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 conducts research in five major areas:

- Magnetically confined plasmas in the development of fusion energy
- The basic physics of plasmas, including magnetic reconnection experiments on the VTF facility, new confinement concepts such as the levitated dipole experiment, development of novel high-temperature plasma diagnostics, novel diagnostics of inertial fusion experiments, basic laboratory and ionospheric plasma physics experiments, and theoretical research
- Fusion technology and engineering development to address problems in areas such as magnet systems, superconducting materials, and system studies of fusion reactors
- Plasma-assisted conversion of hydrocarbon fuels into hydrogen and the development of environmental remediation techniques based on plasma technology
- The physics of waves and beams (gyrotron and high-gradient accelerator research, beam theory development, non-neutral plasmas, and coherent wave generation)

PSFC's R&D programs are supported principally by the Department of Energy's Office of Fusion Energy Sciences. There are approximately 267 personnel associated with PSFC research activities, consisting of 18 faculty and senior academic staff members; 56 graduate students and 15 undergraduates; 77 research scientists, engineers, postdoctoral associates, and technical staff; 50 visiting scientists, engineers, and research affiliates; 25 technical support personnel; and 26 administrative and support staff. Participating students and faculty are from the Aeronautics & Astronautics, Electrical Engineering and Computer Science, Materials Science and Engineering, Mechanical Engineering, Nuclear Engineering, Chemical Engineering, and Physics departments.

The PSFC research budget for FY2004 was $31.9 million, a $3.8 million (13.5%) increase over FY2003. The PSFC's single largest research effort—the Alcator C-Mod project—increased by $3.3 million (nearly 21%), from $15.9 million in FY2003 to $19.2 million in FY2004. Funding for the PSFC's other four research divisions also grew by $0.5 million, for a net gain of $3.8 million over FY2003 for the PSFC as a whole.

A final decision by the government regarding US participation in the International Thermonuclear Experimental Reactor (ITER) Program has been delayed by the current stalemate among ITER's international partners (the European Union, Russia, Japan, China, Korea, and the United States) on the final selection of a construction site for this multi-billion dollar fusion science experiment. During the design phase of the ITER

Program, MIT was given oversight responsibility for the design and construction of a large superconducting central solenoid magnet that served as a prototype of ITER's full-scale central solenoid (CS) coil. Should the siting impasse be resolved, the PSFC would welcome the opportunity to play a significant role in the design of the full-scale ITER CS coil. The US DOE recently announced the organizational structure of the US ITER Project Office management team but has not yet determined which US institution will assume the leadership role for magnet subsystems. The PSFC will actively compete for the leadership role of the ITER central solenoid oversight manager position.

Alcator Division

The Alcator C-Mod tokamak is a major international fusion experimental facility that is recognized as one of three major fusion facilities in the United States. Dr. Earl Marmar, senior research scientist in the Department of Physics and the PSFC, is the principal investigator and project head. The C-Mod team includes full-time equivalent staff of approximately 50 scientists and engineers, with 6 faculty and senior academic staff, plus 24 graduate students and 22 technicians. In addition we have collaborators from around the world, bringing the total number of scientific users of the facility to about 165. The Cooperative Agreement with the Department of Energy, Office of Fusion Energy, for the C-Mod project was renewed effective November 1, 2003, for a five-year period. Including major collaborators, total FY2004 funding for the project is about $22.2 million.

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

Facility operation for research this fiscal year (FY2004) totaled 75.5 days, which was 3.5 days more than the originally planned 18 weeks (@4 days/week), up from 13 weeks in FY2002. Details of the day-by-day operation for FY2004 can be found in a table located at http://www.psfc.mit.edu/cmod/operations/FY04_research_table.html, which includes links to run summaries, mini-proposals, and engineering shot logs. Alcator's operation is largely constrained by funding. Current guidance funding for the project in FY2005 would allow for 14 weeks of planned research operation next year.

Highlights of recent research achievements include the following:

—The C-Mod facility operation was extended this year to 2 MA plasma current for the first time. This extension was made possible, at least in part, by the operation of our new asymmetric control coils, which allow for nulling of the most important component of non-axisymmetric error fields; previously, development of locked modes had prevented operation above 1.6 MA.

—Error fields, and associated locked modes, can lead to confinement degradation and even major disruption. Particularly important for ITER are the questions of field and size scaling of the locking threshold (in B_{error}/B_T). To investigate these issues, we have been carrying out coordinated experiments with DIII-D and JET. Initial results show that previous pessimistic scalings developed from Compass/DIII-D/JET experiments are not confirmed by the C-Mod. To the contrary, the sensitivity to error fields appears to be almost independent of size, and shows a weak scaling with toroidal field. A unique capability of C-Mod is to extend these studies to the actual ITER fields, and beyond.

—Internal Transport Barrier (ITB) investigations were extended with use of high-power ICRF operating at two frequencies, to give simultaneous on- and off-axis minority heating. The ITB is formed with off-axis heating, and then the particle peaking is arrested with the subsequent application of on-axis heating. Modeling with the GS2 gyrokinetic code indicates that it may be the growth of Trapped Electron Modes which are responsible for the clamping of density buildup, leading to the possibility of steady-state. The on-axis heating also results in strong core temperature increases, resulting in central plasma pressure approaching 4 atmospheres (400 kPa).

—Studies on C-Mod to investigate the role of rotation, and relation to the H-Mode threshold for various magnetic configurations (upper and lower single-null, double-null, and limited) have revealed the importance of Scrape-Off-Layer flows. H-Mode thresholds were systematically explored for double-null discharges, upper- and lower-single-null discharges, and inner-wall limited discharges. In addition, a new, fifth configuration, with the plasma limited near the bottom of the vessel on the inner-wall nose, has also been investigated. Inner-wall limited discharges have substantially higher H-Mode threshold than even the unfavorable upper-single-null configuration. The lower nose limited configuration has a threshold which is similar to the favorable lower single-null.

—Another important result of these studies is the extreme sensitivity of the double-null threshold to the proximity to exact double-null, as quantified by the difference in primary and secondary separatrix locations, mapped to the outboard midplane. Just a 1 or 2 mm change in this parameter can dramatically change the threshold. This sensitivity may explain previous reports of inconsistent double-null thresholds from other tokamaks. We are currently investigating the role of flows in the scrape-off layer, which provide the boundary condition for core flows, which are driven by pressure gradients. The combination of drives and boundary conditions may provide a unifying picture for the sensitivities of the H-Mode threshold to magnetic configuration.

—Mode conversion current drive experiments using off-axis ICRF show the ability to strongly influence the amplitude and frequency of the sawtooth relaxation oscillation. In C-Mod experiments done to date, application of about 1.5 MW of RF power, phased to drive current in the direction opposite to that of the main plasma current, increases the sawtooth period by almost a factor of 4. With increased power available in future experiments, it might be possible to stabilize the instability completely, which could be important for profile control and suppressing one of the main triggers for Neoclassical Tearing Modes, which can limit pressure in both current experiments and in ITER.

Physics Research Division

The Physics Research Division, headed by Professor Miklos Porkolab, seeks to improve our theoretical and experimental understanding of the physics of plasmas and fusion science. This division develops basic plasma physics experiments, new confinement concepts, novel diagnostics for both magnetically and inertially confined plasmas, HEDP (high energy density physics) experiments on national pettawatt laser facilities, and space plasma physics experiments, while maintaining strong basic and applied plasma theory and computation programs.

Fusion Theory and Computations

The theory effort, led by Dr. Peter Catto, supports Alcator C-Mod and other tokamak experiments world-wide, the levitated dipole experiment about to begin operation at the PSFC, and the versatile toroidal facility, as well as basic plasma theory research. The following important contributions have been made by this group during the past year.

Tokamak Confinement and Transport

Dr. Darin Ernst, in collaboration with Dr. Paul Bonoli and others, have identified mechanisms for the formation and control of the internal transport barriers in Alcator C-Mod through first-principles kinetic simulations of plasma turbulence. The simulations show that toroidal ion temperature gradient driven modes are initially stable or only weakly unstable in the inner half of the plasma minor radius, allowing the standard inward collisional particle flux to peak the density profile. The stronger density gradient eventually drives trapped electron mode turbulence, producing an outward particle flux that ultimately balances the inward collisional flux, leading to a steady state density profile. The turbulent particle diffusivity from nonlinear simulations is temperature sensitive, allowing control of density peaking, and closely matches the value inferred from measurements.

Dr. Catto's tokamak studies focus on plasma flow and the radial electric field at the edge of Alcator C-Mod in the steep plasma density and temperature gradient region just inside the separatrix. He and Dr. Andrei Simakov (now at Los Alamos National Laboratory) have formulated a complete short mean free path fluid description that is being used to make the predictions about the C-Mod edge flows and electric fields.

Magnetohydrodynamics and Extended MHD

Dr. Jesus Ramos has completed a comprehensive study of the fluid moment equations for strongly magnetized collisionless plasmas, which extends his previous results on the dynamic evolution of the fluxes of thermal energy along the magnetic field to include the higher order effects associated with the finiteness of the charged particle Larmor gyration radii. This work is being incorporated into the large-scale numerical simulation models developed by a national Extended MHD group that Dr. Ramos has joined and has been awarded funding by DOE's Scientific Discovery Through Advanced Computing Initiative (SciDAC).

In addition, Professor Jeff Freidberg's research involves completion of a theoretical model for the plasma arc in the Plasmatron, which was the thesis work of his student, Barrett Burns.

Heating, Current Drive, Advanced Tokamaks, and Nonlinear Dynamics

Principal research scientist Paul Bonoli's funding through the DOE Office of Fusion Energy Science's SciDAC initiative has allowed him and Dr. John Wright to implement state-of-the-art simulation models for current drive, heating, and mode conversion in the ion cyclotron and lower hybrid (LH) range of frequencies. These codes are used extensively by the C-Mod group to analyze heating and mode conversion experiments, as well as assess planned LH current profile control experiments. Recently, the full-wave electromagnetic field solver has been used to demonstrate that significant spectral broadening can occur in the vicinity of LH wave caustics because of diffraction effects, which are not easily accounted for using conventional ray tracing techniques. This spectral broadening may provide a mechanism for closing the ubiquitous spectral gap that exits between injected and absorbed waves in LH current drive experiments.

A key element of the advanced tokamak program on Alcator C-Mod is noninductive current–driven lower hybrid (LH) waves for current profile control experiments. We have an ongoing integrated scenario modeling effort to develop combined models for LH current drive, predictive transport analysis, ion cyclotron radio frequency (ICRF) heating, and ideal MHD stability. During the past year Dr. Bonoli and Dr. Bob Harvey of CompX discovered that exact 2-D velocity space treatments of the Fokker Planck equation yield 30–40 percent more LH current (for planned experiments on C-Mod) than simplified approaches.

The stability of fusion plasmas confined in tokamak magnetic confinement geometries requires control of the current profile. Ohkawa current drive is generated by inducing asymmetric trapping of electrons. A new computer code has been implemented to study this current drive in tokamaks with arbitrary magnetic field and cross-sectional configurations. This work was carried out by Joan Decker as part of his doctoral thesis research under the direction of Professor Bers and Dr. Ram, and in collaboration with Dr. Yves Peysson of Cadarache, France.

Studies of laser-plasma interactions (LPIs) are of importance to inertial confinement fusion. As part of his doctoral thesis research for Professor Bers and Dr. Ram, David Strozzi is focusing on understanding the nonlinear saturation of backscatter due to stimulated Raman scattering (SRS). A one-dimensional Eulerian Vlasov-Maxwell code has been developed which for current experiments indicates that saturation of the SRS occurs when the unstable electron plasma wave reaches amplitudes near wave-breaking.

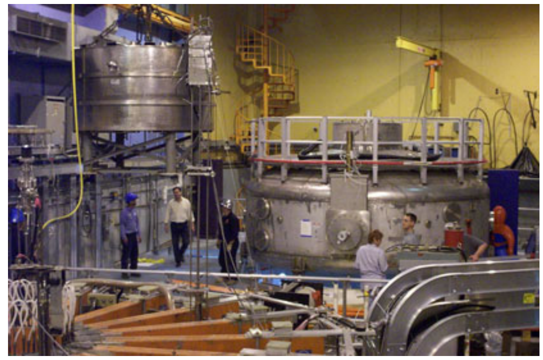
LDX Stability, Heating and Confinement

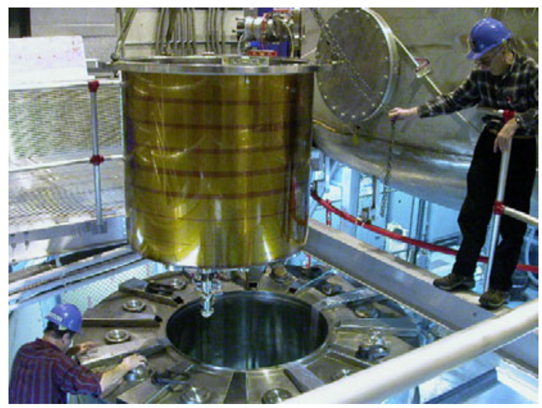
Theory research led by Dr. Jay Kesner in support of the levitated dipole experiment (LDX) has found that dipole magnetic field equilibria are remarkably stable at arbitrary plasma pressure provided the pressure gradient remains below the ideal interchange limit. The formation of large-scale convective cells leading to non-local transport is expected if the interchange limit is exceeded. Simple models are being developed to predict confinement when the ideal stability limit presents a hard limit on the pressure gradient. Non-linear MHD simulations using a recently developed code called NIMROD are being utilized to obtain detailed simulations of the formation of these cells (in the real LDX geometry). Electron cyclotron heating further complicates the stability picture and an investigation is under way.

Experimental Research

Levitated Dipole Experiment

The levitated dipole experiment (LDX) represents a new and innovative approach to magnetic fusion that utilizes a levitated superconducting coil to confine plasma in a dipole magnetic field. LDX is a joint project with Columbia University and is located in Building NW21 at MIT. The principal investigators are Dr. Jay Kesner of MIT and Professor Michael Mauel of Columbia University. The LDX facility has been designed by the engineering division of the Plasma Science and Fusion Center under the leadership of Dr. Joseph Minervini.





The superconducting coils of the levitated dipole experiment at the PSFC-Nabisco Laboratory have been completed and tested to superconducting state up to two hours.

Construction and assembly of the facility are nearly complete, and the project has been renewed by the Department of Energy as a three-year grant at an approximate annual budget of $1.4 million (shared by MIT and Columbia University). LDX utilizes three unique superconducting coils, and it is the only superconducting magnetic confinement experiment in the US fusion research program. The high-performance Nb_3Sn floating coil and cryostat have been successfully tested. The charging coil was built in Russia and arrived at MIT in the fall of 2003. The levitation coil is a high-temperature superconductor, and it also has been successfully tested. The final integrated coil test was performed in June 2004, with the first plasma operations expected to begin in August 2004.

Magnetic Reconnection Experiments on the Versatile Toroidal Facility

During reconnection, magnetic field lines rearrange and change topology. Although the reconnection process is localized, it has a dramatic influence on the system in which it occurs. By way of examples, reconnection controls the evolution of solar flares, it allows the solar wind to enter the earth's magnetosphere, and it is an integral part of magnetic substorms observed in the magnetotail. Based on experimental results from the versatile toroidal facility (VTF) device, a group led by Professor Miklos Porkolab and Dr. Jan Egedal have developed a new kinetic model for reconnection. With researchers from UC Berkeley, the group has applied this model to recent satellite data from the earth's magnetotail. The model accurately represents key aspects of the electron dynamics observed inside an active reconnection region. In addition to this, the VTF device has been upgraded to a new magnetic geometry, which greatly enhances the parameter regime available for future reconnection studies. NSF/DOE is funding this research at a level of $170K per year. In addition, DOE fellowships fund the thesis work of two PhD students, Will Fox and Noam Katz.

The VTF project is also a participant in the new DOE-funded multi-institutional center in basic plasma research on turbulence, called the Fusion Science Center for Multi-scale Plasma Dynamics.

MIT-PSFC/JET Collaboration on Alfvén Wave Instabilities

This program conducts experiments at the Joint European Torus (JET), the world's largest tokamak, in England. In these experiments, 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 a burning plasma experiment where the fusion process generates a substantial alpha particle component. This effort was originally led by Professor Ambrogio Fasoli, who left MIT for Europe, but who continues to participate in this experiment as a visiting professor. Professor Porkolab took leadership of this project, with active involvement by Dr. Joe Snipes of the PSFC, and an MIT postdoctoral fellow located at the JET site in England.

Inertial Confinement Fusion Experiments

Dr. Richard Petrasso and his group continues its longstanding collaborations in inertial confinement fusion (ICF) with the University of Rochester's Laboratory for Laser Energetics (LLE) and with the Lawrence Livermore National Laboratory's National Ignition Facility (NIF). The University of Rochester's 30-kJ, 60-beam OMEGA laser provides the most important current test bed for ICF experiments, and the huge National Ignition Facility (NIF) under construction at Lawrence Livermore will host the next generation of ICF experiments expected to achieve ignition (self-sustaining burn and net energy gain) by imploding fuel capsules with a 2-MJ, 192-beam laser. This year, the PSFC was selected to be a primary member of 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 the NIF at Livermore. 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 essential to an understanding of plasma dynamics and to progress toward ignition in the future. MIT-developed techniques were used to study the time evolution and three-dimensional spatial distribution of 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; an aspect of electron-plasma interaction previously ignored has been shown to be important, and is currently being studied in depth. In addition to the senior staff, these research projects involve the direct participation of four graduate and six undergraduate students.

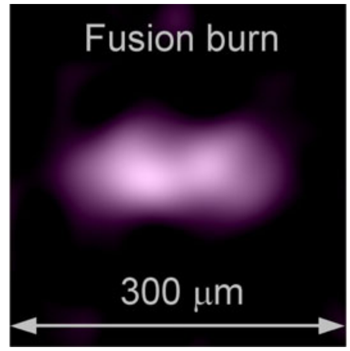


Image of fusion burn in an imploded capsule at the OMEGA laser facility, taken with an MIT-developed proton emission imaging camera.

Novel Diagnostics for Magnetic Fusion Research

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

Professor Porkolab and Dr. Chris Rost, PSFC research scientist, have proposed new upgrades to the phase contrast imaging (PCI) diagnostics on the DIII-D tokamak in San Diego, to measure short wavelength (sub-cm), high frequency (up to 10 Mhz) modes. This proposal also included funding for an upgrade of the C-Mod PCI experiment to look for short wavelength, higher frequency modes. This proposal was funded at $235K per year for three years and the upgrading of the systems has been completed and experiments have begun. Physics graduate student James Dorris joined the DIII-D experiment and relocated to San Diego. Upgrading of the PCI experiment on C-Mod is also in progress, and already novel results have been obtained with the discovery of higher frequency turbulence (by a factor of 4 , up to 2 MHz) than previously observed.

Collective Thomson Scattering off Ions in Textor and Asdex-U

These fusion plasma diagnostic activities involve an international partnership with Risø National Laboratory in Denmark, and Intitut für Plasmaphysik, Jülich and Max-Planck-Institut für Plasmaphysik, Garching, both in Germany. Experiments are being implemented at the TEXTOR (Jülich) and at the ASDEX Upgrade (Garching) tokamaks to develop and use collective Thomson scattering (CTS) for fast ion measurements. The development of fast ion diagnostics is considered essential for the advancement of fusion burning science, which must master the confinement of the energetic product alpha particles to achieve practical fusion energy burn. CTS is one of the most promising diagnostics for delivering these needed measurements. The Plasma Technology Division CTS development activities also involve planning for the ITER fusion burning experiment.

Ionospheric Plasma Research

Space plasma RF heating experiments have been conducted by PSFC’s Ionospheric Plasma Research Group (visiting professor Min-Chang Lee and his students) in Alaska, using DOD's HF Active Aurora Research Program (HAARP) facility, to determine the spatial distribution of HF-modulated electrojet currents and sources of ELF/VLF emissions. This work supported a PhD and a BS thesis, yielding important results to be published in refereed journal articles. PSFC's new All Sky Imaging System (ASIS) has been tested in the lab and in the field with multiple kinds of calibrations, including dark noise, relative spectral, and vignetting. Preliminary study of whistler wave propagation and interactions with space plasmas and radiation belts have been performed near MIT's Millstone Hill Observatory. Further investigation at Arecibo, Puerto Rico, has been scheduled, using the world largest incoherent scatter radar (operating at 440 MHz) together with PSFC's ASIS and Ionospheric Radar Integrated System (IRIS). Experimental and theoretical research will be carried out to examine whistler wave–particle interactions in the earth's radiation belts and the subsequent precipitation of energetic charged particles into the lower ionosphere, producing a broad range of space plasma turbulence.

Students worked in the lab to calibrate ASIS with a light source to determine dark noise, relative spectra, and vignetting.

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 (ECH) of present-day and future plasmas, including the ITER plasma; for high frequency radar; and for spectroscopy. These applications require gyrotron tubes operating at frequencies in the range 90-500 GHz at power levels as high as 1-2 megawatts at 140 GHz for ITER applications.

In 2003–2004, the Gyrotron Group headed by Dr. Michael Shapiro successfully operated a 110 GHz gyrotron for 3 microseconds at power levels of over 1.4 MW and an efficiency of 36 percent. 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 percent. The research at MIT will be followed by a development program for a continuous wave gyrotron that will be built and tested at an industrial vendor, Communications and Power Industries (Palo Alto, CA). R&D in support of the ITER and NSTX programs is also now underway.

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 the Francis Bitter Magnet Lab. In 2003–2004, we demonstrated 3 W of output power at 460 GHz, 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 that could be very useful for developing widely tunable gyrotrons.

PSFC research on high gradient accelerators is focused on high frequency linear accelerators for development of future TeV electron colliders. In 2003–2004, the High Gradient Accelerator Group continued operation of the Haimson Research Corp. 17 GHz electron accelerator. 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. A six-cell photonic bandgap accelerator has been constructed and will be tested soon using the 17 GHz klystron. In the future, we plan to work with the Bates Accelerator research group in the proposed CAST program.

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 coherent radiation generation in crossed field devices, control of halo formation in intense electron and ion beam transport, and the design of metallic photonic band gap structures for use in coherent radiation structures. An important recent achievement is the use of a Green's function–based simulation code to determine the annular beam confinement limit for bunched electron beams in high-power klystrons.

Fusion Engineering and Technology Division

The Technology and Engineering (T&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 this year has been in support of the US Fusion Program, where PSFC has leadership responsibility for the Magnets Enabling Technology program. Funding for fusion technology remained nominally flat this fiscal year, but our magnets program received a modest increase midway through the fiscal year to support increased effort for ITER magnet technology development.

Over the past year, the division has had the principal responsibility to analyze the design of the central solenoid magnet system for ITER and to perform a preliminary cost analysis. If the ITER project proceeds to construction, the United States is likely to supply half or all of the central solenoid magnet system as part of its contribution-in-kind. Supply of the CS is valued at approximately $240 million for three modules plus one spare, or approximately $350 million for the entire six modules plus one spare. Those amounts include contingency, and about two-thirds of the cost is industrial fabrication. MIT is positioned to have the leadership technical role in that project, but the industrial procurement subcontracts will be placed through the Princeton Plasma Physics Laboratory. In the meantime, a superconducting strand development effort has been initiated under the technical responsibility of our division through several small contracts to US strand vendors placed as MIT subcontract awards. Small-scale supporting R&D is also being carried out in our laboratory, partially through graduate student thesis research.

MIT's collaboration with the Lawrence Berkeley National Laboratory (LBNL) and the Lawrence Livermore National Laboratory (LLNL) continued on the OFES-funded inertial fusion energy (IFE) project to develop superconducting magnet technology for the high current experiment (HCX). During this year, MIT took delivery of a unique cryostat that was built by industry under an MIT subcontract award. The cryostat, containing two superconducting quadrupole magnets built by LLNL, was then successfully tested at MIT. We are now designing a new cryostat for HCX which we expect to have fabricated this year by industry, tested at MIT, and installed in the HCX beamline at LBNL.

Division engineers played a leading role in completion of the fabrication and assembly of the magnet systems for the levitated dipole experiment (LDX). Installation and testing of the large charging coil (C-Coil) was completed in February. The D. V. Efremov Institute-Sintez in St. Petersburg, Russia, built this magnet under an MIT subcontract. In early July, the first integrated test of the C-Coil and the floating coil (F-Coil) was a success with induction of 0.6MA of current in the F-Coil. Assembly of the entire LDX machine is near completion. First plasma – a major LDX milestone – is now expected by the end of August.

The division has continued in 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) experiment at Brookhaven National Laboratory's Alternating Gradient Synchrotron facility. Construction on this NSF-funded experiment is planned to begin in FY2006. T & E Division staff member Bradford Smith serves as the MECO magnets subsystem manager. Work accomplished this year includes development of a specification and statement of work for magnet final design, fabrication, and installation, which will be executed under an industrial RFP.

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 is now being fabricated in industry under a Brookhaven National Laboratory subcontract. Titus is also responsible for technical oversight of magnet construction. The present plan calls for the magnet to be tested at PSFC prior to its service with an accelerator beam. Its first use for physics experiments will likely be sometime in FY2005 after installation at CERN in Geneva, Switzerland.

Under a NASA-funded Phase II STTR, MIT collaborated this year with the Advanced Magnet Laboratory, a Florida-based small business, to demonstrate a "Maglifter" type magnetic launch assist concept by testing a prototype superconducting magnet levitation coil at MIT.

The division also completed work this year on an NIH-funded project that focused on the development of a continuous magnetic separation method for biological cells, such as red and white blood cells. As a result of this project, a new technology disclosure has been made. The recently completed work is being used to form the basis for a new proposal to NIH to further develop magnetic separation processes and technology for biological cells and nanoparticles.

Finally, the division has begun a new privately funded project that has the potential to make a significant contribution to cancer radiation therapy. In particular, the division will work with Still River Systems to develop and qualify a manufacturing design for a 250 MeV synchrocyclotron for proton beam radiotherapy. This is expected to be a three-phase effort extending over two years. The first phase is to develop the conceptual design for a synchrocyclotron that can operate at significantly higher magnetic fields—9.5 T—than current state-of-the-art systems that operate at 5.5 T.

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 the "Collective Thomson Scattering off Ions in Textor and Asdex-U" section of this report); and to develop new fusion reactor concepts.

A growing research area for the division is plasma-assisted conversion of hydrocarbon fuels into hydrogen. Drs. Leslie Bromberg and Daniel Cohn are coprincipal investigators in this research. 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. The division's activities in this area contribute to the goals of:

- Developing near-term spin-off applications of fusion energy sciences research
- Expanding collaboration between PSFC and other MIT academic departments and other laboratories
- Increasing industrial support for PSFC research

ArvinMeritor, a major US manufacturer of automotive components, has funded MIT research related to the application of plasmatron reformer devices to vehicles with conventional internal combustion engines.

On one 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 the 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 bio-fuels, 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, Indiana, facility. NO_x emissions were reduced by 90 percent. The technology shows excellent promise for meeting stringent new EPA diesel emissions-reduction regulations, which will be introduced beginning in 2010. The eventual market for this technology could exceed $1 billion per year.

In another project, the division continues to investigate the use of the plasmatron reformer to convert a fraction of the gasoline to hydrogen-rich gas that is then combusted along with the gasoline in a slightly modified engine. The hydrogen-rich gas makes for an ultra-lean fuel mixture that burns cleaner and is more efficient. In particular, lean-burn operation of hydrogen-rich gas in conjunction with turbocharging can lead to increases in net engine system efficiency of 30 percent, as well as large reductions in NO_x, a major air pollutant. The relatively low incremental cost of the plasmatron should lead to a relatively short payback time. The short payback time could potentially make possible widespread implementation on cars and light-duty vehicles with the potential for gasoline savings in the United States of 20 billion gallons a year.

The plasmatron development and vehicular applications project is a collaborative effort with Professor John Heywood of the Mechanical Engineering Department and the Sloan Automotive Laboratory.

A new program for developing clean, high-efficiency gasoline engines using hydrogen enhancement is being proposed to DOE by ArvinMeritor. It is anticipated that MIT will play a substantial role in this program. The motivation for vehicles with significant near-term fuel savings has recently been increased by legislation in California calling for reduced greenhouse gas emissions from vehicles.

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.

This work, supported by the Environmental Management Science Program, has garnered significant recognition, winning an R&D 100 Award for viscosity monitoring, a Best Paper Award by the American Ceramic Society for nuclear waste glass monitoring, investment by the Glass Plus industry consortium to test this technology for glass fiber manufacture, investment by Savannah River Technology Center in purchasing key hardware components for additional tests, and Japanese-initiated exchange visits between MIT and the vitrification facilities at the Japanese Atomic Energy Research Institute in Tokai, Japan, to review this technology. There are also potentially important spin-offs to other areas, including nuclear and fossil fuel power production, and NIH-sponsored research in dynamic nuclear polarization magnetic resonance imaging (DNP-MRI). Most recently, the molten dynamics of salt layer formation were observed in a glass melter for the first time.

Finally, in a program led by Dr. Leslie Bromberg, the Plasma Technology Division has recently begun to develop a promising new approach for greatly increasing the sensitivity for detection of explosives and chemical agents. This approach, the Plasma for Mobility Spectrometer, was recently selected by Lincoln Laboratory for Advanced Concepts funding. This work is relevant to both homeland security and Defense Department needs.

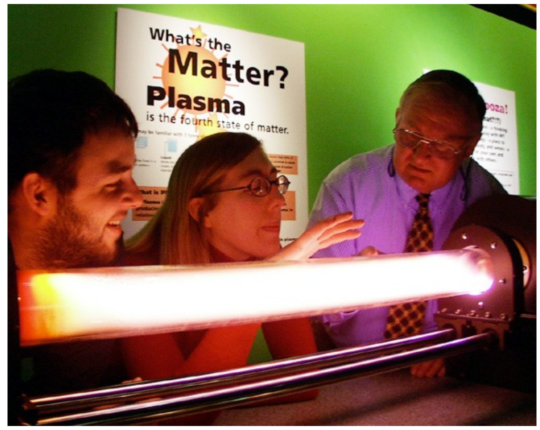
Educational Outreach Programs

The Plasma Science and Fusion Center's educational outreach program is planned and organized under the direction of Paul Rivenberg, communications and outreach administrator. 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 the Minority Introduction to Engineering, Science and Entrepreneurship Program (MITE2S), Keys to Empowering Youth (KEYS), 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. Key to the success of these tour programs is the involvement of PSFC graduate students who volunteer to assist. The experience helps them develop the skill to communicate complex scientific principles to those who do not have advanced science backgrounds.

The Mr. Magnet Program, headed by Paul Thomas, has completed 13 years of bringing lively demonstrations on magnetism into local elementary and middle schools. This year Mr. Magnet presented the program to thousands of students at over 75 schools and other events, reaching students from kindergarten through college freshmen. He makes a special effort to encourage girls to consider science-related careers. In May 2004, Paul Thomas traveled with his truckload of equipment to Washington, DC, at the request of the Department of Energy, to involve participants in the DOE National Science Bowl with his eclectic collection of magnetic and plasma phenomena.

In addition to his program on magnets, Paul Thomas is offering a program about plasma to high schools and museums. This is an interactive demonstration, encouraging participants to investigate plasma properties with audiovisual, electromagnetic, and spectroscopic techniques. Thomas has also been asked by the American Physical Society Division of Plasma Physics (APS-DPP) to give an invited talk on this program at this year's annual meeting in November. Over the past year, Thomas has been working with the Boston Museum of Science to incorporate a plasma display experiment into a new traveling "Star Wars" exhibit, or include it in the permanent exhibit in the museum. He has also developed a workshop for middle schools on how to build an electromagnet and collaborates regularly with the MIT Museum's Sunday science program.



Paul Thomas and PSFC graduate students use a plasma device to interest students in "the fourth state of matter."

The 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 Open House (to which they can bring their students) has become traditional at each year's APS-DPP meeting. Paul Rivenberg, Paul Thomas, and Valerie Censabella, administrative officer in the Nuclear Engineering Department, aided organizers of the 2003 education events in Albuquerque, NM, which attracted about 77 teachers and over 650 students. Here the PSFC featured Paul Thomas and his most recent plasma education device at the education poster session. Paul Rivenberg is in charge of organizing the education events for the 2004 APS-DPP Meeting in Savannah, GA. He hosted a preliminary meeting of local Georgia educators in February 2004 and has already received an enthusiastic response from the area. In conjunction with this local education effort, the PSFC and other US plasma organizations have successfully encouraged Georgia education administrators to add plasma (as the fourth state of matter) to their state science standards.

The 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. PSFC associate director 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, particularly fusion. This year, PSFC division head Dan Cohn spoke at a CPS-sponsored Congressional Luncheon on the topic "Environmental Protection and Energy Savings Using Plasma Technology." 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. He also heads a subcommittee that created and maintains a website to help teachers bring the topic of plasma into their classrooms, and he works with the coalition's Technical Materials subcommittee to develop material to introduce the layman to different aspects of plasma science.

Awards, Appointments, and Promotions

Institute Awards

William Beck, Samuel Pierson, and Alex Zhukovsky were winners of MIT's 2004 Infinite Mile Award, an annual recognition of individuals who provide exemplary service.

Donald Nelson was a corecipient of the Steven Wade Neiterman Award. This award is given annually by the Nieterman family to a computer professional at the Institute who demonstrates exceptional dedication to collaborative problem solving, coaching colleagues, sharing knowledge, and team building.

Appointments

Alcator Division: Ravi Gondhalekar was appointed a research engineer, and Shyri Marazita was appointed an electro-mechanical engineer.

Physics Research Division: Dr. Khashayar Shadman was appointed a postdoctoral associate.

Promotions

Alcator Division: Gary Dekow was promoted to operations and engineering coordinator, Matthew Fulton was promoted to facilities manager, Andrew Pfeiffer was promoted to engineering and diagnostics shop supervisor, Samuel Pierson was promoted to invessel mechanical engineer, and Michael Rowell was promoted to alternator supervisor.

Graduate Degrees

During the past year, the following students were granted degrees with theses in plasma fusion and related areas by the following departments:

Barett Burns, MS	Nuclear Engineering
Davis Lee, PhD	
Brook Schwartz, MS	
David Schmittdiel, MS	
Khashayar Shadman, PhD	
Erik Tejero, MS	
Shinya Kurebayashi, MS	Physics
Nuria Margarit, MS	Aeronautics and Astronautics

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.