the National Academy of Sciences (PNAS)*, and more. He has given a number of invited talks at international conferences to disseminate our major results, with more lined up in the coming year. The group has a pending patent, which is described in the article published in *PNAS* on the breakthrough discovery of Majorana bound states in superconducting gold surface. This deals with a novel topological qubit approach for a highly scalable, robust, reliable, and economical quantum computer realization that has the potential to transform computing technology, benefitting all branches of science and society. This work has already appeared in many worldwide websites including NSF, ONR and DOE agency sites.

Yukikazu Iwasa

In FY2021, the Magnet Technology Group, under Yukikazu Iwasa's leadership, was involved in three NIH-supported programs on NMR and MRI magnets, each briefly summarized below.

Because of the COVID-19 pandemic, MIT locked down on March 13, 2020, forcing our entire experimental activities to stop. The lockdown continued until June 14, 2020. On June 15, 2020, MIT began Phase 1 Research Ramp Up, allowing 25%-capacity laboratory activities. As of June 30, 2021, MIT has not returned to full normalcy.

This completely unanticipated Institute-wide measure has greatly affected progress in our three major programs, all focused on experimental activities.

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

A new four-year phase of this 1.3-GHz LTS/HTS NMR magnet, supported by the National Institute of General Medical Sciences began on August 1, 2020 with an end date of July 31, 2024. In this program, we expect to complete a high-resolution 1.3-GHz

NMR magnet (1.3G). The 1.3G will be delivered to the MIT-Harvard Center for Magnetic Resonance located in the Fracis Bitter Magnet Laboratory.

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

Supported by the National Institute of Biomedical Imaging and Bioengineering (NIBIB) and began April 1, 2017, the project had originally two specific aims: completion of a tabletop, LHe-free, persistent-mode, solid-nitrogen (SN2) cooled superconducting (MgB2) MRI magnet prototype for osteoporosis scanning; and in the fifth year, demonstration, by Dr. Jerome Ackerman, co-investigator of the Athinoula A. Martinos Center for Biomedical Imaging, Massachusetts General Hospital, of the benefits of MgB2/SN2 technology for MRI magnets in the context of a very compact affordable scanner. However, when the program began, NIBIB funded only years one through four activities, with the specific aim to complete this MgB2 "finger" magnet, by December 31, 2020. Because of the COVID-19 pandemic-forced lockdown, hardly any year four work could be conducted, completing only the operation of the "finger" magnet. We will submit to NIBIB a new three-year application to complete this "finger" magnet and in year three of this new program, perform a limited amount of the original (year five) second specific aim. A review result is expected in October 2021.

A 10-K all-REBCO 23.5-T Magnet for Later Development to a Tabletop, Liquid-Helium-Free 1-GHz "Microcoil" NMR Magnet

Supported by the NIBIB that began July 1, 2018, this two-year project where Dongkeun Park is the PI, has four specific aims: 1) design and construct a prototype single-coil all-REBCO 23.5-T/Ø20-mm cold-bore magnet, and achieve a field of 23.5 T at 10 K in a volume of solid nitrogen (SN2); 2) validate a screening-current-inducing field (SCF) reduction method for enhancing field quality; 3) apply an iron yoke design to reduce a 5-gauss fringe field radius; and 4) design a shielded *tabletop LHe-free* 23.5-T/Ø25-mm RT-bore high-resolution NMR magnet, as stated above, incorporating 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 Shanghai Superconductor Technology Corp. Currently, we are practice-winding DP coils. The entire project was successfully completed on June 30, 2021, in year three, the project's first no-cost extension period.

Educational Outreach Programs

Plasma Science and Fusion Center educational outreach is planned and organized by Paul Rivenberg, PSFC education and outreach administrator. Nuno Loureiro oversees 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.

The program focuses on heightening the interest of K–12 students in scientific/technical subjects by bringing them together with scientists, engineers, and graduate students in laboratory and research environments. With the outbreak of COVID-19, and MIT's request to curtail on-campus events, the PSFC sought alternate ways to reach students and the general public through established MIT and national programs.

USA Science and Engineering Festival SciFest All Access (October 2020)

Originally scheduled to attend the April 2020 USA Science and Engineering Festival in Washington, DC, the PSFC participated in a month-long virtual event instead in October 2020. Set in the graphic interior of the Alcator C-Mod tokamak, the booth offered links to MIT/PSFC videos, online plasma outreach and MIT News articles about women researchers at the PFSC, two offering profiles of undergraduate women doing research. More than 75,000 people registered, representing all 50 states and 99 countries.

MIT Energy Nights (October 2020)

As part of a virtual format, graduate students Erica Salazar and Sean Ballinger provided insights into their fusion research projects for rotating groups of viewers. Although the venue was not ideal for engaging the public one-on-one, it did allow for a broader reach.

American Physical Society Division of Plasma Physics (November 2020)

Paul Rivenberg was part of the Education Outreach Planning Committee for the 2019 APS DPP Meeting, scheduled for November 2020 in Memphis, TN. Ultimately, the meeting was held virtually. The committee decided to create a virtual “Science Teachers Day” to replace their usual live day of science workshops for local teachers. This evolved into a two-day event, held on consecutive Saturdays in November, offering 27 teachers from the Memphis area an introduction to fusion, followed by workshops on related physics. Andrew Seltzman, postdoctoral associate at PSFC, offered workshops on “Teaching Plasma Physics Through Classroom Demos.” Rivenberg hosted the middle school workshops in a PSFC Zoom room and recorded them for the APS education site. Seltzman’s workshop received top marks from survey respondents.

Independent Activities Period (January 2021)

Topics this year included the development of plasma rockets (presented by NASA astronaut Franklin Chang Diaz), an introduction to the latest fusion research at MIT, how the PSFC’s Francis Bitter Magnet Laboratory is involved in virus analysis, and a virtual tour of the PSFC’s High Energy Density Physics Lab.

Cambridge Science Festival (April 2021)

Instead of the usual tour, the PSFC provided CSF with 2 PSFC-related videos for their website, which were promoted by CSF through social media for a month. Rivenberg enlisted PSFC cryogenic research engineer Dhananjay Ravikumar to provide a live Zoom introduction to superconductivity. Thirty families joined, most from the Boston area, but also from Chicago; the US west coast; Athens, Greece; and India.

Young Woman’s Conference (May 2021)

For the first time the PSFC joined the Young Woman’s Conference, organized by Princeton Plasma Physics Laboratory and Oak Ridge Associated Universities. Rivenberg created a virtual PSFC booth, featuring videos and articles about women working in plasma science at the PSFC. He recruited undergraduate Sreya Vangara—the subject of one of his articles—to do a live panel about career paths on the day of the event.

Videos

The PSFC is working on a Fusion 101 video, written and narrated by PSFC graduate students, for the website.

Coalition for Plasma Science

Rivenberg continues to work with CPS, supervising the maintenance of their website, which includes a Teacher's Guide to Plasma Science Resources. A change in leadership in June 2021 promises a year of significant growth and outreach.

Computational Physics School for Fusion Research

The first Computationa Physics School for Fusion Research was held in August 2019. Organizers ultimately decided to postpone the second outing, now planned for August 2021. The organizing committee members are: Christina Rea, research scientist; Paul Bonoli, principal research scientist;Francesco Sciortino, graduate student;Jessica Coco, administrator; and Paul Rivenberg.

Honors and Awards

- Mei Hong: 2020 Nakanish Award from the American Chemical Society—Sponsored by the Nakanishi Prize Endowment, this award is given in recognition of application of spectroscopy to biological phenomena.
- Amanda Hubbard: Secretary of Energy's Appreciation Award—The award honors Hubbard's role in the formation of the U.S. Burning Plasma Organization (USBPO), a national association of scientists and engineers involved in researching the properties of magnetically confined burning fusion plasmas.
- Pablo Rodriguez-Fernandez (MIT PhD '19): Forbes 30 under 30 in Science sector, 2021.
- Erica Salazar: Women in Innovation and STEM Database (WISDM)—WISDM is a fellowship program for scientists interested in improving their public speaking capabilities.
- Matt Fulton: MIT Excellence Award—Among the highest honors awarded by MIT, the Excellence Award acknowledges the extraordinary efforts made by members of the community toward fulfilling the goals, values, and mission of the Institute. Fulton was recognized in the category of "Sustaining MIT."
- Benjamin Reichelt: Stewardship Science Graduate Fellowship (SSGF)—The Department of Energy National Nuclear Security Administration SSGF is funded to ensure a continuous supply of highly trained scientists and engineers in areas of study related to high energy density physics, nuclear science, and materials under extreme conditions and hydrodynamics.

- Robert Griffin: National Academy of Sciences—In recognition of "distinguished and continuing achievements in original research." Membership is one of the highest honors that a scientist can achieve.
- Lucio Milanese: 2022 Schwartzman Scholarship

Appointments

- Magnetic Fusion Experiments Division: Sara Ferry was appointed postdoctoral associate; James Ridson was appointed mechanical engineer; and Nicolo Riva was appointed postdoctoral associate
- Plasma Theory and Computation Division: Elizabeth Tolman was appointed research specialist limited-MIT doctoral and Noah Mandell was appointed postdoctoral fellow
- Plasma Science and Technology Division: Hin Yeung Lee was appointed postdoctoral associate; Paul Woskov was appointed research scientist; and Joel-Elliot LClaveau was appointed postdoctoral associate
- Magnets and Cryogenics:Leslie Bromberg was appointed research engineer
- Magnetic Resonance Division:Shu-Wei Wang was appointed postdoctoral associate; Andrew Dane was appointed postdoctoral associate; Yasen Hou was appointed postdoctoral associate; and Alessandro Lodesani was appointed postdoctoral associate

Promotions

In the Magnetic Fusion Experiments Division, Michael Rowell was promoted to MFE machine shop process development supervisor; Thomas Toland was promoted to process systems specialist; Vincent Fry was promoted to mechanical engineer; Pablo Rodriquez Fernandez was promoted to research scientist; and Kevin Woller was promoted to group leader, Accelerators and Molten Salt Laboratories.

Graduate Degrees

- Nuclear Science and Engineering: Brandon Lahmann, PhD
- Chemistry: Daniel Banks, PhD; Martin Gelenter, PhD
- Mechanical Engineer: Caroline Sorensen, PhD
- Physics: Kevin Montes, PhD

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