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:

- The science of magnetically confined plasmas in the development of fusion energy, in particular the Alcator C-Mod tokamak project
- 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, and theoretical plasma physics and fusion science research
- The physics of high-energy-density plasmas, which includes the Center's activity on inertial confinement laser-plasma fusion interactions
- The physics of waves and beams (gyrotron and high gradient accelerator research, beam theory development, nonneutral plasmas, and coherent wave generation)
- 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)

Administratively, each of these areas constitutes a separate research division. PSFC's research divisions are the Alcator Project, Physics Research, High-Energy-Density Plasma Physics (HEDP), Waves and Beams, and Fusion Technology and Engineering. Note that what previously had been PSFC's sixth and smallest division—the Plasma Technology division—was recently disbanded after a protracted, multiyear decline in sponsored research funding. The remaining individuals have been reassigned to other PSFC divisions. As such, the former division's expertise in plasma-assisted conversion of hydrocarbon fuels into hydrogen and the development of environmental monitoring and remediation techniques based on plasma technology remains at PSFC in a limited form and without funding. There were no graduate students involved in this work in the past year.

PSFC research and development programs are supported principally by the Department of Energy's Office of Fusion Energy Sciences (DOE-OFES). There are approximately 252 personnel associated with PSFC research activities. These include 20 faculty and senior academic staff, 56 graduate students, and six undergraduates, with participating faculty and students from the Departments of Aeronautics and Astronautics, Chemical Engineering, Electrical Engineering and Computer Science, Materials Science and Engineering, Mechanical Engineering, Nuclear Science and Engineering, and Physics. PSFC also has 76 research scientists, engineers, postdoctoral associates, and technical staff; 37 visiting scientists, engineers, and research affiliates; three visiting students; 31 technical support personnel; and 23 administrative and support staff.

Total FY08 funding for PSFC's five research divisions was $32.59 million, slightly higher (by 0.71%) than the FY07 funding level of $32.36 million. Funding for the Center's single largest program, the Alcator C-Mod project, increased by 12.7% from $20.02 million in FY07 to $22.57 million in FY08. The healthy increase of Alcator's funding over FY07 levels was due primarily to an additional $1.8 million of supplemental funding provided by the Department of Energy in the FY08 budget. This increase was because of Congressional directives to increase the runtime of the major US fusion facilities. Funding also increased (by 1.8%) for HEDP over last year, from $1.67 million in FY07 to about $1.70 million in FY08.

The three other PSFC divisions experienced declines in their research volumes. Funding for PSFC's Physics Research division decreased by 5.4% from $3.91 million in FY07 to $3.70 million in FY08, and funding for the Wave and Beams division dropped by 3.1% from $2.24 million in FY07 to about $2.17 million in FY08.

The largest decline, however, occurred in Fusion Technology and Engineering, the Center's second-largest division at the time, which saw its funding drop by 45.6% from $4.52 million in FY07 to $2.46 million in FY08. This precipitous drop was due in large part to the loss of funding for two programs: the International Thermonuclear Experimental Reactor (ITER), which is in the early stages of construction in Cadarache, France, and a second program with an industrial sponsor who sought to bring more cost-effective medical imaging technology to market.

The ITER cuts were an unanticipated consequence of a logjam in the federal government's FY08 budget process. In spite of initial general agreement between the President and Congress over the level of funding for fusion research in the FY08 budget, including $160 million dollars for US participation in the ITER program, a subsequent battle over late earmarks and the size of the overall federal budget resulted in the reduction of the ITER funds to $10.6 million. As of this writing, Congress restored only $15.5 million in funds for the US ITER program in the FY08 supplementary budget, but MIT will not receive any of these funds, which were designated by the Department of Energy to support the ITER home team at Oak Ridge.

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 MIT full-time equivalent staff of approximately 50 scientists and engineers, including eight faculty and senior academic staff, plus 27 graduate students (Figure 1) and 25 technicians. Additionally, we have collaborators from around the world,

Figure 1. C-Mod graduate students in the experimental hall.

bringing the total number of scientific facility users 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, total FY08 funding for the project is about $27 million ($24.4 million direct funding at MIT). We have just submitted the renewal proposal for funding through October 2013. The proposal was peer reviewed, including a panel site visit, in May 2008.

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, edge pedestal, boundary physics, and magnetohydrodynamic stability, as well as in the integrated topical areas of advanced tokamak and burning plasma science.

Facility operation for research FY2008 was planned to total approximately 15 weeks. As of May 23, 2008, 15.7 weeks of the research operations were completed. Details of the day-to-day operation can be found at http://www-cmod.psfc.mit.edu/cmod/cmod_runs.php, which includes links to run summaries, miniproposals, and engineering shot logs. We are now in the middle of a major maintenance effort for the facility, which includes a complete disassembly of the tokamak core for inspection and any necessary refurbishment, to prepare for the next five years of operation. Parallel to this, the MIT-owned alternator, which provides most of the pulsed power needed to run the magnet systems, is also undergoing a major inspection.

Recent Research Achievement Highlights

One focus of the 2008 research campaign was the study of plasma flows and momentum transport. Plasma convection is important for many reasons in tokamaks. It can lead to stabilization of large coherent magnetized fluid modes that sometimes destroy the plasma stability, and can also reduce microturbulence, which is usually responsible for the dominant drive of cross-field energy and particle transport. C-Mod uses heating and current drive tools that do not normally provide any direct momentum input into the hot confined plasma, a situation characteristic of likely conditions in any fusion reactor, and so the study of bulk plasma flow is of particular interest in C-Mod. These investigations are also part of a wider coordinated effort among the three major US fusion facilities (the DIII-D tokamak at General Atomics in San Diego, the NSTX spherical torus at the Princeton Plasma Physics Laboratory, and Alcator C-Mod here at PSFC). One example is a C-Mod measurement of toroidal velocity due to mode conversion flow drive (MCFD). Mode conversion of fast magnetohydrodynamic waves launched from an antenna at the wall of the tokamak vessel into shorter wavelength ion cyclotron waves within the plasma is being explored as a tool to generate local current drive and plasma flow. The layer at which the mode conversion takes place is spatially localized. C-Mod has measured a very large toroidal flow velocity in the direction parallel to the plasma current, in a mode-conversion-dominated experiment. Concomitant to the strong toroidal rotation, a poloidal flow, in the ion diamagnetic direction, is observed in the MCFD plasma. A significant flow appears in the midradius region of the confined plasma, and peaks at ~2 km/s (~0.7 km/s per MW of RF power). Use of this exciting new tool has promise for controlling not just the flow, but also its spatial gradient, which could be used to directly suppress turbulence and improve plasma confinement. State-of-the-art numerical models are being applied to try to understand the theoretical underpinnings of these effects, which in turn should lead us to predictions for future large experiments, including ITER.

Using our microwave current drive system, a complementary set of experiments in the lower hybrid range of frequencies has shown that this tool can be used to drive plasma flows in the direction opposite to the plasma current. Added to the mode-conversion cocurrent flow drive, this gives the prospect for even finer control of the sheared rotation planned for future experiments.

Another important area of research on C-Mod uses one of the unique features of the device—namely, solid metallic plasma facing components. All other high performance tokamaks with advanced shaping use carbon for this purpose, with the exception of ASDEX-Upgrade in Germany, which uses thin tungsten coatings on carbon tiles. A key question for plasma facing components is related to the retention of hydrogen isotopes. In ITER, strict site limits for total in-vessel tritium inventory place tight constraints on the quantity of this hydrogen isotope that can be stored in the plasma facing components. It has long been known that carbon could store very significant densities of hydrogen (and therefore tritium) in the bulk tiles; based on laboratory tests with ion beams and low fluence plasmas, high Z metals showed promise for solving this problem. Detailed experiments on C-Mod have revealed that hydrogen storage can also be very significant in metals, and a picture for the processes involved is emerging, which includes trap creation by the plasma bombardment and diffusion of the hydrogen isotopes in the bulk metal. Hydrogenic removal techniques, including the purposeful use of plasma disruptions, are also being investigated on C-Mod, as are the prospects for removal as tiles are heated to high temperatures.

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 plasma physics experiments and new confinement concepts.

Fusion Theory and Computations

The theory effort, led by Dr. Peter Catto and funded by the DOE-OFES, focuses on basic and applied fusion plasma theory and simulation research. It supports Alcator C-Mod and other tokamak experiments worldwide, LDX, and the VTF experiment at MIT. Our new 260-processor, high-performance computer cluster is one of the most powerful in the US Fusion Energy Sciences program. We are currently seeking funding that would enable us to double the performance of this cluster.

Tokamak Confinement and Transport

Tokamak turbulence is modeled using gyrokinetic simulations to retain finite orbit effects such as gyromotion and magnetic drift departures from constant pressure surfaces. These simulations employ a Poisson's equation to determine the electrostatic potential, with turbulence levels often regulated by the shear of the axisymmetric radial electric field or zonal flow. Catto and students have published major new results, including an improved version of the gyrokinetic equation, and a new version of gyrokinetics that is particularly convenient in the well-confined edge of a tokamak just inside the separatrix (the pedestal). This work showed that the ion temperature cannot always vary as strongly as the ion density in weakly collisional pedestals. They also published a formulation of a hybrid gyrokinetic—a fluid description of electrostatic turbulence in a tokamak that retains all collisional transport as well as turbulent transport while maintaining the charge neutrality of the confined plasma.

Dr. Darin Ernst and students continued first principles gyrokinetic simulations of trapped electron mode (TEM) turbulence, including the first direct comparison of gyrokinetic simulations and fluctuation wavelength spectra. Zonal flow regulation of density gradient-driven TEM turbulence was found to be sensitive to other parameters such as the electron temperature gradient. Secondary instabilities combined with the linear stability properties link zonal flow to various plasma parameters. A comprehensive tokamak stability diagram for electron modes was developed. A new collaboration with Professor Scott Parker at the University of Colorado will compare simulations of zonal flow dynamics for the first time using both particle-in-cell and continuum gyrokinetic simulations to study TEM turbulence. Ernst has received new funding to hire a postdoc as part of the DOE Scientific Discovery through Advanced Computing (SciDAC) Center for the Study of Plasma Microturbulence.

Magnetohydrodynamics and Extended Modeling

Dr. Jesus Ramos participates in two SciDAC projects, the Center for Extended Magnetohydrodynamic (MHD) Modeling (CEMM) and the Center for Simulation of Wave Interactions with MHD (CSWIM), with the purpose of implementing an advanced fluid description of magnetized plasmas in large-scale nonlinear simulations. His main contributions to these projects during FY07 have concentrated on the derivation of drift kinetic equations to be used in the kinetic closure modules of the CEMM and CSWIM suites of codes. Two such drift kinetic descriptions have been developed, one applicable to collisionless fast dynamics with far-from-Maxwellian distribution functions and another applicable to weakly collisional slow dynamics with near-Maxwellian distribution functions intended for the study of neoclassical tearing instabilities, including their interaction with applied radio frequency waves. Collaboration with members of the National Institute for Fusion Science in Japan has continued, with new published results on the equilibrium of axisymmetric plasmas with flows.

Work by Professor Jeffrey Freidberg and graduate students focuses on the stabilizing influence of plasma compressibility using a more realistic plasma model than ideal MHD. One application of interest is LDX, which can be reasonably well modeled by a cylindrical hard core Z-pinch, for which only axisymmetric or sausage instability is possible. An exact quadratic energy integral valid for arbitrary 3-D static MHD equilibria is derived, including both ergodic and closed field line configurations. At marginal stability it shows the compressibility stabilization term vanishes identically—there is no compressibility stabilization—due to the retention of resonant particle effects.

Heating, Current Drive, Advanced Tokamaks, and Nonlinear Dynamics

Drs. Paul Bonoli and Dr. John Wright participate in the multi-institutional SciDAC Center for Simulation of Wave Plasma Interactions. Bonoli serves as the principal investigator of this nationwide SciDAC project. The addition of our upgraded computer cluster has accelerated progress in the modeling of lower hybrid (LH) waves during the past year. The faster through-put on local resources has enabled parametric scans that have led to new understanding of the propagation of LH waves in 3-D. Close collaboration with the Alcator C-Mod LH project has facilitated validation of the code model and improved understanding of the experimental results. In particular, the role of diffraction in broadening the deposition in the plasma may explain discrepancies between the experiment and currently accepted models. Bonoli and Wright also participate in the CSWIM Fusion Simulation Project that aims to perform multiphysics and multiscale simulations between short timescale plasma wave simulations and large scale plasma fluid models. The simulation project has been applied to a C-Mod experimental case in which the temporal plasma fluctuations known as "sawteeth" have been reproduced with very good fidelity. Dr. Steve Richardson, a DOE Fusion Fellow, is working with Bonoli and Wright on novel mathematical techniques for solving the plasma wave equations based on extending the validity of ray tracing and using wave packet analysis.

Dr. Abhay Ram, along with Dr. Yannis Kominis and Professor Kyriakos Hizanidis at the National Technical University of Athens, has developed a quasilinear theory for wave-particle interactions in toroidal magnetic geometry. This theory, the first of its kind, describes diffusive transport of electrons in momentum and configuration space due to their interaction with radio frequency waves. The theory is fully relativistic and includes the effects of magnetic perturbations (e.g., due to neoclassical tearing modes). The momentum space diffusion leads to plasma currents that are necessary for steady-state operation of a tokamak reactor. The configuration space diffusion describes the radial current profile.

Experimental Research

Levitated Dipole Experiment

LDX is a joint collaborative project with Columbia University and is located in Building NW21 at MIT. The principal investigators are Dr. Jay Kesner (MIT) and Professor Michael Mauel (Columbia University). The first fully levitated dipole experiments took place in December 2007. LDX now operates regularly in the fully levitated configuration with the 12,000-pound coil floating for up to 2.5 hrs. LDX is heated by electron cyclotron resonance heating. Recently an additional heating source has been added, which triples the available heating power. LDX now uses 15 kW of heating power at frequencies 2.45, 6.4, and 10.5 GHz respectively. Levitation eliminates losses along the magnetic field. An improved stability of the hot electron species with respect to the hot electron interchange instability was observed, which is consistent with an expected increase in the background plasma density and a broadening of the hot electron density profile. The confinement of the background plasma was observed to increase by a factor of 3 to 5.

An interferometer array has been developed that permits the observation of the plasma density profile and the measurements indicating the formation of peaked plasma density profiles. A spontaneous relaxation (self-organization) of the density profile is sometimes observed, which would confirm an important property of dipole confinement, the tendency to form internally peaked density and pressure profiles. Low-frequency fluctuations are often observed and after this "natural" peaked profile the plasma appears to be more quiescent. Further measurements utilizing a visible light array are planned to obtain the structure of the observed low-frequency fluctuations. Additional diagnostics and additional heating sources are planned.

Low-frequency fluctuations are observed and it is not yet clear whether they are consistent with the nonlinear development of the entropy mode. Theoretical considerations had indicated low frequency instability for a sufficiently flat background plasma temperature profile (the temperature profile is not presently measured). Furthermore, nonlinear simulations indicate that the development of turbulence is tied to the appearance of zonal flows. A spontaneous relaxation (i.e., a self-organization) of the density profile has sometimes been observed, which is consistent with recent theoretical nonlinear predictions by Kouznetsov, Freidberg, and Kesner. This observation would confirm an important predicted property of dipole confinement—namely, the tendency to form internally peaked density and pressure profiles.

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 the Versatile Toroidal Facility (VTF) under the leadership of Professor Jan Egedal. Other participants in this work include Professor Porkolab and a number of graduate and undergraduate students. The experimental observations in the VTF have lead to the development of a new kinetic theory for reconnection, which can account for detailed measurements of reconnection obtained by the WIND spacecraft in the Earth magnetotail. This kinetic theory has now been confirmed in large kinetic simulations of reconnection. The simulations were carried out by personnel at the University of Maryland and at Los Alamos National Laboratory. On the experimental side, the VTF was recently upgraded with a large number of new magnetic and electrostatic diagnostics. The new data obtained show that the onset of reconnection includes strong three-dimensional effects, which often are neglected in theoretical investigations. Additional work has discovered the presence of large-scale nonlinear clumps of electron holes and associated potential structures, 40 to 60 debye in length, parallel to the magnetic field, and of comparable size perpendicular to the field. These nonlinear structures occur during or shortly after the reconnection events. Recent nonlinear simulations by University of Colorado scientists predict the existence of such nonlinear structures in the presence of an energetic electron tail. The experimental program is now focused on characterizing the spontaneous onset of reconnection including the 3-D dynamical effects. The experimental activities are funded by a DOE/National Science Foundation (NSF) award at a level of $120,000 per year and by a DOE Junior Faculty Award at the level of $150,000 per year.

Collaboration on Alfvén Wave Propagation and Instabilities

Professor Porkolab leads this project from MIT, with active involvement by Dr. Joe Snipes of PSFC (now departed for the ITER Project in France), and an MIT postdoctoral fellow, Alex Klein, located at the Joint European Tokamak (JET) site near Oxford, England. This program conducts experiments at JET, the world's largest tokamak, and involves collaboration with Professor Ambrogio Fasoli of the Centre de Recherches en Physique des Plasmas in Lausanne. 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 have been carried out in the past year. A large database has been obtained in recent experiments and it is presently being analyzed. 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. In the future new RF amplifiers will be installed to improve on the spectral resolution of launched waves. A new proposal was submitted to the DOE for continuing financial support of this project for another three years. Dr. Paul Woskov of PSFC would replace Doctor Snipes and Doctor Klein in the new proposal period.

Novel Diagnostics for Magnetic Fusion Research

Phase Contrast Imaging Diagnostic of Waves and 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 graduate students on DIII-D and C-Mod have upgraded the Phase Contrast Imaging (PCI) diagnostics to detect short wavelength (cm to sub-cm), high frequency (up to 5 MHz) modes. The shorter wavelength modes (the so-called TEM and ETG modes) should play a fundamental role in determining particle and energy transport, one of the frontiers of fusion research. Meanwhile, localization measurements of modes along the laser beam have also been carried out with the aid of a rotating mask, which can be modeled with a synthetic diagnostic software package. These experiments are providing important new information on short wavelength instabilities related to transport, and various instabilities in the Alfvén wave regime (reversed shear Alfvén waves, or RSA) during plasma current evolution. The latter should shed light on the radial diffusion of current-carrying electrons during sawtooth events in tokamaks. On DIII-D low-frequency turbulence has been measured during ECH heating and the results are being compared with predictions of the state-of-the-art GYRO code (gyrokinetic code), which has been upgraded to include a synthetic diagnostic package for a better interpretation of PCI data. On C-Mod, data is being compared with the synthetic PCI diagnostic, studying low-frequency turbulence (transport), Alfvén wave cascades (current diffusion), and high-frequency mode converted waves (plasma flows) during ion cyclotron resonance heating (ICRH) in multi-ion species plasmas. Mode converted ion cyclotron waves have been detected during flow drive (both toroidal and poloidal) associated with intense ICRH in C-Mod (see earlier Alcator C-Mod section). Three students are preparing their PhD theses on these topics and several articles have been written.

Collective Thomson Scattering of Ions in Textor and Asdex-U

An international partnership consisting of PSFC, Risø National Laboratory (Denmark), Institut für Plasmaphysik (Jülich, Germany), and Max-Planck-Institut für Plasmaphysik (Garching, Germany) is pursuing the development of fast ion collective Thomson scattering (CTS) diagnostics. CTS experiments have been implemented at the TEXTOR (Jülich) and ASDEX-Upgrade (Garching) tokamaks using the available high-power gyrotron infrastructure at these facilities with the addition of sensitive scattered signal receiver systems, which PSFC was a key contributor in designing. In FY2008 the DOE terminated participation in this work. A final campaign with PSFC participation was carried out at TEXTOR with neutral beam heating of the plasma in January 2008. At ASDEX-Upgrade, initial CTS plasma measurements also began in FY2008 and these initial measurements are very encouraging. The higher performance plasmas of ASDEX-Upgrade are expected to provide a more definitive test of CTS for fast ion studies. The final progress report is being written by Dr. Paul Woskov in order to phase out this project at MIT.

High-Energy-Density Plasma Physics Division

PSFC continues a major effort in inertial-confinement fusion (ICF) and High-Energy-Density Physics (HEDP). This division is led by Dr. Richard Petrasso, and for two decades it has performed pioneering work in the development of novel diagnostics and their use in understanding implosion physics and basic plasma physics in the high energy density regime. To this point, the division's work has recently resulted in major publications in *Science* and *Physical Review Letters*. Therein, unique work on MG reconnection and the mapping of fields and areal density about implosions was reported. These and several other accomplishments were made possible by the development, also through the work of HEDP, of monoenergetic-charged-particle radiography. Five PhD students are currently intensely involved in this and related work.

The HEDP division collaborates extensively with the University of Rochester Laboratory for Laser Energetics, where the 30-kJ, 60-beam OMEGA laser provides the most important current test bed for ICF experiments worldwide. Extensive collaborations are also ongoing with the Lawrence Livermore National Laboratory, where the huge National Ignition Facility (NIF) will lead the next generation of ICF experiments. NIF is expected to achieve ignition (self-sustaining burn) by imploding fuel capsules with a 2-MJ, 192-beam laser, and these experiments will commence in 2010. MIT has a major role in two critical ignition diagnostics at the NIF, and it is the only such university to play such a key role in the NIF ignition program.

A significant effort last year was the development of a major diagnostic, the Magnetic Recoil Spectrometer (MRS), for measurements of the absolute neutron spectrum, from which areal density (rR), ion temperature (Ti), and yield can be determined for cryogenic DT implosions at the NIF and OMEGA. Important to the design is that the MRS spectral response covers all essential details of the entire neutron spectrum. Both Ti and yield can be inferred from the primary 14.1 MeV neutron spectrum, while the areal density, an essential implosion parameter, can be determined from the down-scattered neutron spectrum in the range 6-10 MeV. The MRS diagnostic is considered essential to the

OMEGA cryogenic program, as it offers the only method of measuring the high areal densities that are anticipated.

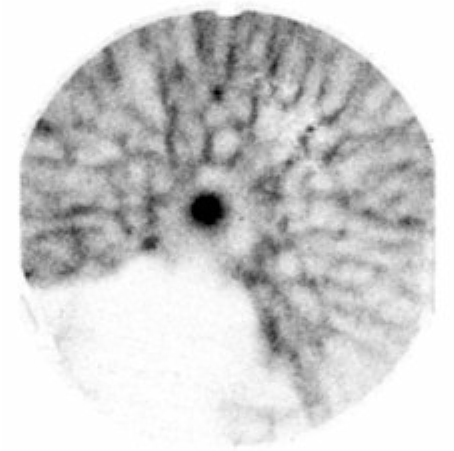

Figure 2. Inertial confinement fusion capsule imploding in response to laser drive.

Figure 2 shows a monoenergetic-proton radiography image of an inertial-confinement-fusion capsule that is imploding in response to laser drive. This image, recently published in the journal *Science*, shows previously unobserved and unexpected electromagnetic field structures with possible implications for fusion physics. These include complex magnetic or electric fields outside the capsule, showing up here as bifurcating radial filaments, and a spherically symmetric radial electric field inside the capsule, manifesting itself here by the dark region inside the capsule. The light region in the lower left is the shadow of a gold cone.

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 Waves and Beams.

Gyrotrons are under development for electron cyclotron heating 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 of 90–500 GHz at power levels up to several megawatts. In 2007–2008, the Gyrotron Group, headed by Dr. Michael Shapiro, continued a program of research aimed at increasing the efficiency of a 1.5-MW, 110-GHz gyrotron with an internal mode converter and a depressed collector. The gyrotron, a form of electron cyclotron maser operated at high frequency, is needed for heating large-scale plasmas in the program of fusion energy research. Our previous research had identified a new source of efficiency reduction in the gyrotron that occurs as the electron beam leaves the interaction cavity, called the after cavity interaction (ACI). Additional experimental data was taken to further define the ACI efficiency reduction. Theoretical research is also under way on improved mode converters for use inside the gyrotron. We need to improve these converters to increase gyrotron efficiency and also to help mitigate the ACI effect. Research is continuing on the origin of low-frequency oscillations, in the 50–200 MHz range, found in the beam tunnel of the gyrotron. In 2007–2008, we have carried out extensive theoretical analysis of these oscillations. The research at MIT is the basis for a development program for a continuous wave gyrotron, which has been built by an industrial vendor, Communications and Power Industries (Palo Alto, CA).

We are also continuing research on low-loss microwave transmission lines in support of the ITER project. In 2007–2008, we made a major discovery concerning the design of these transmission lines. We found that small amounts of high order mode content that copropagate with the design mode, the HE11 mode of corrugated waveguide, can significantly alter the transmission line efficiency. Further analysis of this new effect is under way and a test facility has been built to measure the effect. The gyrotron group is using the megawatt power level pulse gyrotron to study breakdown in air and in other gases. This study has led to a surprising new effect, the production of filaments in the breakdown (Figure 3). Intensive research, under the direction of Dr. Jagadishwar Sirigiri, continues on 140–600 GHz gyrotron oscillators and amplifiers for use in electron spin

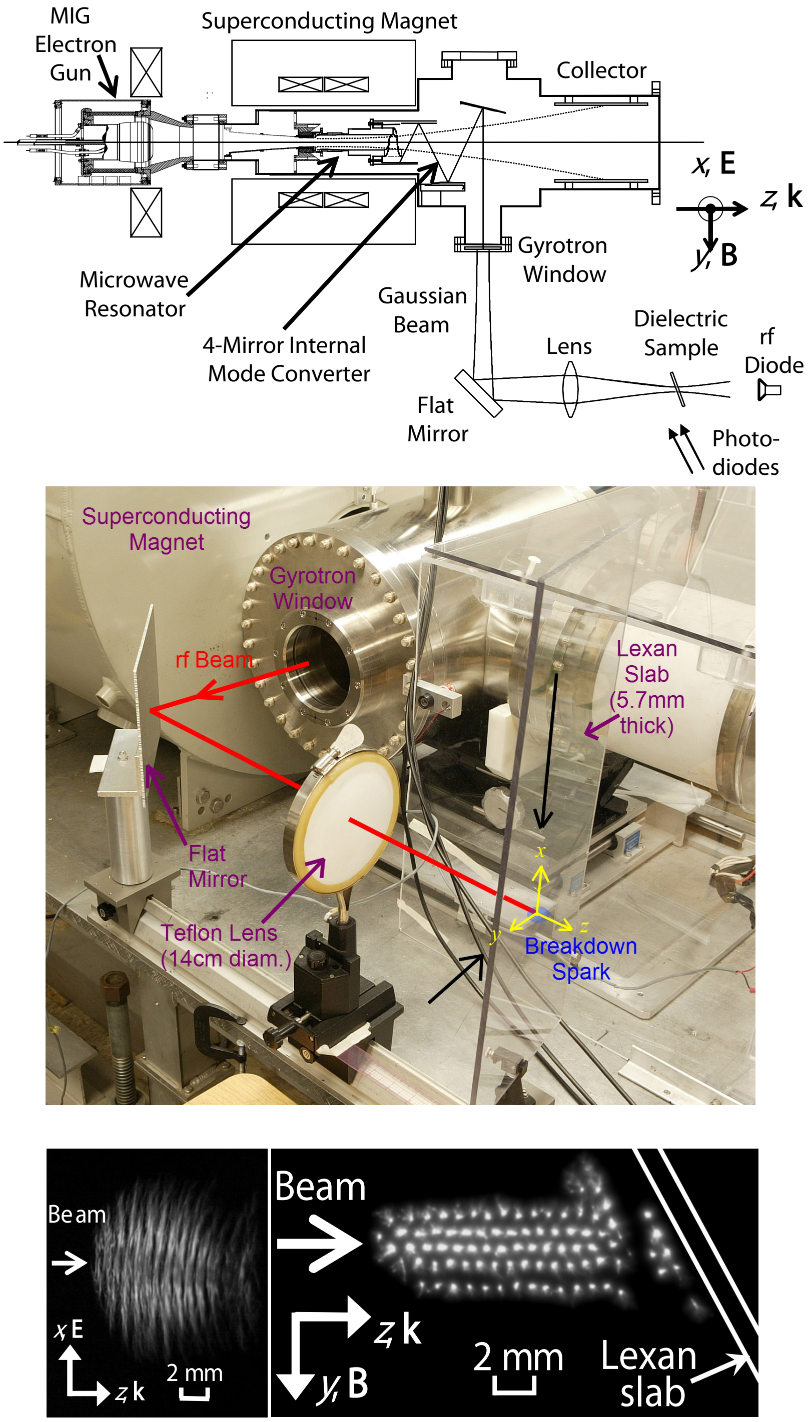

Figure 3. Air breakdown experiments at MIT, showing schematic, photo, and observed filamentary array in two planes.

resonance and nuclear magnetic resonance studies. In 2007–2008, we have successfully rebuilt the 460-GHz gyrotron for improved efficiency and frequency tunability of up to 1 GHz. We also obtained operation of a 140-GHz pulsed amplifier at the 800-watt power level with over 30 dB of gain.

Research on high-gradient accelerators is focused on high-frequency linear accelerators for application to future multi-TeV electron colliders. The Accelerator Research Group operates the Haimson Research Corporation/MIT 25-MeV, 17-GHz electron accelerator. This is the highest power accelerator on the MIT campus and the highest frequency stand-alone accelerator in the world. The Group also participates in a High Gradient Collaboration that includes major labs in the US as well as the CERN and KEK labs. In 2007–2008, we completed measurements of the wakefields emitted by an electron beam passing through a photonic bandgap accelerator structure. The photonic structure is intended to minimize the unwanted wakefields because it does not support higher order modes. The measured wakefields were in good agreement with theory. A high gradient test structure manufactured by Haimson Research was tested in 2007–2008. This copper accelerator structure, which employs small pieces of stainless steel at the locations of the highest field strength, looks very promising for high gradient accelerator operation.

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 research support has historically been from DOE-OFES. In FY08, funding to support the OFES Fusion Technology Program and, subsequently, the Enabling Magnet Technology Program, was reduced yet again, from $619,000 to $410,000. However, after explanation to the director of OFES of the severe long-term negative programmatic consequences resulting from these cuts, the Office has added $450,000 of supplemental funding this fiscal year. We expect that FY09 budget will be at least at the total FY08 funding level of $960,000. We are requesting a level program funding for FY09 of $2 million, but that is unlikely to happen because of the expected level funding required under a Continuing Resolution.

The division also suffered another very serious funding reduction when Congress failed to increase funding for ITER-related activities for FY08. We were funded by a subcontract from Oak Ridge National Laboratory and had established a budget and work scope for $2.7 million in FY09. After notification of the budget reduction, our scope and funding was reduced to $900,000 for the fiscal year. The combination of these fusion-related budget reductions caused us to place the entire FT&E staff on work termination notice. In a few cases, some engineering staff were successfully transferred to other PSFC divisions, including the two technicians employed by our division. Two research engineers have taken other employment outside MIT (one at half-time). Fortunately, we have sufficient funding to allow the three remaining PhD candidates to finish their dissertations and graduate by the end of 2008.

Most of the remaining staff has funding until fall 2008. We have some expectation that the division will survive but with a significantly reduced staff level, although we have submitted a significant number of new proposals for funding.

Work on a privately funded project to develop a 250-MeV synchrocyclotron for proton beam radiotherapy came to an abrupt halt at the end of 2007 when MIT could not reach an agreement at reasonable terms with the company Still River Systems, which was funding the effort. This was unfortunate, not only because it contributed to the FY08 funding crisis, but also because we believe the development and deployment of this critically important cancer therapy system will be delayed by this cut-off of our development expertise.

The field of compact cyclotrons, however, can serve a broad range of advanced technical applications. Dr. Timothy Antaya, a principle research engineer in the division, has successfully begun a new program with funding from Raytheon for the development of the Nanotron Strategic Nuclear Materials (SNM) Inspection System, a rapidly relocatable system for the active interrogation of objects for concealed SNM. He will also receive basic research funding for compact cyclotrons from the Defense Threat Reduction Agency (DTRA), and has several active proposals for significant additional funding with DTRA, Raytheon, and NSF.

We are pleased to report that we received first-round seed funding from the MIT Energy Initiative for a "Program to Develop High Efficiency Power and Energy Systems Using Superconducting and Cryogenic Technology." This is allowing us to further develop this concept with the expectation that it will lead to follow-on work with industry. As a result we are beginning to establish collaboration with a Spanish company, Tecnalia, for the development of a high-temperature superconducting linear generator for offshore ocean wave power generation.

We have also just submitted three additional proposals to the MITEI Seed Fund Round 2 in areas of clean coal technology, clean internal combustion engine technology, and advanced fusion magnet technology. Furthermore, a proposal has been submitted to NSF for a "Novel Cell Separation Method for a Unique Slow Continuous Plasma-Separation."

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 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 laboratory and research environments. This kind of interaction, it is hoped, encourages young people to consider science and engineering careers. Tours of our facilities are also available for the general public. Visitors to PSFC have included the National Youth Leadership Forum and teachers from the National Science Education Leadership Association. Visitors, students, and potential incoming graduate students are now able to get an educational overview of the fusion process and our Alcator C-Mod Project by visiting the PSFC home page.

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 scientific principles to those who do not have advanced science backgrounds.

The Mr. Magnet Program, headed by Paul Thomas, has been bringing lively demonstrations on magnetism into local elementary and middle schools for 16 years. This year Mr. Magnet presented the program to many thousands of students at over 65 schools and other events, reaching kindergartners through college freshmen. In addition to his program on magnetism, he offers an interactive lecture about plasma to high schools. The Traveling Plasma Lab encourages students to learn more about plasma science while having fun investigating plasma properties using actual laboratory techniques and equipment. The Plasma Lab is offered two weeks during the academic year. Paul is often recognized from his appearance on the History Channel's *Modern Marvels* program in the episode "Magnets," which featured experiments from both traveling shows in 2006.

PSFC's associate director, Professor Jeffrey Freidberg, has helped organize educational events oriented toward the MIT community, including PSFC's annual IAP Open House. PSFC has continued its educational collaboration with the MIT Energy Club, bringing an interactive plasma demonstration to their very successful Energy Night at the MIT Museum in October 2007, and supporting the MIT New England Energy Showcase at the Kendall Marriott in April 2008. These events were attended by hundreds of MIT students, as well as business entrepreneurs, who learned about the latest directions of plasma and fusion research.

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) is a tradition at each year's American Physical Society Division of Plasma Physics meeting. This year Mr. Rivenberg contributed to the effort in Orlando, FL, which attracted 59 teachers. He is currently heading the 2008 outreach committee for the meeting in Dallas, TX.

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 Dr. Richard Temkin 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. Like Dr. Temkin, Paul Rivenberg is a member of the CPS Steering Committee. He works with CPS on new initiatives, including an effort to have the study of plasma placed in the science standards of every state in the US. He continues 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

PSFC director Professor Miklos Porkolab was awarded the first Simony Karoly Memorial plaque and prize by the Hungarian Nuclear society in November 2007, in Budapest, Hungary.

Senior research engineer Paul Woskov was elected to the Executive Committee of the Plasma Science and Applications Committee, IEEE Nuclear and Plasma Sciences Society, at the end of 2007 by a mailed ballot vote of the 3000 members of that society.

Mark London, systems programmer/analyst, and Katherine Ware, senior fiscal officer, received 2008 MIT Infinite Mile Awards for their contributions to PSFC and MIT.

Appointments

In the Alcator division, Ms. Lihua Zhou was appointed mechanical engineer, Mr. Dorin Neacsu was appointed high power systems design engineer, and Mr. Shunichi Shiraiwa was appointed postdoctoral associate.

Promotions

In the Physics Research division, Dr. Paul Bonoli was promoted to senior research scientist and Dr. Paul Woskov was promoted to senior research engineer.

Graduate Degrees

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

- Aeronautics and Astronautics: Mr. Mario Manuel, MS
- Nuclear Science and Engineering: Ms. Sarah Angelini, MS; Ms. Ksenia Samokhvalova, PhD; Mr. Kirill Zhurovich, PhD
- Physics: Ms. Eunmi Choi, PhD

Miklos Porkolab
Director
Professor of Physics

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