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, with research activities in five major areas:

1. Magnetically confined plasmas in the development of fusion energy
2. The basic physics of plasmas, including magnetic reconnection experiments on the versatile toroidal facility (VTF), new confinement concepts such as the levitated dipole experiment (LDX), development of novel high-temperature plasma diagnostics, novel diagnostics of inertial fusion experiments, basic laboratory and ionospheric plasma physics experiments, and theoretical research
3. A broad program in fusion technology and engineering development that addresses problems in several areas (e.g., magnet systems, superconducting materials, and system studies of fusion reactors)
4. Research into plasma-assisted conversion of hydrocarbon fuels into hydrogen and the development of environmental monitoring and remediation techniques based on plasma technology
5. The physics of waves and beams (gyrotron and high-gradient accelerator research, beam theory development, non-neutral plasmas, and coherent wave generation)

PSFC research and development (R&D) programs are supported principally by the Department of Energy's Office of Fusion Energy Sciences (DOE-OFES). Approximately 266 personnel are associated with PSFC research activities. These include: 19 faculty and senior academic staff; 57 graduate students and 14 undergraduates; 78 research scientists, engineers, postdoctoral associates, and technical staff; 39 visiting scientists, engineers, and research affiliates, and six visiting students; 27 technical support personnel; and 26 administrative and support staff. Participating faculty and students come from the departments of Chemical Engineering, Electrical Engineering and Computer Science, Materials Science and Engineering, Mechanical Engineering, Nuclear Science and Engineering, and Physics.

PSFC's research budget in FY2005 was $32.0 million, a 2.1% increase over its FY2004 research budget of $31.3 million. Funding for the center's single largest program, the Alcator C-Mod project, varied only slightly from FY2004, decreasing by 1.1% from $19.7 million in FY2004 to $19.5 million in FY2005. Funding for the Physics Research Division, the second largest division at PSFC, also varied only slightly at $5.1 million in FY2005, down 0.9% from its FY2004 level of $5.2 million. Two PSFC research divisions grew this year. The Fusion Technology and Engineering Division grew by over 24% to $4.0 million in FY2005 and the Wave and Beams Division grew by 8.7% to $2.5 million. The Plasma Technology Division, on the other hand, experienced a mild downturn, decreasing 5.4%, from $0.90 million in FY2004 to $0.85 million in FY2005.

In June 2005, an 18-month stalemate over site selection for the multi-billion dollar International Thermonuclear Experimental Reactor (ITER) was resolved when the six participating parties (the European Union, Russia, Japan, China, Korea, and the United

States) agreed that ITER will be built at the French Atomic Energy Commission's (CEA) research center in Cadarache, France. In the coming months, the US ITER Project Office will begin assigning responsibility for various project tasks. Having been responsible for US participation in the design and construction of a very successful CS model coil (the world's largest pulsed niobium-tin superconducting magnet) during the Engineering Design Activity phase of the ITER Program (1992–1998), PSFC is expected to lead the design and supervise the construction of the ITER central solenoid. We anticipate that this will be a $300 million activity over the next 8–10 years, and will require additional staff and office space at PSFC.

With the US government committed to the ITER process, Congress must appropriate funds to pay for the US contribution to the overall cost of ITER (approximately $1.2 billion over the next eight years). Congressional support for ITER had been qualified prior to the recent announcement of an ITER construction site and there have been concerns within the US fusion community that support for ITER could come in part at the expense of certain elements of DOE's national fusion program.

Alcator Division

The Alcator C-Mod tokamak is a major international fusion experimental facility and is recognized as one of three major US national fusion facilities. Dr. Earl Marmar, senior research scientist in the Department of Physics and PSFC, is the principal investigator and project head. The C-Mod team includes full-time equivalent staff at MIT of approximately 50 scientists and engineers, including six faculty and senior academic staff, plus 25 graduate students and 28 technicians (Figure 1). In addition, we have collaborators from around the world, bringing the total number of scientific users of the facility to about 200. The Cooperative Agreement with DOE-OFES, which funds the C-Mod project, was renewed effective November 1, 2003 for a five-year period. Including major collaborators—who are funded at about $2.6 million—total FY2005 funding for the project is about $22.1 million.

Research on C-Mod continued during the past year in high-performance, compact magnetic plasma confinement. Experiments this year are being carried out in the topical science areas of transport, wave-plasma interactions, boundary physics and magnetohydrodynamic stability, as well as in the integrated topic areas of advanced-tokamak and burning plasma science.

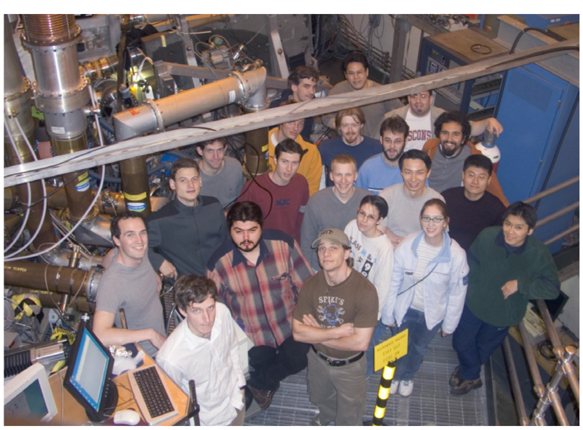

Figure 1. Some of the graduate students who work on the Alcator C-Mod tokamak.

Facility operation for research this fiscal year (FY2005) is planned to total 17 weeks (±10%), similar to the 18.9 weeks operated in FY2004. As of July 15, 2005, 12.5 weeks of the research operations have been completed. Details of the day by day operation for FY2005 can be found at http://www-cmod.psfc.mit.edu/cmod/cmod_runs.php, which includes links to run summaries, mini-proposals and engineering shot logs. Alcator's operation is largely constrained by funding. Current presidential funding guidance funding for the project in FY2006 would allow for 12 weeks of research operation next year; however initial congressional funding would be higher, supporting at least 17 weeks of research operation, the FY2005 level.

Highlights of Recent Research Achievements

Extensive investigations have been made into operation of C-Mod with all metallic (molybdenum) plasma facing components (PFCs), including divertors, and limiters. In preparation for these studies, during the pre-campaign invessel activities, all boron-nitride protection structures were removed from C-Mod and were replaced, and surface coatings of boron from nearly 10 years of wall conditioning and operations were removed. These studies are of broad interest, and particularly important in the context of PFC choices for ITER, where carbon structures may prove incompatible with allowed tritium retention and inventories on that device. Experiments have shown that the high-power density ion cyclotron radio frequency (ICRF) antennas operate reliably with the high-Z metallic protection tiles. Detailed studies of impurity dynamics and the effects of radiated power on plasma energy confinement show that molybdenum impurity concentrations in the plasma must be kept below critical values in order to access the highest pressure plasma regimes in the tokamak. Careful wall conditioning experiments are ongoing to evaluate the underlying physics. One result of our ability to couple 5 MW of ICRF heating power into clean plasmas has been the achievement of the world's highest volume average pressure plasma ever confined in a tokamak, 1.8 atmospheres. This was done at the same magnetic field (5.3 tesla) and the same normalized plasma pressure relative to pressure limits (β_N) as those envisioned for ITER.

Tokamaks are subject to events leading to prompt and total loss of confinement (the so-called major disruption). Many aspects of the physics of major disruptions are understood from worldwide research over the last 20 years. However, no reliable means to completely avoid them has yet been discovered. The consequences of major disruptions can be significant: large forces result from eddy and halo currents induced in structures during the fast plasma decay; direct deposition of plasma energy can cause localized erosion; large inductive voltages are generated during the plasma current decay, which can accelerate some of the plasma electrons to very high energies (>10 MeV) and the interaction of these "runaway" electrons with material surfaces can be deleterious. Approaches to the amelioration of the negative results of disruptions are urgently needed for next-step experiments, especially ITER. Currently, the most promising approach is to use a rapid injection into the disrupting plasma of noble gas at very high pressure. Results of studies on the DIII-D tokamak have shown that this can soften the impacts of the disruption, at least in plasmas with moderate pressure. These results must now be tested with higher absolute pressure plasmas (on Alcator C-Mod) and larger size plasmas (Joint European Torus, in Culham, UK). In collaboration with the University of Wisconsin, the C-Mod experiments have begun and have already shown that the disruption time scale can be shortened and halo currents reduced. Additional studies will be carried out to look at radiation dynamics, surface power loading and the growth of magnetohydrodynamic (MHD) instabilities during the gas jet penetration. Detailed comparisons of these results are being made with predictions from state-of-the-art 3-D MHD simulation calculations.

An important milestone was reached during the current campaign with the installation and first operation of the lower hybrid microwave system, which is a key tool for control of current profiles in advanced scenarios. The long-term goals of this research are to: demonstrate and develop predictive models for current profile control, leading to full noninductive current drive for pulse lengths that are long compared to current profile relaxation times; produce, understand, and control core transport barriers with strongly coupled electrons and ions; and attain and optimize plasma pressure up to the no-wall β limits, with normalized β_N of at least 3. The initial lower hybrid experiments have shown excellent control of wave phasing in the multi-waveguide launcher arrays, and wave-plasma coupling, which is in agreement with model predictions. Following modifications to remove titanium from the launchers (which was found to be incompatible with the C-Mod environment), lower hybrid experiments will resume in the coming fiscal year.

Physics Reseach Division

The goal of the Physics Research Division, headed by Professor Miklos Porkolab, is to improve theoretical and experimental understanding of plasma physics and fusion science. This division maintains a strong basic and applied plasma theory and computation program while developing basic plasma physics experiments, new confinement concepts, novel inertial fusion diagnostics, and space plasma physics experiments.

Fusion Theory and Computations

The theory effort, led by Dr. Peter Catto and predominantly funded by DOE, focuses on both basic and applied fusion plasma theory research. It supports the Alcator C-Mod and other tokamak experiments worldwide, LDX (which began operation within the last year), and VTF. A key support tool to carry out the center's state-of-the-art computational work is a 50-processor computer cluster (with high speed and low latency interconnect) that was assembled last year by the theory group. To follow are highlights of important contributions made by this group during the past year.

Tokamak Confinement and Transport

Dr. Darin Ernst has continued investigations of the mechanisms for the formation and control of the internal transport barriers in Alcator C-Mod using first principles kinetic simulations of plasma turbulence. He has also discovered a new nonlinear upshift of the critical density gradient for onset of trapped electron mode turbulence and found that the simulated turbulent spectra are in qualitative agreement with experimental phase contrast imaging measurements.

Turbulence levels are sometimes controlled by the shear in the plasma flow and the radial electric field. Dr. Catto's tokamak studies continue to focus on these effects at the edge (in the steep plasma density and temperature gradient region just inside the separatrix) of Alcator C-Mod and other tokamaks. He and Dr. Andrei Simakov, of Los Alamos National Laboratory, have employed their recently developed short mean free path fluid description to evaluate the radial electric field in tokamaks of arbitrary cross sections.

Magnetohydrodynamics and Extended MHD

Drs. Jesus Ramos, Catto, and Simakov have begun developing fluid and kinetic descriptions for strongly magnetized plasmas of arbitrary collisionality by extending their previous finite Larmor radius results on particle, energy, and momentum fluxes in collisionless and strongly collisional plasmas. Dr. Ramos's earlier collisionless extended MHD work is being supported by DOE's Scientific Discovery Through Advanced Computing Initiative (SciDAC) and is being incorporated into their numerical simulation models.

In addition, Professor Jeff Freidberg has nearly completed an introductory plasma energy textbook for first-year graduate students in which the material is presented from an engineering viewpoint.

Heating, Current Drive, Advanced Tokamaks, and Nonlinear Dynamics

Drs. Paul Bonoli and John Wright's funding through DOE-OFES's SciDAC initiative has allowed them to further develop a full-wave electromagnetic field solver to simulate millimeter waves in the lower hybrid range of frequencies. The code was rewritten in collaboration with Professor Marco Brambilla of the Max-Planck-Institut für Plasmaphysik (Garching, Germany), and the new version greatly improves numerical stability at very high resolution. Detailed studies compared the full-wave code predictions of diffraction induced spectral broadening at wave caustics with ray tracing predictions. This work is crucial to lower hybrid current drive experiments just beginning on Alcator C-Mod, and also for future experiments in ITER that will likely rely on lower hybrid current profile control for steady-state operation.

Magnetically confined toroidal plasmas rely on plasma currents for stability. PhD student Joan Decker, working with Dr. Abhay Ram (PSFC) and Yves Peysson (CEA), and advised by Professor Abe Bers (MIT), has shown how Bernstein waves in the electron cyclotron frequency range can generate current both in the core and outer half of the plasma. The former is done by an asymmetric modification to the plasma resistivity, and the latter by inducing asymmetric electron trapping. This allows tailoring of the current profile to control MHD instabilities and optimize confinement of the plasma in spherical tori.

Levitated Dipole Experiment Stability, Heating, and Confinement

Theory research in support of LDX, led by Dr. Jay Kesner, has found that dipole equilibria can be stable at arbitrary plasma pressure provided the pressure gradient remains below the ideal interchange limit and weak resistive modes saturate at low amplitudes. Now that LDX is operating with electron cyclotron heating, the role of hot electrons on stability is being investigated. Dr. Catto and PhD student Natalia Krasheninnikova are studying the impact of resonant hot electrons on the interchange mode, while Dr. Kesner and Ms. Krasheninnikova are focusing on the higher-frequency hot electron interchange instability.

Experimental Research

Levitated Dipole Experiment

LDX represents a new and innovative approach to magnetic fusion, which will utilize a levitated superconducting coil to confine plasma in a dipole magnetic field. LDX is a joint collaborative project with Columbia University and is located in Building NW21 at MIT (Figure 2). The principal investigators of this project are Dr. Jay Kesner (MIT) and Professor Michael Mauel (Columbia University). The project was renewed in FY2004 by DOE as a three-year grant at an approximate annual budget of $1.4 million (shared between MIT and Columbia University).

Figure 2. Dr. John Willis (US Department of Energy) and Professor Alice Gast (vice president for research and associate provost) cut ceremonial ribbon at the dedication of the DOE-funded Levitated Dipole Experiment at PSFC as other staff, students, and visitors look on.

The LDX facility was designed collaboratively by the LDX physics group and the engineering division of the Plasma Science and Fusion Center under the leadership of Dr. Joseph Minervini. LDX utilizes three unique superconducting coils and is the only superconducting magnetic confinement experiment in the US fusion research program. The coils include a high performance Nb_3Sn "floating coil" and cryostat, an 11 MJ "charging coil" (built in Russia), and a "levitation coil" that utilizes a high-temperature superconductor. The construction and assembly of the facility has been completed and experimentation began in August 2004.

During the initial experimental campaign that is presently under way, the dipole coil is mechanically supported within the LDX vacuum chamber. Initial experiments indicate a clear transition into a high-pressure plasma regime, as had been predicted. These experiments also provide a database for supported operation to be compared with the later levitated experiments and provide an opportunity to test the coil operation, the diagnostic set and the control system. In the next phase of operation, beginning in fall 2005, the dipole coil will be levitated.

Magnetic Reconnection Experiments on the Versatile Toroidal Facility

Magnetic reconnection plays a fundamental role in magnetized plasmas as it permits rapid release of magnetic stress and energy through changes in the magnetic field line topology. It controls the spatial and temporal evolution of explosive events such as solar flares, coronal mass ejections, and magnetic storms in the earth's magnetotail, driving the auroral phenomena. Magnetic reconnection is studied in VTF (Figure 3). Experimental observations in VTF have lead to the development of a new kinetic theory for reconnection. This year a Physical Review Letter was published documenting how this new theory can account for detailed measurements of reconnection obtained by NASA's Wind spacecraft in the earth's magnetotail. Dr. Jan Egedal has recently been appointed an assistant professor in the Physics Department, and will become the new VTF group leader on September 1. He will continue the study of magnetic reconnection in a new improved magnetic geometry based on the VTF device. The experimental activities are now funded by DOE/National Science Foundation (NSF) at a level of $175,000 per year. Also, two physics graduate students working with Dr. Egedal (Will Fox and Noam Katz) have both won DOE fellowships to sponsor their thesis research on VTF.

Figure 3. Visible light image of an argon plasma discharge in the PSFC's Versatile Toroidal Facility applied for the study of magnetic reconnection in collisionless plasmas.

PSFC/Joint European Torus Collaboration on Alfvén Wave Propagation and Instabilities

Professor Porkolab leads this project, with active involvement by Dr. Joe Snipes (PSFC) and an MIT postdoctoral fellow located at the Joint European Torus (JET) site in, Culham, UK. This program conducts experiments at JET, the world's largest tokamak, near Oxford, UK. In these experiments, waves are launched by specially built antennas, the most recent of which has just been installed in JET. Studies of wave propagation and damping processes will be carried out in the coming year. In addition, instabilities driven by high-energy particles, such as neutral beam ions, RF-driven energetic ions, and ultimately, alpha particles, are studied. These studies lead to an improved understanding of plasma stability and transport that will be important in future burning plasma experiments where the fusion process generates a substantial alpha particle component.

Inertial Confinement Fusion Experiments

Dr. Richard Petrasso and his group (Figure 4) continues its longstanding work and collaborations in inertial confinement fusion (ICF) with the University of Rochester's Laboratory for Laser Energetics and the National Ignition Facility (NIF), which is under construction at Lawrence Livermore National Laboratory. The University of Rochester's 30-kJ, 60-beam OMEGA laser provides the most important current test bed for ICF experiments, and the huge NIF will host the next generation of ICF experiments. NIF is expected to achieve ignition (self-sustaining burn and net energy gain) by imploding fuel capsules with a 2-MJ, 192-beam laser. This is to happen in 2010, and MIT is intensely involved in preparing for these ignition experiments.

This year, PSFC began its participation in a newly formed national Fusion Science Center on Extreme States of Matter and Fast Ignition that will be situated at the University of Rochester. Dr. Petrasso's group also plays the lead role in organizing and coordinating the basic science users community for NIF. Especially noteworthy in the last year have been experimental measurements of important aspects of fusion burn in ICF experiments on OMEGA. While not yet self-sustaining, this burn represents the achievement of fusion-relevant conditions in ICF plasmas; its characterization is

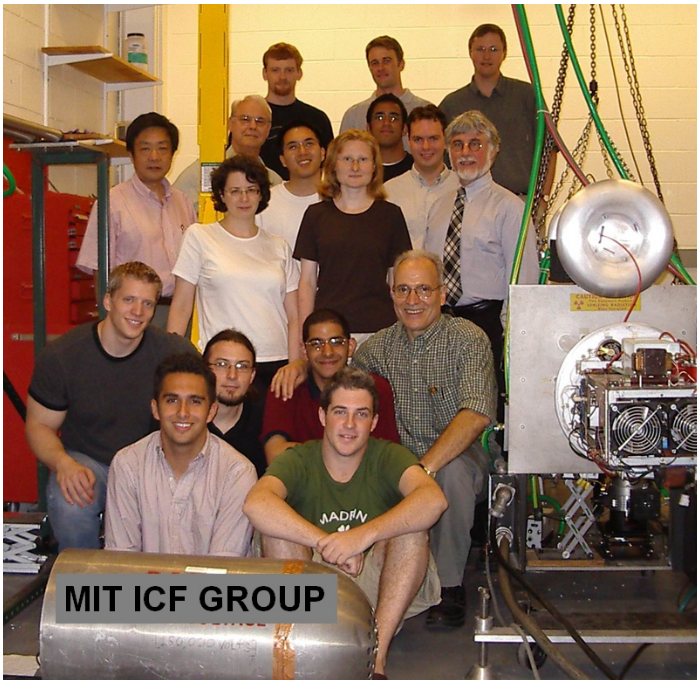

Figure 4. PSFC's High Energy Density Plasma and Inertial Confinement Fusion Physics Group, headed by Dr. Richard Petrasso (second row, fourth from left). Also pictured is PSFC director Miklos Porkolab (fourth row, adjacent and to the right of the yellow column).

essential to an understanding of plasma dynamics and to progress toward ignition in 2010. MIT-developed techniques were used to study the time evolution and 3-D spatial distribution of nuclear burn by detecting charged fusion products. The burn time evolution, with direct information about implosion dynamics and shock-wave coalescence, is measured with a proton temporal diagnostic (PTD); the burn spatial distribution is determined by multiple proton emission imaging cameras. Images of asymmetric burn distributions, generated by asymmetric laser drive, are being used in conjunction with PTD data and charged-particle spectra to determine how fuel-capsule implosion dynamics, spatial distributions of both hot and cold plasma, and fusion burn are related to laser drive symmetry. Another important area of work has been theoretical studies of how an intense beam of energetic electrons, which may someday start the ignition process in a fuel capsule previously compressed through laser drive, actually interacts with the fuel plasma. In addition to the senior staff, these research projects involve direct participation of 4 PhD and 6 undergraduate students.

Novel Diagnostics for Magnetic Fusion Research

Phase Contrast Imaging Diagnostic of Turbulence on DIII-D and C-Mod

Under the leadership of Professor Porkolab, PSFC research scientist Dr. Chris Rost (at DIII-D in San Diego) and postdoc Nils Basse (at C-Mod) and graduate students at DIII-D and C-Mod, have upgraded the phase contrast imaging diagnostics to detect short wavelength (sub-cm), high-frequency (up to 10 MHz) modes. The shorter wavelength modes (the so-called TEM and ETG modes) should play a fundamental role in determining electron transport, one of the frontiers of fusion research. These experiments have commenced on C-Mod, but have been delayed on DIII-D until next spring, when the DIII-D tokamak will resume operation after a lengthy modification of the neutral beam system. Meanwhile, the pioneering mode conversion experiments during ICRF heating on C-Mod will continue.

Collective Thomson Scattering off Ions in Textor and Asdex-U

An international partnership consisting of PSFC, Risø National Laboratory (Denmark), Intitut für Plasmaphysik (Jülich, Germany), and Max-Planck-Institut für Plasmaphysik, (Garching, Germany) is pursuing the development of fast ion collective Thomson scattering (CTS) diagnostics. Experiments have been implemented at the Textor (Jülich) and ASDEX-Upgrade (Garching) tokamaks using powerful millimeter-wave gyrotron sources available at these facilities. Recently measurement of fast confined beam ions have been carried out in Textor, demonstrating the viability of this diagnostic. The development of fast ion diagnostics is considered essential for the advancement of fusion burning science, which must measure the energetic product alpha particles during fusion burn. This activity also involves the design and application of CTS to ITER fusion alpha product diagnostics.

Ionospheric Plasma Research

A series of space plasma experiments were conducted by PSFC's Ionospheric Plasma Research Group (visiting scientist Min-Chang Lee and MIT Undergraduate Research Opportunities Program students) last summer and winter at Arecibo, Puerto Rico, using NSF's 430 MHz incoherent scatter radar together with PSFC's optical and radio plasma diagnostic instruments (Figure 5) to investigate source mechanisms producing ionospheric plasma turbulence over Arecibo. Very intense space plasma turbulence was detected on December 26, 2004, about 26 hours after the occurrence of the disastrous tsunami associated with the magnitude 9.0 earthquake off the west coast of northern Sumatra, Indonesia. Supported satellite measurements by the Department of Defense's Defense Meteorological Satellite Program, the Arecibo experiments and theoretical analysis suggest that tsunami-generated gravity waves traveled from Asia to Puerto Rico in a day and, subsequently, triggered interchange instabilities to yield large-scale ionospheric plasma turbulence. These results will be published in a paper in *Geophysical Research Letters*, reporting the evidence that air-sea interactions can be a potential source of significant space plasma turbulence. Preliminary experiments aimed at examining whistler wave-particle interactions in the earth's radiation belts over Puerto Rico have shown that a broad range of short-scale plasma turbulence can be created by the precipitated energetic charged particles in the ionosphere.

Figure 5. MIT students setting up radar electronics for experiments at the Arecibo Observatory in Puerto Rico.

Waves and Beams Division

The Waves and Beams Division, headed by Dr. Richard Temkin, conducts research on novel sources of electromagnetic radiation and on the generation and acceleration of particle beams. Substantial graduate student involvement is emphasized in all research programs within the division.

Gyrotrons are under development for electron cyclotron heating of present day and future plasmas, including ITER plasma; for high-frequency radar; and for spectroscopy. These applications require gyrotron tubes operating at frequencies in the range of 90–500 GHz at power levels of up to several megawatts. In FY2005, the Gyrotron Group headed by Dr. Michael Shapiro designed a novel resonator for a 110 GHz gyrotron. It operated for 3 microseconds at power levels of over 1.6 MW and an efficiency of over 40% without a depressed collector. These results have now been analyzed by the University of Maryland's nonlinear, multimode code MAGY and agreement between theory and experiment is very good. The experiment has been rebuilt to test a depressed collector, which can increase the overall efficiency to more than 50%. The research at MIT will be followed by a development program for a continuous wave gyrotron, which will be built and tested at an industrial vendor, Communications and Power Industries (Palo Alto, CA). R&D in support of the ITER program is also now under way.

Intensive research continues on 250–500 GHz gyrotrons for use in electron spin resonance and nuclear magnetic resonance studies. This research, funded by the National Institutes of Health, is a collaboration with Professor Robert Griffin of MIT's Francis Bitter Magnet Laboratory. In FY2005, we demonstrated 8 W of continuous wave output power at 460 GHz for one hour, a world record for power at this frequency. We also observed wide range tuning—up to 2 GHz—of modes at the fundamental frequency, near 230 GHz, a result which could be very useful for developing widely tunable gyrotrons.

PSFC research on high-gradient accelerators is focused on high-frequency linear accelerators for application to future multi-TeV electron colliders. In FY2005, the High Gradient Accelerator Group continued operation of the Haimson Research Corp. 17 GHz electron accelerator (Figure 6). This is the highest-power accelerator on the MIT campus and the highest frequency stand-alone accelerator in the world. Smith-Purcell radiation at THz frequencies was measured when the electron beam from the accelerator passed over the grating. Bunch-to-bunch coherence was observed for the first time and analyzed with a new theory. A six-cell photonic bandgap accelerator was tested using 2 MW of power from a 17 GHz klystron, producing electron acceleration at 35 MV/m.

The Intense Beam Theoretical Group, led by Dr. Chiping Chen, has contributed to our understanding of coherent radiation generation and particle acceleration. Topics covered include control of halo formation in intense electron and ion beam transport, and the design of dielectric photonic band gap structures for use in coherent radiation sources and accelerators. An important recent achievement is a new theory describing the formation and transport of sheet electron beams.

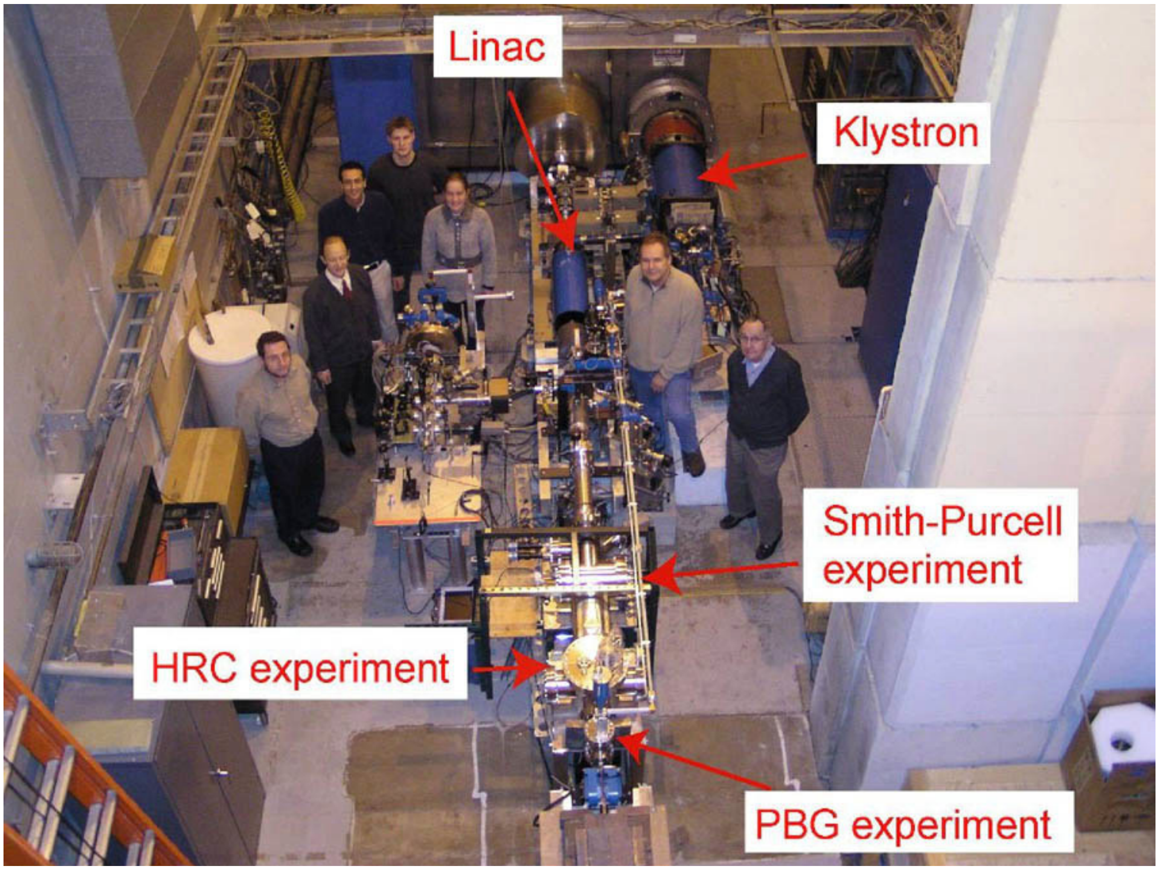

Figure 6. Haimson Research Corp./MIT 17 GHz Accelerator Laboratory, the highest frequency, stand-alone accelerator in the world and a world-class facility for advanced accelerator research.

Fusion Technology and Engineering Division

The Fusion Technology and Engineering (FT&E) Division, headed by Dr. Joseph Minervini, conducts research on conventional and superconducting magnets for fusion devices and other large-scale power and energy systems. The division's major emphasis continues to be support of the US Fusion Program, where PSFC has the leadership responsibility for the Magnets Enabling Technology program. The primary fusion magnet technology task (D&T-01) had been flat at the nominal $1,800,000 level for several years, but with the revival of the ITER project a new focus has been given to magnet technology. In this project, the US would contribute its share of the machine cost (about 10%) as contributions-in-kind hardware. Foremost among these in cost and highest in priority is all or part of the central solenoid (CS) magnet system. If the US contributes the entire magnet, this project is expected to cost as much as $400 million over the next 10 years, including engineering and supporting R&D, industrial procurements, and contingency. In preparation for this new, major project, an additional $1.25 million was made available to MIT in FY2005 to begin critical R&D and manufacturing development for the central solenoid magnet. In September 2005, PSFC will compete to become the principal laboratory responsible for the ITER central solenoid with FT&E Division personnel playing leadership roles in CS project management and supporting R&D and engineering. We conservatively estimate that direct funding at MIT would average approximately $3–4 million per year for eight years. Some increase in division staff will be necessary to support this project.

The division continued its leadership role for solenoid magnet systems of the muon-to-electron conversion experiment (MECO), which is part of the Rare Symmetry Violating Processes (RSVP) project. The experiment is to be installed at Brookhaven National Laboratory in conjunction with the Alternating Gradient Synchrotron facility. FT&E Division staff member Bradford Smith serves as the MECO magnets subsystem manager and this year has been promoted to MECO magnet project manager. Recent changes in RSVP senior project management have resulted in an increased role for MIT. In March, we received supplemental funding of nearly $700,000 as the project expected to enter the construction phase in FY2006. The RSVP project underwent a baseline review by NSF in April 2005. Although the review of the magnet system was successful, recent congressional budget actions have placed construction of the RSVP experiments in jeopardy. At this time, the most likely outcome is that all construction funding will be eliminated. It is possible that NSF may request that the RSVP collaboration redesign or rescope the project and hopefully some limited funding would be available in FY2006. The division, however, does not expect this to happen and present plans call for all division personnel working on MECO to be reassigned to ITER work, which should have sufficient funds to absorb these personnel.

PSFC also continues its collaboration with Brookhaven National Laboratory, Princeton University, and other institutions that are developing mercury jets as targets for a muon collider or neutrino factory. Peter Titus leads the MIT effort to design a cryogenically cooled, pulsed copper magnet that can produce 15T and be used for the mercury jet targetry experiment. The magnet fabrication is nearing completion in industry under MIT oversight. Upon completion later this summer, the magnet and cryostat will be shipped to PSFC and tested using power supplies and a liquid nitrogen cooling system that are part of the division's Pulse Test facility.

The division has made substantial progress on a privately funded project to develop a 250 MeV synchrocyclotron for proton beam radiotherapy. This work is carried out under the direction of Dr. Timothy Antaya of the FT&E Division. K250 is a synchrocyclotron capable of accelerating protons to 250 MeV and delivering a continuous current of up to 100 nA to treat cancer patients. The magnet system is a split dipole pair, providing most of the field needed for synchronous acceleration of ions, along with a warm iron yoke to add field and shape the field index. An additional warm iron shield is used to reduce magnetic field leakage to 20 g at 2 m from the magnet/cyclotron center. The magnet and cyclotron system will be mounted on a rotating gantry in a patient treatment room and must operate safely and reliably, while being rotated 180° around the patient. This project will continue through FY2006 with the major goal of developing the design to a level detailed enough to be manufactured by industry. Subsequently, we expect that MIT will remain responsible for oversight of the industrial fabrication of the device, as well as installation and start-up operations in a clinical environment. This new cancer therapy system has already attracted substantial offers from several leading hospitals and clinics from around the US to host the first and subsequent installations of this advanced medical technology.

An MIT collaboration with the Lawrence Berkeley National Laboratory and the Lawrence Livermore National Laboratory for the Inertial Fusion Energy (IFE) project to develop superconducting magnet technology was cancelled because DOE-OFES eliminated funding for IFE technology in FY2005 and beyond.

Finally, the FT&E Division is developing two new proposals for application of electromagnets and superconducting magnets to two new advanced technologies, which we expect to have a high probability of being awarded in FY2006.

Plasma Technology Division

The objectives of the Plasma Technology Division, led by Drs. Daniel Cohn and Paul Woskov, are to develop new fusion spin-off applications, particularly in the environmental and hydrocarbon energy efficiency areas; to develop new environmental technology diagnostics and fusion diagnostics (see section on Collective Thomson Scattering off Ions in Textor and Asdex-U); and to develop/improve on new fusion reactor concepts.

A major research area for the division has been plasma-assisted conversion of hydrocarbon fuels into hydrogen. Hydrogen has potential environmental advantages as a fuel additive that can greatly reduce pollution from motor vehicles and stationary electricity generation systems. It can also be used to increase the efficiency of converting hydrocarbon fuels into mechanical power or electrical power. Special plasma technology, referred to as plasmatron reformers, can provide important technical advantages for enhancing the generation of hydrogen from hydrocarbon fuels.

From 2001 to 2004, ArvinMeritor, a major US manufacturer of automotive components, provided $1 million per year for MIT research related to the application of plasmatron reformer devices to vehicles with conventional internal combustion engines. This funding included support for investigations of the effects of hydrogen on gasoline engine operation, which were carried out at the MIT Sloan Automotive Laboratory under the direction of Professor John Heywood.

On a DOE-supported project, the Plasma Technology Division has investigated the use of plasmatron reformer–generated hydrogen as a means to significantly improve catalytic elimination of NO_x in diesel engine exhaust. In parallel, under a licensing agreement with the MIT Technology Licensing Office, ArvinMeritor is working to develop this technology into a commercial product using intellectual property developed at PSFC. Plasmatron enhanced catalytic NO_x reduction could play an important role in substantially reducing diesel vehicle emissions. The DOE-sponsored research also studies the use of plasmatron reformer technology to convert biofuels, including ethanol and bio-oils, into hydrogen-rich gas for vehicular applications.

ArvinMeritor, has successfully tested MIT's plasmatron enhanced emissions abatement technology on a bus on a test track at their Columbus, IN, facility. NO_x emissions were reduced by 90%. The technology shows excellent promise for meeting stringent new Environmental Protection Agency diesel emissions reduction regulations, which will be introduced beginning in 2010. The eventual market for this technology could exceed

$1 billion per year. Unfortunately, in FY2005 ArvinMeritor discontinued funding of this program at PSFC.

The division is pursuing support for a new concept for greatly reducing the fuel energy requirement for diesel exhaust aftertreatment. The concept uses spatially selective application of the hydrogen-rich gas from the plasmatron reformer. A factor of five reduction in the fuel energy requirement may be attainable.

The Plasma Technology Division is also developing and applying advanced diagnostics and online monitoring technologies for fusion plasma research and nuclear waste vitrification processing. The online monitoring capabilities for nuclear waste vitrification use millimeter-wave (MMW) technologies. Electromagnetic radiation in the 10–0.3 mm (30–1000 GHz) range of the spectrum is ideally suited for remote measurements in harsh, optically unclean, and unstable processing environments. Millimeter waves are long enough to penetrate optical/infrared–obscured viewing paths through dust, smoke, and debris, but short enough to provide spatially resolved point measurements for profile information. Another important advantage is the ability to fabricate efficient MMW melter viewing components from refractory materials. The same ceramics and alloys from which the melter is constructed can be used to fabricate MMW waveguide/ mirror components that go into the melter for long-life survivability.

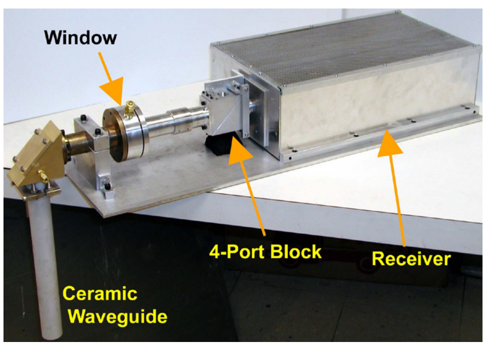

Figure 7. Millimeter-wave receiver and waveguide for high-temperature research of nuclear waste glass melts at the US Department of Energy's Savannah River Site.

This year, the Savannah River National Laboratory has installed key hardware components of the millimeter-wave diagnostic system for additional tests on the slurry-fed melt rate furnace (SMRF) at the Savannah River site. Melt pour dynamics on SMRF were observed for the first time. Also this year, the molten dynamics of salt layer formation have been studied in that laboratory to better understand earlier field measurements. The potential for salt layer formation in nuclear waste vitrification facilities is currently considered a major issue that must be resolved for fast and cost-effective remediation of high-level and low-activity wastes.

Finally, in a program led by Dr. Leslie Bromberg, the Plasma Technology Division has recently began to develop a promising new approach for substantially increasing the sensitivity and selectivity for detection of explosives and chemical agents. This approach, the Plasma for Mobility Spectrometer, was recently selected for advanced concepts funding by Lincoln Laboratory. This work is relevant to both Department of Homeland Security and Department of Defense needs. Dr. Bromberg has recently been informed that the Department of Homeland Security would like to fund proposed research on a compact, low-cost sensor for explosives and chemical warfare agents.

Educational Outreach Programs

The Plasma Science and Fusion Center's educational outreach program is planned and organized under the direction of Mr. Paul Rivenberg, communications and outreach administrator of PSFC. The program 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 real laboratory and research environments. Hopefully, this kind of interaction encourages young people to consider science and engineering careers. Tours of our facilities are also available for the general public. Annual visitors include participants from the Keys to Empowering Youth and the National Youth Leadership Forum. Outreach Days are held twice a year, encouraging high school and middle school students from around Massachusetts to visit PSFC for hands-on demonstrations and tours. PSFC graduate students who volunteer to assist are key to the success of our tour programs. The experience helps them develop the skill of communicating complex science principles to those who do not have advanced science backgrounds.

The Mr. Magnet Program, headed by Mr. Paul Thomas, has been bringing lively demonstrations on magnetism into local elementary and middle schools for 14 years. This year Mr. Magnet presented the program to many thousands of students at over 75 schools and other events, reaching kindergartners through college freshmen. He makes a special effort to encourage girls to consider science-related careers. In April 2005, Paul Thomas traveled with his truckload of equipment to Washington, DC, at the request of the Department of Energy, to involve participants of the DOE National Science Bowl with his demonstration of magnetic and plasma phenomena. In addition to his program on magnets, he is offering a program about plasma to high schools and museums. This interactive demonstration encourages participants to investigate plasma properties using audiovisual, electromagnetic, and spectroscopic techniques. In November, Mr. Thomas gave an invited talk on these programs at the American Physical Society—Division of Plasma Physics (APS-DPP) annual meeting. He has also developed a workshop for middle schools on how to build an electromagnet. Over the past year, he has also been working with Boston's Museum of Science to bring plasma and magnet education to the museum. Separate from this, Paul Rivenberg, along with research scientists Jay Kesner and Darren Garnier, have worked with the museum to create a simple video exhibit about the cutting-edge research going on in the levitated dipole experiment.

PSFC continues to collaborate with other national laboratories on educational events. An annual Teacher's Day (to educate middle school and high school teachers about plasmas) and Plasma Sciences Expo (to which teachers can bring their students) has become a tradition at each year's APS-DPP meeting. This year Mr. Rivenberg led the effort for the meeting's education events in Savannah, GA, which attracted 72 teachers and over 3,000 students. Mr. Thomas and Ms. Valerie Censabella, Nuclear Engineering Department administrator, were also involved, along with numerous PSFC graduate students. In conjunction with this local education effort, PSFC and other US plasma organizations successfully encouraged Georgia education administrators to add plasma (as the fourth state of matter) to their state science standards.

PSFC also continues to be involved with educational efforts sponsored by the Coalition for Plasma Science (CPS), an organization formed by members of universities and national laboratories to promote understanding of the field of plasma science. Associate director Dr. Richard Temkin, who oversees PSFC education efforts, is working with this group on goals that include requesting support from Congress and funding agencies, strengthening appreciation of the plasma sciences by obtaining endorsements from industries involved in plasma applications, and addressing environmental concerns about plasma science. Paul Rivenberg continued his duties as editor of the coalition's Plasma Page, which summarizes CPS news and accomplishments of interest to members and the media. Mr. Rivenberg also heads a subcommittee that created and maintains a website to help teachers bring the topic of plasma into their classrooms. He also works with the coalition's Technical Materials subcommittee, to develop material that introduces the layman to different aspects of plasma science.

Awards, Appointments, and Promotions

During the past year, a number of PSFC staff have received awards, received appointments, or have been promoted:

Awards

Mr. David Terry and Dr. Stephen Wukitch received MIT 2005 Infinite Mile Awards for their contributions to the Alcator Project; Physics graduate student Ronak Bhatt received a Best Student Paper prize at the Particle Accelerator Conference in Knoxville, TN.

Appointments

Alcator Division: Mr. Douglas Knight was appointed mechanical engineer, Mr. J. Fred Riley was appointed RF engineer, Dr. Theodore Biewer was appointed research scientist, Mr. David Johnson was appointed high-power microwave control engineer, and Mr. Thomas Willard was appointed mechanical engineer.

Waves and Beams Division: Dr. Ronald Stowell was appointed postdoctoral associate.

Fusion Technology and Engineering Division: Dr. Ji Hyun Kim was appointed postdoctoral associate.

Physics Research Division: Ms. Jocelyn Schaeffer was appointed research specialist and Mr. Sean McDuffee was appointed research specialist.

PSFC Fiscal Office: Ms. Moonmoon Chakravarthy was appointed assistant fiscal officer.

Promotions

Waves and Beams Division: Dr. Jagadishwar Sirigiri was promoted to research scientist.

Graduate Degrees

During the past year, three departments awarded students degrees with theses in plasma fusion and related areas:

- Nuclear Science and Engineering: Jennifer Ellsworth, MS; Brian Youngblood, MS; Joseph Deciantis, MS; Taekyun Chung, PhD; Jerry Hughes, PhD; Balint Veto, MS; Howard Yuh, PhD.
- Physics: Stephen Korbly, PhD; Evgenya Smirnova, PhD.
- Electrical Engineering and Computer Science: James Anderson, PhD; Joan Decker, PhD; Melissa Hornstein, PhD.

Miklos Porkolab
Director
Professor of Physics

More information about the Plasma Science and Fusion Center can be found online at http://www.psfc.mit.edu/.