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 (HED) 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; and research in magnetic resonance, which includes nuclear magnetic resonance, electron paramagnetic resonance, and magnetic resonance imaging (MRI); and on the aforementioned 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 the Departments of Aeronautics and Astronautics, Chemistry, Mechanical Engineering, Nuclear Science and Engineering, and Physics; 85 research scientists, engineers, postdoctoral associates or fellows, and technical staff; 44 visiting scientists, engineers, and research affiliates; 18 technical support personnel; 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 SPARC (a compact, high-field, net fusion energy device) program. At 47%, industry support is the single largest portion of PSFC funding. The US Department of Energy (DOE) Office of Fusion Energy Sciences (OFES) comes in at approximately 28%. Support from other DOE (i.e., non-OFES)—departments is at 10%, and National Institute of Health (NIH) support is approximately 11% of total funding.

Magnetic Fusion Experiments Division

The Magnetic Fusion Experiments Division at the PSFC is home to world-leading experts in all areas of magnetic confinement fusion research. The experimental work on confinement experiments—mostly funded by the US Department of Energy through grants and a cooperative agreement—is primarily carried out at off-site facilities, both in the United States and internationally. The division is also intensely involved in support and preparations for the next major tokamak facility, SPARC, that will be hosted by the private company Commonwealth Fusion Systems, which is the primary funder for SPARC-related research at MIT. Students, postdocs, research scientists, engineers,

technicians, and faculty all contribute strongly to every facet of the research. These efforts are critical to maintaining scientific and educational excellence in magnetic fusion experiments at the PSFC.

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, TCV, EAST, KSTAR, JET, and WEST. Our experimental work contributes to a broader physics basis for burning plasma experiments including SPARC and ITER—the largest fusion project worldwide, conceived as an experiment to investigate and develop the technologies to prepare the way for the future fusion power plant. Most of these efforts directly support the PhD research of graduate students in multiple MIT academic departments.

Zachary Hartwig

Professor Zachary Hartwig leads multiple efforts in the Department of Nuclear Science and Engineering (NSE) and at PSFC. These are principally focused on accelerating the deployment of commercial fusion energy through the advancement of fusion science, engineering, and technology. Professor Hartwig's efforts to-date were recognized in the previous year with his promotion to associate professor without tenure. He was also named the Robert N. Noyce Career Development Professor in the MIT School of Engineering.

For the period 2019–2021, Professor Hartwig was the principal investigator (PI) and project head of the SPARC Toroidal Field Model Coil Project, a two-year project in partnership with Commonwealth Fusion Systems. Hartwig led a joint team of approximately 80 scientists, engineers, and technicians to design and build a first-of-kind high-field superconducting magnet based on high temperature superconductor for fusion applications. The group will also design, build, and commission a large-scale superconducting magnet test facility at MIT.

In the first week of September 2021, the magnet successfully demonstrated full performance, achieving more than 20.5 tesla peak field-on-coil—a world record for a magnet of this scale—and meeting or exceeding all technical specifications in steady-state operations. The successful test of the magnet as well as a number of key ancillary technologies in the test facility are now being utilized to further the design and construction of the SPARC tokamak.

Fast Particle-Wave Interactions and Alfvén Eigenmodes in JET Tokamak Plasmas

The world's largest operating tokamak—JET in Oxfordshire, UK—proceeded with its planned Deuterium-Tritium campaign at the end of 2021, during which MIT's Alfvén Eigenmode Active Diagnostic collected data with thousands of stable Alfvén` Eigenmodes (AEs), a type of magnetohydrodynamic wave in a toroidally confined plasma. The novel damping (growth) rate measurements included simultaneous unstable and stable AEs in the search for nonlinear coupling to alpha particles, turbulence, and AEs, as well as first-ever stability measurements during energetic particle "afterglow" experiments. Ongoing modeling, a key predictor of future burning plasma performance, is proceeding to identify AEs and assess their stability in the

presence of energetic ion beams and alpha particles. Continuation of this program to FY2023 depends on DOE approval.

Turbulent Transport Studies

Anne White is head of the Department of Nuclear Science and Engineering and the School of Engineering Distinguished Professor of Engineering. Her research group 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 and validation of high-fidelity simulations that will inform the design of future net-energy fusion devices. The group participates in heat, particle, and momentum transport experiments in fusion plasmas. Integrated modeling using reduced transport models plays a key role in developing novel validation tools, some employing machine learning, for the design of future fusion devices such as ITER and ARC (affordable, robust, compact). This year the team has worked primarily at the ASDEX Upgrade tokamak, where the experimental team leads experiments and develops diagnostics and leads validation projects using advanced turbulence simulation codes.

Plasma Theory and Computation Division

The Plasma Theory and Computation Division conducts basic and applied plasma theory and simulation in support of domestic and international toroidal confinement devices. The division head is Senior Research Scientist Paul Bonoli and the assistant head is Nuno Loureiro, professor of physics and professor of nuclear science and engineering.

Professor Jeffrey Freidberg and Luca Guazzotto, associate professor of physics at Auburn University, completed fusion neutron source studies comparing the effects of high magnetic field on steady state and possible pulsed neutron sources for application to fusion. Freidberg and Professor Dennis Whyte, along with NSE student Joseph Jerkins '21, also developed a 2D large aspect-ratio model of the Liquid Sandwich Vacuum Vessel.

Peter Catto, NSE senior research scientist, and Elizabeth (Libby) Tolman, PhD '20, Institute for Advanced Study, studied resonant plateau behavior at narrow collisional velocity space boundary layers that form about wave-particle resonances and lead to results that appear to be independent of collisions (2021 *Journal of Plasma Physics* 87, 905870606). Nathan Howard, PhD '12, has studied discharges from the ASDEX-Upgrade and DIII-D tokamaks using single scale (ion and electron) gyrokinetic turbulence simulation to evaluate them as candidates for multi-scale simulation. Darin Ernst and Manaure Francisquez, Princeton Plasma Physics Laboratory, and the FASTMath SciDAC Institute implemented a new multi-rate method to accelerate simulations of coupled ion and electron scale turbulence.

High Energy Density Physics Division

The High Energy Density Physics Division is in its fourth year as a DOE-designated Center of Excellence (COE) for implementing advanced diagnostics and platforms for studying inertial confinement fusion, laboratory astrophysics, and HED plasmas. MIT built the COE by combining MIT researchers with researchers from four partner institutions: the University of Michigan, the University of Nevada-Reno, the University of Rochester, and the Virginia Institute of Technology. Under the COE, two exceptional

students graduated and were hired in 2022 by National Nuclear Security Administration (NNSA) laboratories. Brandon Lahmann, ScD '21 was hired by Lawrence Livermore National Laboratory (LLNL) and Neel Kabadi, PhD '22, was hired by the Laboratory for Laser Energetics, University of Rochester.

A key element of the COE is the use of MIT's Magnetic Recoil neutron Spectrometer (MRS)—in addition to several other MIT-developed diagnostics—in support of the inertial confinement fusion programs at the LLNL National Ignition Facility and the OMEGA laser facility at the University of Rochester. These diagnostics have been used for decades; the MRS data have been a cornerstone for guiding the campaigns at the National Ignition Facility toward ignition conditions. On the historic ignition shot on August 8, 2021—the first-ever demonstration of ignition in a laboratory—the MRS provided critical data for the assessment of the implosion performance. This ignition result was published in *Physical Review Letters*, recognizing the important contributions of the MIT students who worked on the program. Eight students are co-authors on this historic paper.

Plasma Science and Technology Division

High Gradient Electron Acceleration

Research on high-gradient accelerators is focused on greatly reducing the size and cost of future accelerators. In 2021–2022, research was conducted at Argonne National Lab, where a novel metamaterial structure was tested using a train of eight electron bunches of 65 MeV with 355 nanocoulombs of charge, yielding a record-high output power level of 565 MW in a 2.7 ns pulse at 11.7 GHz. In collaboration with the accelerator research group at SLAC National Accelerator Laboratory, we are preparing to test a novel field emission electron gun and accelerator at 110 GHz using pulses from a megawatt gyrotron.

Electron Cyclotron Heating Technology Research

Electron Cyclotron Heating technology includes research on gyrotron high power microwave sources and the transmission lines used to transmit power to the application. Gyrotrons are used for plasma heating and for double resonance spectroscopy in nuclear magnetic resonance research, requiring gyrotron sources operating in the frequency range of 100–800 GHz at power levels from watts to megawatts. In 2021–2022, we worked on testing a 527 GHz gyrotron and a 250 GHz gyroamplifier.

THz Pulse Compressor and Ring Resonator

At millimeter wave and THz frequencies, high power pulses on the nanosecond scale are difficult to generate. In 2021–2022, we built and demonstrated at 250 GHz a resonant ring that stores power for one microsecond and then couples out the power in a 5.8 ns pulse using a laser driven silicon switch, yielding a power gain of 16.

Geothermal Energy

The Advanced Research Projects Agency-Energy (ARPA-E) project "Millimeter-Wave Technology Demonstration for Geothermal Direct Energy Drilling" continued through FY2022. The partners in this project are AltaRock Energy, Geoffrey Garrison, principal investigator; and Quaise Energy, Carlos Arque, CEO—a company founded to lead this development and commercialize the technology. MIT partners are Paul Woskov of

PSFC; Herbert Einstein of the MIT Rock Mechanics Laboratory, Department of Civil and Environmental Engineering; Ken Oglesby of Impact Technologies; and Tim Bigelow at Oak Ridge National Laboratory (ORNL). The goals of the planned three-year effort (that has been extended due to the Covid-19 pandemic delays) are to advance the depth to diameter borehole ratio from about 1:1 achieved at the PSFC, to 10:1 by the end of the first year, and then to 100:1 by year three using one of ORNL's more than 100 kW continuous wave gyrotrons. During this past year the development work shifted to ORNL with the shipment of diagnostic instrumentation from PSFC. Much of the year was spent in rebuilding lost shipment of diagnostics, conditioning the gyrotron, which had not been used in many years, and trying two non-optimum iterations of the gyrotron transmission line. Full gyrotron power was not achieved, a collimated single mode beam was not transmitted to the rock samples, and there were significant arcing issues. Rock melts showed that the gyrotron beam had a very poor mode quality. New experiments are commencing as of this writing with a new transmission line design and gyrotron mode converter reconditioning.

Magnetic Resonance Division

Recently we determined the structure of $A\beta_{1-42}$ fibrils, the toxic species in Alzheimer's disease. Furthermore, several publications describing high-resolution structures of amyloid-β (Aβ) and other fibrils have demonstrated that magic-angle spinning (MAS) NMR spectroscopy is an ideal tool for studying amyloids at atomic resolution. Nonetheless, MAS NMR suffers from low sensitivity, requiring relatively large amounts of samples and extensive signal acquisition periods, which in turn limits the questions that can be addressed by atomic-level spectroscopic studies. Here, we show that these drawbacks are removed by utilizing two relatively recent additions to the repertoire of MAS NMR experiments—namely, ^{1}H detection and dynamic nuclear polarization (DNP). We show resolved and sensitive 2D and 3D correlations obtained on ^{13}C,^{15}N-enriched and fully-protonated samples of $M_0A\beta_{1-42}$ 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 $M_0A\beta_{1-42}$ (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. An estimate of the sensitivity of the two approaches indicates that the DNP experiments are currently around 6.5-fold more sensitive than ^{1}H detection. These results suggest that ^{1}H detection and DNP may be the spectroscopic approaches of choice for future studies of Aβ and other amyloid systems.

Jagadeesh Moodera

Jagadeesh Moodera is a senior research scientist and a group leader at the Department of Physics, with its research labs located in PSFC; his research effort is in nanoscience condensed matter physics with a 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, Office of Naval Research, and National Science Foundation (NSF) research grants. Collaborators on this research are Professors Patrick Lee and Liang Fu of Physics. He is also part of the large NSF-funded 10-year Science and Technology Centers program

initiated between the Center for Integrated Quantum Materials (CIQM) and MIT, Harvard University, Howard University, and the Museum of Science. Based on the program's success during the past years, the CIQM program will continue until 2023. Another large project acquired funding from the NSF Convergent Accelerator Program (Phase I) on quantum technology. The aim is to investigate and develop robust fault-tolerant, topological qubits based on Majorana states in order to build a scalable, economical, and reliable quantum computer. IBM, the industry leader in quantum computing, has shown significant interest in our Majorana qubit idea. Currently we are seeking funding for this major project.

Recently a four-year project, as a single PI, was granted by NSF. Based on the recent breakthrough results of an exotic property of superconductor structures (under review by a major journal), this project is being funded by the Air Force Office of Scientific Research (AFOSR) starting this month. This is the first grant from AFOSR, which has good potential for continued support.

Yukikazu Iwasa

During AY2022, the Magnet Technology Group, under Senior Research Scientist Yukikazu Iwasa's leadership, was involved in one NIH-supported program on NMR magnets, briefly summarized below.

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 in August 01, 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 Francis Bitter Magnetic Laboratory.

Educational Outreach Programs

The Plasma Science and Fusion Center's educational outreach is planned and organized by Paul Rivenberg. Professor Nuno Loureiro oversees the US Department of Energy 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 public, the national and international scientific communities, and the MIT community.

Our outreach focuses on 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. With the outbreak of Covid-19, PSFC sought alternate ways to reach students and the public through established MIT and national programs.

- USA Science and Engineering Festival (USASEF) SciFest All Access, October 18–24, 2021: This virtual version of the USASEF offered links to MIT and PSFC videos, online plasma outreach, and MIT News articles about women researchers at the PFSC.

- MIT Energy Nights, October 2021: Graduate student Justin Kunimune presented a poster.
- American Physical Society Division of Plasma Physics, November 2021: The PSFC helped plan and staff in-school plasma science talks and demonstrations for Pittsburgh area schools, and a day of virtual workshops for teachers. Postdoctoral Candidate Andrew Seltzman held a workshop.
- Independent Activities Period, January 2022: seven seminars were held, three were recorded for PSFC's YouTube channel, with an effort to introduce undergraduate students to the Undergraduate Research Opportunity Program at PSFC.
- Young Women's Conference, May 2022: PSFC created a virtual booth featuring videos and articles about women working in plasma science at the PSFC. Fifth-year undergraduate Zoe Fisher staffed a panel about career paths.
- Videos: The PSFC has created a Fusion 101 video, narrated by PSFC research scientist Pablo Rodriguez Fernandez, for the website.
- Coalition for Plasma Science: The PSFC continues to work with the Coalition for Plasma Science, supervising the maintenance of their website and growing the organization.
- The Third Computational Physics School for Fusion Research (CPS-FR), August 2022: CPS-FR hosted 34 students, of which eight are from MIT.
- Communications Internship: The PSFC engaged its first high school intern to create content for a series of posters that explain terms and concepts important for understanding the experimental focus of the PSFC.
- Tours: Since March 2022, the PSFC has been able to offer tours to visiting groups. New graduate students were trained to provide tours.

Honors and Awards

- Best Student Paper Award at IEEE International Vacuum Electronics Conference: Julian Picard '21
- Department of Energy National Nuclear Security Administration Laboratory Residency Graduate Fellowship (LGRF), 2022: Justin Kunimune, graduate student
- Frederick A. Howes Scholar in Computational Science Award: Noah Mandell, postdoctoral associate
- Infinite Mile Award: Vinny Fry, mechanical engineer; Ted Golfinopoulos, research scientist; Andy Pfeiffer, operations coordinator; Sam Pierson, deputy engineering coordinator; Phil Michael, research scientist; and Rui Vieira, deputy head of Magnetic Fusion Energy Engineering—honored for their roles in designing and building the world's preeminent large-scale High Temperature Superconductor magnet

- Innovations in Nuclear Technology R&D Awards, second place: Steven Jepeal, PhD ’21
- MIT’s Bose Award for Excellence in Teaching: Michael Short
- MIT’s Henry Ford II Award: Sreya Vangara ’22
- NNSA Secretary’s Honor Award and LLNL Director’s Science and Technology Award for the Creation of a Burning Plasma in the Laboratory: Maria Gatu Johnson, research scientist, and Johan Frenje, senior research scientist and division head
- Ruth and Joel Spira Awards for Excellence in Teaching: Nuno Loureiro
- Robert N. Noyce Career Development Professor appointment, MIT School of Engineering: Zach Hartwig
- University of Saskatchewan Alumni Achievement Award: Dennis White

Appointments

- Bamidele Ebiwonjumi and Sean Ballinger were appointed postdoctoral associates.
- Plasma Theory and Computation Division: Erika Ye, Jan-Peter Bahner, and Soren Hansen were appointed postdoctoral associates.
- High-Energy-Density Physics Division: Brandon Lahmann and Neel Kabadi were appointed research specialists.
- Plasma Science and Technology Division: Guangjiang Li was appointed a postdoctoral associate.
- Magnets and Cryogenics: Carl Bunge and Vasileios Triantopoulos were appointed postdoctoral associates and Armen Sihvashi was appointed a postdoctoral fellow.
- Magnetic Resonance Division: YingYing Wu was appointed a postdoctoral associate and Fangliang Dong was appointed a postdoctoral fellow.

Promotions

- Magnetic Fusion Experiments Division: Ethan Peterson, Andrew Seltzman, Sara Ferry, Adam Kuang, and Roy Tinguely were promoted to research scientists; Samuel Pierson was promoted to DIII-D collaborative resident electrical engineer; Amelia Watterson was promoted to technical associate II; Mohamed Mohamed was promoted to RF engineer; and Ivan Garcia was promoted to staff electrical engineer I.
- High-Energy-Density Physics Division: Johan Frenje was promoted to division head.

Graduate Degrees

- Nuclear Science and Engineering: William McCarthy, Bodhisatwa Biswas, and Abhilash Mathews received PhDs.
- Chemistry: Alexander Scherbakov, Aurelio James Dregni, Madeleine Sutherland, and Brian Michael, received PhDs.

Dennis Whyte
Director, Plasma Science and Fusion Center
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