Plasma Science and Fusion Center

MIT's Plasma Science and Fusion Center (PSFC) is known internationally as a leading university research center for the study of plasma and fusion science and technology with research activities in five major areas:

1. The science of magnetically confined plasmas in the development of fusion energy; in particular, the Alcator-C-Mod tokamak project
2. The basic physics of plasmas including magnetic reconnection experiments on the versatile toroidal facility (VTF), confinement concepts such as the levitated dipole experiment (LDX), development of novel high-temperature plasma diagnostics, and theoretical plasma physics and fusion science research
3. The physics of high-energy-density plasmas (HEDP), which includes the Center's activity on inertial confinement laser-plasma fusion interactions
4. The physics of waves and beams (gyrotron and high-gradient accelerator research, beam theory development, non-neutral plasmas, and coherent wave generation)
5. 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. In order of research area above, the PSFC's research divisions are the Alcator project, physics research, high-energy-density plasma physics, waves and beams, and fusion technology and engineering.

PSFC research and development programs are supported principally by the Department of Energy's Office of Fusion Energy Sciences (DOE-OFES). There are approximately 235 personnel associated with PSFC research activities, including 22 faculty members and senior academic staff; 52 graduate students and 11 undergraduates, with participating faculty and students (in alphabetical order) from Aeronautics and Astronautics, Electrical Engineering and Computer Science, Mechanical Engineering, Nuclear Science and Engineering, and Physics; 64 research scientists, engineers, postdoctoral associates, and technical staff; 26 visiting scientists, engineers, and research affiliates; 6 visiting students; 26 technical support personnel; and 26 administrative and support staff.

Total FY2009 funding for the PSFC's five research divisions was $37.72 million, significantly higher than the FY2008 funding of $32.38 million, due to the inclusion this year of $5.90 million of federal stimulus funding for the PSFC's Alcator project (more on this below). With the stimulus funding, total Alcator division funding increased by 18.5 percent to $26.84 million. Although to date Alcator was the only PSFC research division to receive stimulus funding (the PSFC's LDX is still under consideration for a stimulus funding increment), three other divisions experienced double-digit growth in their funding relative to FY2008—physics research division funding increased 20.6 percent to $4.38 million, waves and beams division funding increased 26.1 percent to $2.78 million, and HEDP division funding increased by 14.0 percent to $1.72 million. Only funding to the fusion technology and engineering division diminished relative to FY2008, decreasing by 19.5 percent to $1.72 million. This drop was attributed primarily to the division's loss of funding for the International Thermonuclear Experimental Reactor (ITER) program.

In the past year, the nation experienced one of the most severe contractions in the US economy since the Great Depression. Congress and the new administration responded to the extraordinary plunge in global markets and corresponding economic crisis by passing the American Recovery and Reinvestment Act of 2009. The bill, a massive stimulus plan, commits loans and investments of more than $700 billion over 18 months to spur job creation, free up credit markets, and jump-start the economy. Significant stimulus funding is being made available through federally sponsored research programs, and the PSFC will see an increase in funding because of it. In particular, through OFES, DOE is providing the PSFC $5.9 million in stimulus funding, with $0.94 million for enhanced operations of the Alcator C-Mod experiment—that is, funds that will allow C-Mod six additional weeks of operations this fiscal year and $4.96 million in equipment money. Stimulus funds are an unexpected windfall that will boost funding over the next 18 months but not beyond.

In another development, DOE-OFES announced it will fund (at a level of $6.9 million for five years) a new science center—the Plasma Science Center on Plasma-Surface Interactions. Plasma-surface interactions (PSI) pose an immense scientific challenge to magnetic confinement fusion energy, and the new center should advance the fusion community's understanding of PSI science. The center will consist of three equal co-centers, one located at the PSFC in addition to co-centers at the University of California, San Diego, and the University of California, Berkeley. Sandia National Laboratory at Livermore will also be a collaborative partner in the new center. The co-center at MIT will make use of the CLASS Accelerator Laboratory, the DIONISOS Plasma Experiment, and the Alcator C-Mod experiment. Professor Dennis Whyte (Department of Nuclear Science and Engineering) will be principal investigator for MIT's co-center.

The new center will focus on an innovative approach to PSI sciences: an approach that exploits access to state-of-the-art laboratory PSI experiments and modeling as well as fusion confinement devices. The organizing principle is to develop synergistic experimental, diagnostic, and modeling tools that treat the truly coupled multiscale aspects of the PSI issues in confinement devices. Proposed center research themes include surface and film dynamics, synergistic effects of radiation and plasma damage, plasma fuel retention, sheath physics, and material erosion and transport. About one-third of the program's $6.9 million funding will come to the MIT co-center. This new source of funding will be reflected in the FY2009 budget.

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 the 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 8 faculty members and senior academic staff, plus 30 graduate students and 25 technicians. Additionally, we have collaborators from around the world, bringing the total number of scientific facility users to more than 200. The cooperative agreement with DOE-OFES, which funds the C-Mod project, was renewed effective November 1, 2008, for a five-year period. Including major collaborators, total FY2009 funding for the project is about $25 million ($21.2 million direct funding at MIT).

Research on C-Mod continued during the past year in high-performance, high-magnetic-field 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 (MHD) stability as well as in the integrated topical areas of advanced tokamak and burning plasma science.

Facility operation for research this fiscal year (FY2009) is planned to total nine weeks. 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 have just completed a major year-long maintenance effort, which included a total disassembly of the tokamak core for inspection and necessary refurbishment. In parallel, the MIT-owned alternator, which provides most of the pulsed power needed to run the magnet systems, also underwent a major inspection and has been recertified for continuing operation. Plasma operations were successfully restarted in June 2009.

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, which sometimes destroy the plasma stability, and can also reduce the microturbulence, which is usually responsible for the dominant drive of cross-field energy and particle transport. C-Mod uses heating and current drive tools, which 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 the PSFC). One example is a C-Mod measurement of toroidal velocity due to mode conversion flow drive. Mode conversion of fast waves launched from an antenna at the wall of the tokamak vessel into shorter wavelength ion 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 experiment. Concomitant to the strong toroidal rotation, a poloidal flow, in the ion diamagnetic direction, is observed in the mode conversion flow drive plasma. A significant flow appears in the mid-radius region of the confined plasma and peaks at ~2 km/s (~0.7 km/s per MW of radio frequency power). Use of this exciting new tool has promise for controlling not just the flow but 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. This work has attracted international attention, with publications in *Physical Review Letters* and *Physics of Plasmas* and a special news article in *Physics Today* (Charles Day, "Resonant Radio Waves Rotate Tokamak Plasma," *Physics Today*, Vol. 62, No. 6, June 2009). A complementary set of experiments, using our microwave current drive system in the lower hybrid range of frequencies, has shown that this tool can be used to drive plasma flows in the direction opposite the plasma current. Added to the mode-conversion co-current flow drive, this procedure gives the prospect of even finer control of the sheared rotation planned for future experiments.

Recent experiments and modeling on Alcator C-Mod indicate a possible solution to the potential problem of runaway electron production during MHD events, which lead to a sudden loss of plasma confinement, termed major disruptions. During these disruptions, rapid cooling of the plasma increases its electrical resistance and raises the electric field sharply. For very large devices, like ITER, this situation could lead to massive generation of runaway electrons, with the potential of causing severe localized damage when they eventually affect material surfaces. However, if the magnetic fields become disordered or "stochastic," so that the electrons become poorly confined in the plasma, then the runaway process can be suppressed. Alcator has been able to bring unique tools to bear on the problem of quantifying the stochastic losses. A key problem in studying runaways is that no present device is as large as ITER (C-Mod is one-ninth the size), and so the runaway amplification factors are exponentially smaller. This shortcoming has been overcome in C-Mod by using the high-powered microwave current drive system to produce a target plasma that is already seeded with a large population of energetic electrons (not runaways) and then intentionally terminating the plasma with a massive gas injection to examine the runaway formation as would happen in ITER. Calculations show that, if the fast electrons were confined, approximately half of the 1 million amperes of plasma current, present before the disruption, would be converted into a runaway electron "tail" due to the hot electron acceleration. Indeed, C-Mod diagnostics show the electrons becoming runaways; however, these runaways are lost by transport in a millisecond, well before the current decay phase of the disruption. State-of-the-art modeling using the three-dimensional NIMROD MHD code has been used to shed light on the issue of runaway confinement. A C-Mod–University of California, San Diego, collaboration previously upgraded NIMROD to include impurity radiation physics to study disruption mitigation by massive gas injection. That work found that the mitigation is successful because of the evolution of vigorous MHD activity caused by the large edge cooling; this activity allows the impurities to access the energy of the plasma. Trace electrons were followed through the same three-dimensional code solution. The original fast electrons from LH are accelerated to near the speed of light by the cooling-induced electric field. However, at the same time the field lines become "messy" (stochastic), allowing these electrons to leave the plasma in less than a millisecond, in agreement with the experimental results. These experiments and calculations strongly suggest that the same mechanism responsible for mitigation can also suppress runaways. This is the first time such a tool has been brought to bear on this problem and it promises, with further refinement, the ability to predict runaway confinement and losses in ITER.

Physics Research 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 novel plasma physics diagnostic experiments and new confinement concepts. Students are an essential component of all aspects of the research.

Fusion Theory and Computations

The theory effort, led by Dr. Peter Catto and funded by DOE-OFES, focuses on basic and applied fusion plasma theory and computational plasma physics research. It supports Alcator C-Mod and other tokamak experiments worldwide, along with the LDX and VTF experiments at MIT. The division's new high-performance computer cluster is heavily used by students, staff, and collaborators and has become the main computational resource for PSFC experimental and theory thesis research. Additional DOE funding has allowed the cluster memory to be tripled and the number of cores increased from 260 to 520. A further cluster upgrade is in progress that will increase the core total to 600 and provide improved operational flexibility.

Tokamak Confinement and Transport

Gyrokinetic descriptions are used throughout the magnetic fusion program to simulate tokamak turbulence as they are able to retain finite orbit effects such as gyromotion and magnetic drift departures from constant pressure surfaces. These simulations use a Poisson's equation to determine the electrostatic potential, with turbulence levels often regulated by the shear of the resulting axisymmetric radial electric field—its zonal flow. Catto and his former student Felix Parra Diaz have investigated the limitations of these approaches. In particular, they demonstrated that it is impractical to obtain the axisymmetric radial electric field in this way. Instead, it must be obtained by using conservation of toroidal angular momentum. Moreover, Catto and his student Grisha Kagan have developed a gyrokinetic formulation valid for the edge of a tokamak just inside the separatrix (the pedestal) as well as the core. They used their model to evaluate modifications to core behavior by deriving the zonal flow enhancement and neoclassical ion heat diffusivity reduction in the pedestal.

Dr. Darin Ernst is leading a collaboration investigating the parametric variation of zonal flows and underlying mechanisms for trapped electron mode (TEM) turbulence. The collaboration, involving colleagues from the SciDAC Center for the Study of Plasma Microturbulence (University of Colorado, Lawrence Livermore National Laboratory, Missouri University of Science and Technology, and University of Maryland), carried out extensive and detailed parametric studies through a series of linear and nonlinear gyrokinetic simulations. This work identified a critical boundary in parameter space linking zonal flows to linear stability properties. Outside the boundary TEMs are shorter wavelength and zonal flows are unimportant. Ernst also collaborated with colleagues from the University of Maryland, continuing his work on implementing a new gyrokinetic collision operator in the GS2 code and, with Catto, developed a model collision operator and an implementation procedure for gyrokinetic particle simulations.

Magnetohydrodynamics and Extended Modeling

Dr. Jesus Ramos participates in two SciDAC projects, the Center for Extended 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. During the past year, he has continued to work on the drift kinetic equations to be used in the kinetic closure modules of the CEMM and CSWIM suites of codes, concentrating on the case of weakly collisional slow dynamics with near-Maxwellian distribution functions. In collaboration with Professor Eduardo Ahedo, on sabbatical leave from the Polytechnic University of Madrid, new analytic results were derived for a class of two-fluid resistive instabilities that have quickly been adopted by the extended MHD community as a standard for verifying the numerical codes.

Ideal MHD predicts that plasma compressibility has a stabilizing role in closed field line configurations, such as LDX. A more realistic model for collisionless plasmas, kinetic MHD, shows that this result can be extended to ergodic field line configurations, such as tokamaks, and that trapped particles are responsible for the compressibility stabilization. Professor Jeffrey Freidberg and his student Antoine Cerfon introduced a model that describes the motion of the hot ions more accurately. They derived an exact quadratic energy integral valid for arbitrary three-dimensional static MHD equilibria and used it to show that in both field line configurations the compressibility predicted by ideal MHD and kinetic MHD vanishes because of the resonant particle effects and short perpendicular wavelengths. Therefore, in fusion grade plasmas, MHD marginal stability is incompressible: there is no compressibility stabilization within this improved model.

Heating, Current Drive, Advanced Tokamaks, and Nonlinear Dynamics

In addition to participating in the multi-institutional SciDAC Center for Simulation of Wave Plasma Interactions, discussed separately below, Dr. Paul Bonoli and Dr. John Wright participate in the prototype fusion simulation project CSWIM that aims to perform multiphysics and multiscale simulations between short timescale plasma wave simulations and large-scale plasma fluid models. The parallel computing framework developed through the CSWIM project has been used to simulate a type of radio-frequency heating known as minority ion cyclotron heating in the Alcator C-Mod tokamak, with a degree of spatial and temporal physics resolution in the wave propagation and absorption that has never before been possible. In a close collaboration with the Alcator C-Mod project, a sophisticated model for lower hybrid wave propagation and absorption, based on a ray tracing treatment of the wave propagation, has been validated against experimental measurements of hard x-ray data and current density profiles on C-Mod.

For steady operation of a tokamak fusion reactor, a substantial fraction of the plasma current has to be generated by electromagnetic plasma waves. Dr. 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. The model treats the electromagnetic fields as wave packets rather than plane waves filling up the entire tokamak. 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.

SciDAC Center for Simulation of Wave-Plasma Interactions

During 2009, MIT continued to serve as the lead laboratory for the multi-institutional SciDAC Center for Simulation of Wave-Plasma Interactions (CSWPI), where Dr. Paul Bonoli serves as principal investigator for the center. During the past year, members of the CSWPI at MIT made significant progress in developing the first combined full-wave electromagnetic field solver and Fokker Planck code, applicable in the lower hybrid range of frequencies (LHRF). In 2008, this field solver was implemented on the powerful Loki parallel computing cluster at the PSFC. In 2009, an extensive effort was undertaken to verify that the solver was working properly. The solver was also coupled to an electron Fokker Planck code and self-consistent solutions for wave damping in the presence of a nonthermal electron tail were obtained by iterating the full-wave solver and Fokker Planck code to convergence. An example of this is shown in Figure 1 for parameters typical of LHRF experiments in Alcator C-Mod. This full-wave approach includes important effects not treated by ray tracing such as focusing and diffraction as well as proper reconstruction of the wave front at cutoffs (near the plasma edge). During the coming year, the nonthermal electron distributions from this simulation model will be validated against experiment by comparing the simulated hard x-ray spectra based on these distributions with hard x-ray spectra measured during LH current drive experiments in Alcator C-Mod.

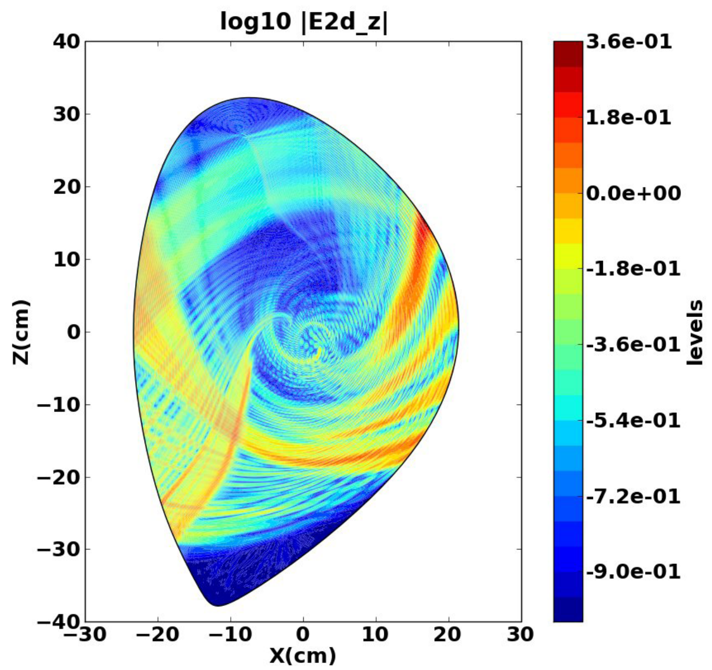

Figure 1. Electromagnetic field simulation of LH waves in Alcator C-Mod damping on a self-consistent, nonthermal (quasilinear) electron tail. Simulation performed on the Loki computing cluster at the PSFC using a numerical resolution of 600 radial elements and 1,023 poloidal modes. Shown in the figure are contours of the magnitude of the real part of the parallel electric field.

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 of this project are Dr. Jay Kesner (MIT) and Professor Michael Mauel (Columbia University). The first fully levitated superconducting ring dipole experiments took place in December 2007. LDX now operates regularly in the fully levitated configuration with the 12,000-lb coil floating for up to two and a half hours. LDX plasmas are heated by electron cyclotron resonance heating; recently, an additional electron cyclotron resonance heating source has been added that triples the available heating power. (LDX now uses 15 kW of heating power at frequencies of 2.45, 6.4, and 10.5 GHz). Levitation eliminates losses along the magnetic field. Particle confinement was observed to increase by a factor of 3–5, and plasma pressure doubled during levitation, in contrast to the earlier mechanically supported ring experiments. The hot electron mode, previously seen in supported mode operation, was observed to be harder to destabilize.

An interferometer array has been developed that permits observation of the plasma density profile, and measurements indicate the formation of peaked plasma density profiles. A spontaneous relaxation (self-organization) of the density profile is sometimes observed, which confirms 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 with a visible light array are planned to determine the structure of the observed low frequency fluctuations. Additional diagnostics and additional heating sources are planned.

Magnetic Reconnection Experiments on the Versatile Toroidal Facility

Magnetic reconnection is a fundamental process in plasmas that converts magnetic energy into particle energy while changing the topology of the magnetic field lines. 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. The latter drive the auroral phenomena. Although reconnection occurs in microscopic diffusion regions, it often governs the macroscopic properties and behavior of the system. Magnetic reconnection is studied in the Versatile Toroidal Facility (VTF) under the leadership of assistant professor Jan Egedal. Other participants in this work include professor Miklos Porkolab and a number of graduate and undergraduate students. Last year, we reported that the experimental observations in the VTF have led to development of a kinetic theory for reconnection. This theory has now been tested against detailed measurements of reconnection obtained by the wind and the cluster spacecraft missions in the Earth's magnetotail. Based on the kinetic theory a new fluid model has been derived that accounts for the strong temperature anisotropy that develops within the reconnection region. The model provides a framework for obtaining accurate large-scale simulations of reconnection as required for understanding the plasma conditions in the near earth environment (space weather). On the experimental side, the research program on VTF is focused on the three-dimensional dynamics observed during the onset of reconnection. We have identified a plasma mode external to the main reconnection site that triggers the onset of reconnection. More than 1,000 diagnostic probe channels are being used to measure and understand the nonlinear interaction that leads to the explosive reconnection dynamics. The experimental activities are funded by a DOE/National Science Foundation (NSF) award of $120,000 per year and by a DOE Junior Faculty Award of $150,000 per year. In addition, Professor Egedal recently won a NSF Junior Faculty Award providing funding of $150,000 per year until 2014.

MIT-PSFC/JET/CRPP Collaboration on Alfvén Wave Propagation and Instabilities

Professor Porkolab leads this project from MIT, with past involvement by Dr. Joe Snipes (now at the ITER project in France) and ex-MIT postdoctoral fellow Alex Klein. This program conducts experiments at JET, the world's largest tokamak located near the Culham Laboratories, UK, and involves collaboration with professor Ambrogio Fasoli of CRPP, Lausanne, Switzerland. In these experiments, Alfvén waves are launched by a specially built antenna array, consisting of eight phase-locked loops, all of which were installed in JET during the past two years. Studies of wave propagation and damping processes were carried out in the past year. These studies are expected to lead to improved understanding of plasma stability and transport that will be important in future burning plasma experiments in which the fusion process generates a substantial alpha particle component that may drive Alfvén waves unstable. A new proposal was submitted last summer to DOE for continuing financial support of this project for another three years. The proposal was reviewed and approved and funding was obtained for partial support (25 percent full-time equivalent) of Dr. Paul Woskov of the PSFC who will redesign, as well as procure, eight new amplifiers to upgrade the phase array radio-frequency power drive system. In the third year of this project, a postdoc will be hired and relocated at JET to participate in the upgraded experiments.

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 (centimeter to subcentimeter), high-frequency (up to 80 MHz) modes. The shorter-wavelength modes (the so-called ITG, 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 been carried out with the aid of a rotating mask that can be modeled with a "synthetic diagnostic" software package. These experiments are providing important information on short-wavelength turbulence related to energy transport and various instabilities in the Alfven wave regime (reversed shear Alfven waves) 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 (gyro-kinetic code), which has been upgraded to include a "synthetic diagnostic" package for a better interpretation of PCI data. On C-Mod, data have been compared with the synthetic PCI diagnostic, studying low-frequency turbulence (transport), Alfven 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). Two students on Alcator (Liang Lin and Eric Edlund) successfully defended their PhD theses earlier this year and several papers related to this research have been published, including one invited talk at each of the November (2008, 2009) DPP APS meetings. One new student has joined the Alcator PCI project to continue this work with two others.

Other Research

Applications of Fusion Technology to Engineered Geothermal Systems

Successful development of engineered geothermal systems (EGS) as a source of energy depends most strongly on the availability of a natural or artificially created underground fracture system that does not deteriorate with time and that circulates the fluid to heat exchangers. The economic and technical feasibility of EGS depends very much on drilling cost and speed. At present, the well costs can account for 60 percent or more of the total capital cost. An advance in rock penetration rates of more than 10 times over conventional rotary drilling systems at lower cost would enable rapid and widespread exploitation of sustainable geothermal energy. Such an advance in rock penetration systems may now be possible with efficient (>50 percent) high-energy millimeter-wave gyrotron sources originally developed for fusion energy research. During FY2009 Dr. Woskov, sponsored by the MIT Energy Initiative, studied the thermodynamics of rock ablation and reviewed the results of past laser rock drilling experiments. This study supports the possibility that millimeter-wave directed energy penetration rates in hot crystalline rock formations could greatly exceed the limits of mechanical drilling technology with currently available megawatt gyrotron sources. Dr. Woskov has teamed with Professor Einstein at the MIT Rock Mechanics Laboratory for follow-up work. A proposal has been submitted to DOE to pursue experimental research of millimeter-wave directed energy rock penetration with a gyrotron system at the PSFC.

Thermal Analysis of GEN IV Nuclear Reactor Materials

The development of Generation IV (Gen IV) very-high-temperature nuclear reactor (VHTR) technology depends on the development and characterization of high-temperature materials that can reliably meet the diverse fuel and structural requirements in extreme VHTR environments. During spring 2009, Dr. Woskov successfully teamed with Dr. Sundaram of Pacific Northwest National Laboratory to propose the development and application of novel millimeter-wave thermal analysis tools to address VHTR needs for materials analysis. The DOE grant that has been awarded will commence at the end of FY2009 for three years. Millimeter-wave thermal analysis instrumentation measurement techniques will be developed and applied to characterization of graphite and alloy materials at high temperatures.

High-Energy-Density Plasma Physics Division

This division, led by Dr. Richard Petrasso, continues to expand on its two decades of pioneering work in inertial-confinement fusion (ICF) and HEDP. Its development and use of novel diagnostic techniques for understanding ICF implosion physics and basic plasma physics in the high-energy-density regime have led to several important research accomplishments and publications in major journals during the last year.

The HEDP division collaborates extensively with the University of Rochester Laboratory for Laser Energetics (LLE), where the 30-kJ, 60-beam OMEGA laser provides the most important current test bed for ICF experiments worldwide. One important MIT experiment performed at OMEGA this past year was the first study of electric and magnetic fields in indirect-drive ICF experiments, where laser beams impinge on the inner walls of a small container (called a hohlraum) to generate x-rays that impinge on an ICF fuel capsule and cause it to implode. MIT-developed techniques of monoenergetic proton radiography were used to determine that interaction of the laser with the hohlraum walls did result in generation of plasma jets and electric and magnetic fields, which may have important effects on hohlraum physics and overall implosion performance by reducing heat transport and modifying plasma conditions (Figure 2). Other MIT experiments with proton radiography at LLE this year included studies of laboratory-scaled versions of astrophysical jets. This year MIT undertook a major effort to organize all external OMEGA researchers in the first OMEGA laser users' group conference, bringing scientists and students from all over the world together to discuss current HEDP research and to help LLE refine its procedures for working with outside scientists.

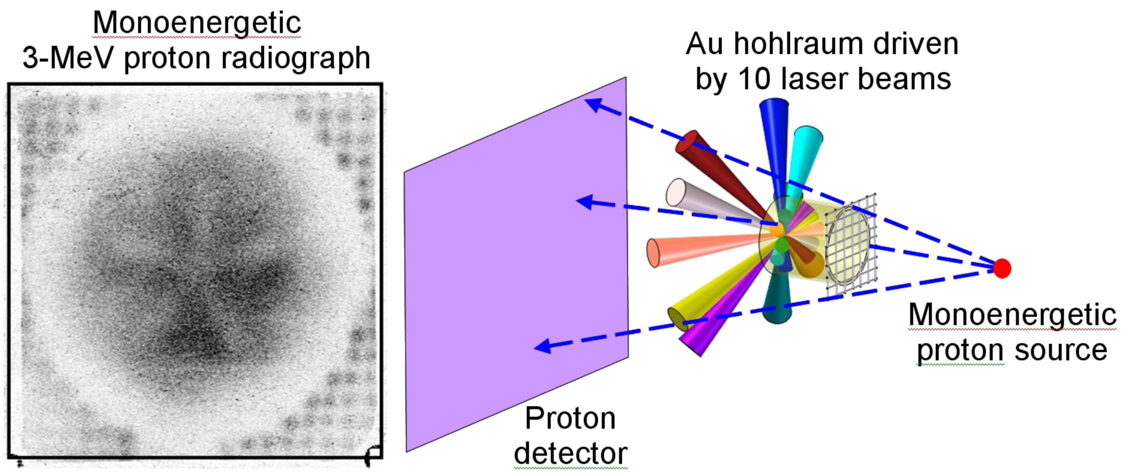

Figure 2. A recent experiment at the OMEGA laser facility used a proton source that produced monoenergetic 3.3-MeV protons and 15-MeV protons to make a radiograph of a gold hohlraum that was driven by 10 laser beams in five groups of two. The 3-MeV image on the left, in which regions of high proton fluence are dark, shows the circular shadow of the hohlraum wall and a five-pronged, asterisk-like shape that indicates gold plasma jets traveling from the wall to the center between the locations where the five laser-beam groups hit the wall. Other images made with the two proton energies indicate the presence of magnetic and electric fields in the hohlraum. This work is discussed in Physical Review Letters, Vol. 102, page 205001 (2009).

Extensive collaborations are ongoing with the Lawrence Livermore National Laboratory, where the huge National Ignition Facility (NIF) will lead the next generation of ICF experiments. The NIF is expected to achieve ignition (self-sustaining burn) by imploding fuel capsules with a 2-MJ, 192-beam laser, and ignition experiments will commence in 2010. MIT has a major role in two critical ignition diagnostics at the NIF, and it is the only university to play such a key role in the NIF ignition program. One of these diagnostics is an MIT-developed, high-resolution neutron spectrometer called the magnetic-recoil spectrometer (MRS), which is now being implemented.

The primary objective of the MRS is to measure the absolute neutron spectrum in the energy range 5–30 MeV for experimental information about fuel areal density and any asymmetries it has as well as ion temperature and fusion yield. Such measurements will be important, particularly because proper assembly of fuel capsule mass, as manifested in the evolution and symmetry of fuel areal density, is essential for achieving the hot-spot ignition planned at the NIF. Another MRS has been built and activated on OMEGA, at LLE, University of Rochester, to comprehensively test the technique and, more importantly, measure the absolute neutron spectrum from energy-scaled direct-drive cryogenic DT implosions. The results from the first MRS measurements, obtained last year, have been essential to the progress of the cryogenic program at LLE.

In addition to the research results, the HEDP division places equal importance on the training and accomplishments of its five PhD students, who were intensely involved in every project. They also completed a major project this year in renovating the division's Cockroft-Walton accelerator at the PSFC's Nabisco Laboratory and redesigned an extensive and modern user interface.

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.

Gyrotron and Accelerator Research

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 2008–2009, the gyrotron group, headed by Dr. Michael Shapiro, conducted 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. The 1.5-MW power level gyrotron is needed to upgrade the heating system of the DIII-D tokamak at the General Atomics Corp. in San Diego, CA; that system now uses 1-MW power level gyrotrons. Our current research is aimed at increasing the efficiency of the internal mode converter of the gyrotron. The converter changes the high-order waveguide mode into a Gaussian-like mode in free space. A novel converter with simple, smooth mirrors, developed by University of Wisconsin, Calabazas Creek Research, and MIT, is now under test. Theoretical research is also under way on a novel interaction circuit that will eliminate efficiency reduction due to a second zone of cyclotron resonance interaction in the gyrotron. The research at MIT serves as 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). The gyrotron group is using the megawatt power level pulsed gyrotron to study breakdown in air and in other gases, including the discovery of filaments in air breakdown. That research is featured as the cover article in the May 2009 issue of the scientific journal *Physics of Plasmas*.

We are continuing research on low-loss microwave transmission lines in support of the ITER project. In 2008–2009, we made a series of advances in the design of these transmission lines. The transmission lines use low-loss circular waveguides that have quarter-wavelength-deep corrugations. The ITER project will have more than 2 km of these lines. We have recently formulated a new description of the eigenmodes of these waveguides, replacing the usual mode set with a set of modes that have linear polarization, which is the expected polarization of the modes that will be encountered. Using new codes, we have calculated the loss of power of the waveguide modes as they propagate through waveguide components, such as miter bends, on the line, including both ohmic loss and mode conversion loss. A complete loss calculation was recently presented at a meeting held by the ITER Organization. The results will be used to plan the ITER system and to place limits on the parasitic mode content of the 170-GHz gyrotrons being built for ITER.

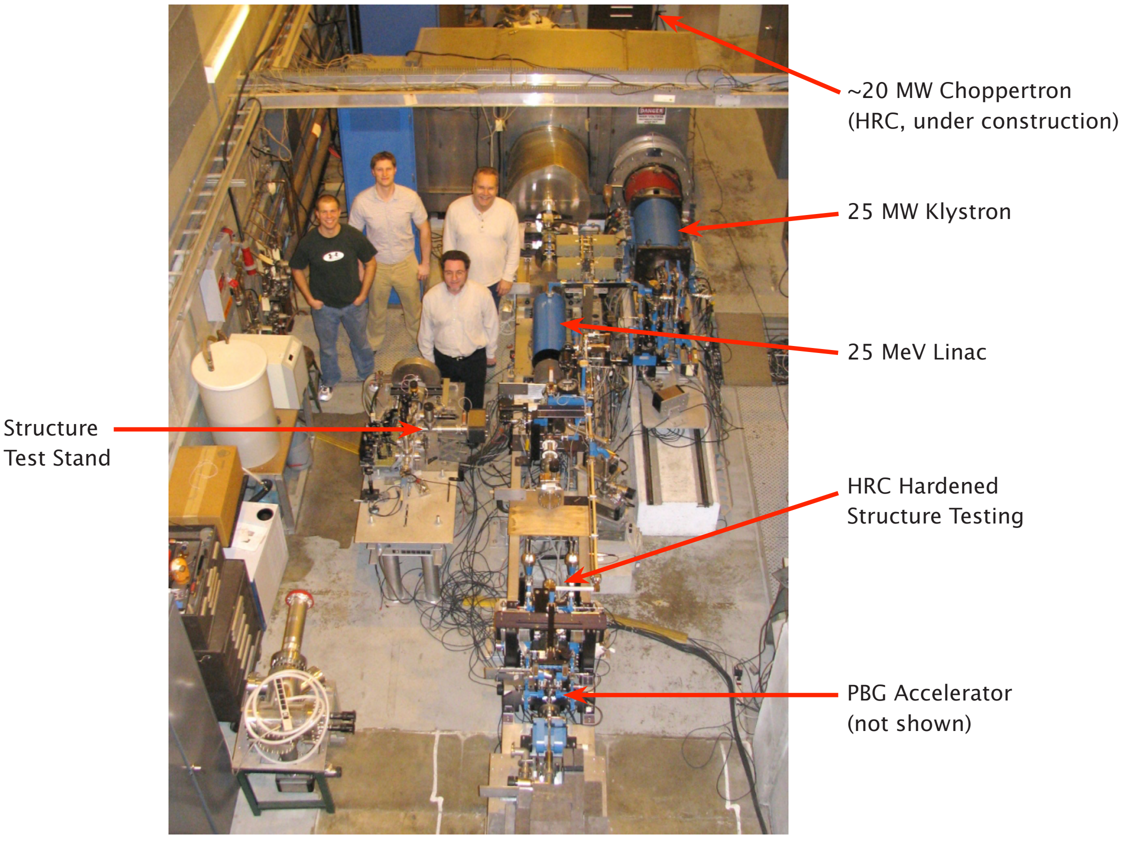

Figure 3. MIT PSFC 25 MeV electron accelerator lab, powered by the 17 GHz, 25 MW klystron.

Intensive research, under the direction of Dr. Jagadishwar Sirigiri, continues on 140- to 600-GHz gyrotron oscillators and amplifiers for use in electron spin resonance and nuclear magnetic resonance studies. In 2008–2009, we successfully rebuilt a 250-GHz gyrotron for improved efficiency and power. A tunable 330-GHz gyrotron is under construction.

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 (Figure 3). It 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 United States as well as the CERN and KEK labs. In 2008–2009, we completed a study of breakdown effects in a photonic band gap accelerator structure. The structure was designed at MIT and built and tested at SLAC National Accelerator Laboratory, Menlo Park, CA. The report of this research by Mr. Roark Marsh, a graduate student in Physics, led to a first place award at the 2009 Particle Accelerator Conference.

Fusion Technology and Engineering Division

The Fusion Technology and Engineering 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. As we described in last year's report, our FY2009 funding guidance from OFES was originally set at only $410K. At that level, the total US magnet technology program at MIT would support a little more than just one full-time employee. This, combined with the termination in January 2008 of $2M in research funding the division was performing for the US ITER project caused a financial crisis in the division, which resulted in many layoffs and retirements of senior engineering staff with many years of experience. The PSFC strongly thanks MIT for the financial support applied from Institute funds during that crisis period to support layoff notice periods. Subsequent requests to OFES for increased funding resulted in FY2009 funds being increased to $910K. This amount supports three engineering research staff members working on a program directed at developing high-temperature superconductors for fusion magnet applications.

At the recent fusion Research Needs Workshop meeting (ReNew) organized by DOE, the programmatic importance for increased research in the area of high-temperature superconducting magnet technology was identified. Thus, we are optimistic that this area of research will get increased emphasis and future funding from DOE-OFES.

One of our remaining graduate students, Luisa Chiesa, completed her PhD dissertation in nuclear science and engineering and accepted a tenure-track assistant professor position in the Department of Mechanical Engineering at Tufts University.

By the efforts of Dr. Timothy Antaya, a principal research engineer in the division, we have been successful in developing a program based on designing very compact cyclotron accelerators for detection of strategic nuclear materials (SNM). This new type of inspection system will result in a rapidly relocatable system for the active interrogation of objects for concealed SNM. Funding for these projects has been received from Raytheon, the Defense Threat Reduction Agency, and Domestic Nuclear Detection Office. Several other large proposals are pending with indications that there is a good chance of success. We expect this to be a rapidly growing program in our division.

In other areas of research, based on earlier work on a privately funded project to develop a 250-MeV synchrocyclotron for proton beam radiotherapy (Jermey N.A. Matthews, "Accelerators Shrink to Meet Growing Demand for Proton Therapy," *Physics Today*, Vol. 62, Issue 3, March 2009), we have had extensive discussions with other major companies established in this area of medical technology. We expect that in FY2010, at least one of these companies will fund further research at PSFC for radiotherapy compact cyclotrons and is also likely to license this technology through the Technology Licensing Office.

Research we performed last year through a first-round seed fund grant from the MIT Energy Initiative was summarized in a final report, *Superconducting DC Power Transmission and Distribution*. This technology is based on applying high-temperature superconducting cables to power distribution systems. We focused the initial application on increasing the efficiency of very-large-scale data server centers. This is a growing area of research and we are submitting a joint proposal with several companies to install and operate a high-temperature superconducting power distribution cable in an operating data center in a high-rise building in New York City.
This work has also formed the basis of a major project we would like to develop on campus for an MIT Green Energy Park. It would be major initiative for MIT and a very high profile demonstration, test, and research facility designed to include both faculty and students engaged in advanced renewable energy and energy efficiency research.

Educational Outreach Programs

The PSFC educational outreach program is planned and organized under the direction of Paul Rivenberg, communications and outreach administrator of the 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 can also be arranged for the general public, as well as corporations and political representatives. California congressman Jerry McNerney toured the center in May 2009 to learn more about fusion as a future energy source (Figure 4). Visitors, students, and potential incoming graduate students are also able to get an educational overview of the fusion process and of the Alcator C-Mod project by watching a video on 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 17 years. This year, Thomas retired his traveling show in March, and at this stage in his career has decided to reduce his level of effort at the PSFC to 50 percent, with four hours per week devoted to outreach. Thomas will continue to do some educational outreach in-house and will participate in the American Physical Society Division of Plasma Physics (APS-DPP) annual Plasma Expo, as he did this past year. His years of traveling outreach were recognized in May 2009, with a certificate of appreciation from President Hockfield (Figure 5).

Figure 4. California congressman Jerry McNerney and his son Greg (center) visited fusion experiments at the PSFC, accompanied by (from left) MIT vice president for research and associate provost Claude Canizares, PSFC senior research scientists Earl Marmar and Jay Kesner, PSFC director Miklos Porkolab, and Darren Garnier of Columbia University.

PSFC's associate director, Professor Jeffrey Freidberg, has helped organize educational events oriented toward the MIT community, including PSFC's annual Independent Activities Period Open House. PSFC has continued its educational collaboration with the MIT Energy Club, participating in their very successful Energy Night at the MIT Museum in October 2008, and supporting the MIT New England Energy Showcase at the Kendall Marriott in March 2009. Hundreds of MIT students, as well as business entrepreneurs, attended these events, affording them the opportunity to learn about the latest directions of plasma and fusion research.

Figure 5. PSFC director Miklos Porkolab (left) and vice president for research and associate provost Claude Canizares (right) honored Paul Thomas at a celebration of his 17 years of school visits as Mr. Magnet.

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 APS-DPP meeting. This year, Paul Rivenberg headed the effort in Dallas, TX, which attracted 90 teachers and 1,500 students. He continues to work with the APS-DPP Education Committee on outreach for the 2009 meeting in Atlanta, GA.

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 United States. Rivenberg also heads a subcommittee that created and maintains a website to help teachers bring the topic of plasma into their classrooms.

Awards, Appointments, and Promotions

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

Awards

PSFC director Miklos Porkolab was awarded the 2009 James Clerk Maxwell Prize by the American Physical Society. The prize was established to recognize outstanding contributions to the field of plasma physics and honors Professor Porkolab for his scientific achievements, educational contributions, and leadership in the plasma physics community. The citation reads: "For pioneering investigations of linear and nonlinear plasma waves and wave-particle interactions; fundamental contributions to the development of plasma heating, current drive, and diagnostics; and leadership in promoting plasma science education and domestic and international collaborations."

Joseph V. Minervini, head of the Fusion Technology and Engineering Division, received the 2008 Technical Accomplishment Award from the American Nuclear Society, Fusion Energy Division. Minervini was honored for technical accomplishments achieved in developing superconducting magnet technology for magnetic confinement fusion experiments; specifically for the development of large-scale cable-in-conduit-conductor technology for the ITER magnets as well as for the successful design, fabrication, and testing of the central solenoid model coil for ITER, a joint international research and development project that aims to demonstrate the scientific and technical feasibility of fusion power.

Recipients of the 2009 Infinite Mile Award were Thomas Hrycaj, administrative officer; Richard Lations, project technician; Philip Michaels, research engineer; and Rui Vieira, head mechanical engineer.

In fall 2008, PSFC received from Provost Rafael Reif the Environment, Health and Safety Special Recognition Award "for superior performance in achieving the standards of MIT's Environment, Health and Safety Management System."

Appointments

Alcator Division: Roman Shugayev was appointed high power systems design engineer.

Waves and Beams Division: Dr. Hae Jin Kim was appointed postdoctoral associate.

Graduate Degrees

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

- Aeronautics and Astronautics: Felix Parra Diaz, PhD
- Electrical Engineering and Computer Science: Edward Comfoltey, SM
- Nuclear Science and Engineering: Ryan Bergmann, SM; Luisa Chiesa, PhD; Larissa Cottrill, PhD; Marco Ferrara, PhD; Alex Ince-Cushman, PhD; Jin-Seok Ko, PhD; Scott Mahar, PhD; and Rachael McDermott, PhD
- Physics: Alex Boxer, PhD; Cliff Chen, PhD; Eric Edlund, PhD; William Fox, PhD; Liang Lin, PhD; and Roark Marsh, 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.