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), plasma-surface interactions, 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); and (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), and non-fusion related development primarily directed at medical and homeland security applications. Administratively, each of these areas constitutes a separate research division. In order of research area above, PSFC's research divisions are: the Alcator Project, Physics Research, High Energy Density Plasma Physics, Waves and Beams, and Fusion Technology and Engineering (FT&E).

PSFC research and development programs are supported principally by the Department of Energy's Office of Fusion Energy Sciences (DOE-OFES). There are approximately 262 personnel associated with PSFC research activities, including 24 faculty and senior academic staff members, 56 graduate students and 16 undergraduates. The participating faculty and students are from the following departments (in alphabetical order): Aeronautics and Astronautics, Electrical Engineering and Computer Science, Nuclear Science and Engineering, and Physics. In addition, there are 75 research scientists, engineers, postdoctoral associates and technical staff; 34 visiting scientists, engineers, and research affiliates; 4 visiting students; 27 technical support personnel; and 26 administrative and support staff.

Total funding for PSFC in FY2011 is projected to be $40.94 million. This includes $0.31 million in stimulus funding from the American Recovery and Reinvestment Act (ARRA) of 2009. The $40.94 million is an increase of more than eighteen percent over the center's FY2010 funding of $34.60 million, which also included ARRA funding of $1.16 million. When the ARRA funds are excluded, the net increase in PSFC research funding between FY2010 and FY2011 is an estimated $7.15 million.

The largest portion of this increase—$6.48 million—is attributable to PSFC's FT&E division, whose funding jumped from $2.93 million in FY2010 to $9.42 million in FY2011, with growth in three homeland security related programs. These programs are hardware intensive and include equipment fabrications totaling $4.96 million. Excluding fabricated equipment funds, the division's research funds will increase by over 50 percent from $2.93 million in FY2010 to $4.46 million in FY2011.

The next largest component of the increase in PSFC total funding is a net increase of $1.0

million for the Alcator experiment, from $22.72 million in FY2010 to $23.72 in FY2011, an increase of 4.4 percent. The increase is due to several factors, including an increase in the scheduled number of weeks in the FY2011 experimental campaign relative to FY2010 and support for various systems upgrades.

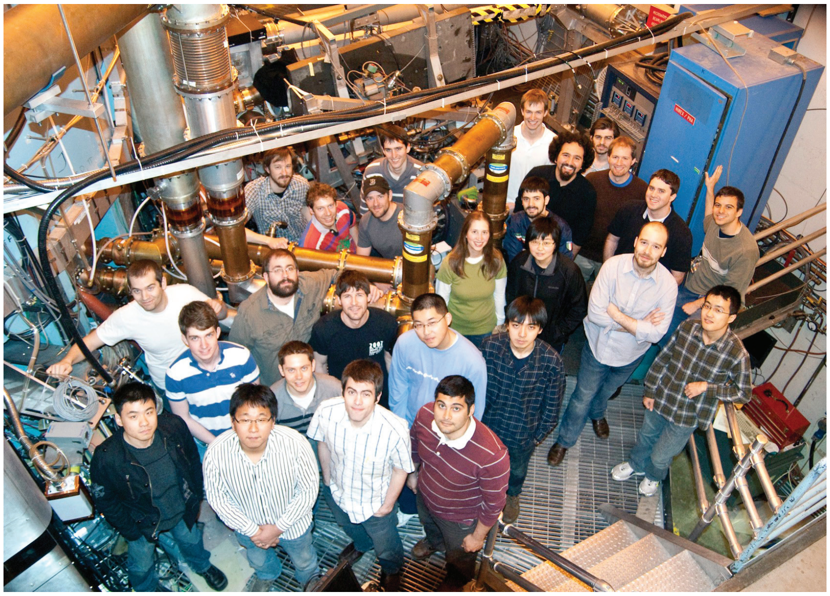
Funding to the High Energy Density Physics Division will remain constant at $2.0 million in FY2011 relative to FY2010, and neglecting the one-time contribution from ARRA funds in FY2010, base funding for the Waves and Beams Division will also remain constant in FY2011 relative to FY2010, at $1.8 million.

Finally, funding to the Physics Research Division will decrease by $0.58 million in FY2011 relative to FY2010, due primarily to DOE’s sudden cancellation of the joint MIT-Columbia University Levitated Dipole Experiment in November 2010.

Alcator Division

The Alcator C-Mod tokamak is a major international fusion experimental facility 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 consists of an MIT full-time equivalent staff of approximately 50 scientists and engineers, including 10 faculty and senior academic staff, plus 31 graduate students and 25 technicians (see figure 1). Additionally, a large number of Alcator collaborators from around the world bring 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 FY2011 funding for the project is about $27.7 million ($23.7 million direct funding at MIT).



Alcator C-Mod and students in the experimental cell.

Research on C-Mod continued during the past year in high-performance, high magnetic field, plasma confinement. State-of-the-art experiments are being carried out this year in the critical science areas of transport, wave-plasma interactions, edge pedestal, boundary physics, and magnetohydrodynamic stability, as well as in plasma integration areas involving advanced tokamak and burning plasma science.

A significant number of facility and diagnostic upgrades have been completed in the last year or are in progress: complete refurbishment of the Diagnostic Neutral Beam, used for many important plasma parameter profile measurements including ion temperature, current density, and rotation; upgrades to high resolution imaging x-ray spectrometers; addition of a polarimeter laser system to measure current profile and magnetic fluctuations; edge reflectometers to measure density profiles in front of microwave and radio frequency launchers; upgrades to turbulence diagnostics including core reflectometery, Electron Cyclotron Emission diagnostics, Phase Contrast Imaging and Gas-Puff Imaging; construction of an advanced Ion Cyclotron RF antenna aimed at a dramatic reduction of impurity sources during high power plasma heating; and a unique accelerator facility designed to probe surface conditions following each plasma discharge for plasma-wall-interaction studies.

Facility operation for research this fiscal year (FY2011) is planned to total 15 weeks, and more than 90 percent (14.5 weeks) was completed in April, with a short end of fiscal year campaign planned for September. We currently plan to keep operating at the start of FY2012 (October 2011) with a planned total of 17 research weeks in FY2012 assuming we receive our guidance budgets ($28.6M for the national C-Mod program). Details of the day-to-day operation, including links to run summaries, miniproposals, and engineering shot logs can be found at http://www-cmod.psfc.mit.edu/cmod/cmod_runs.php.

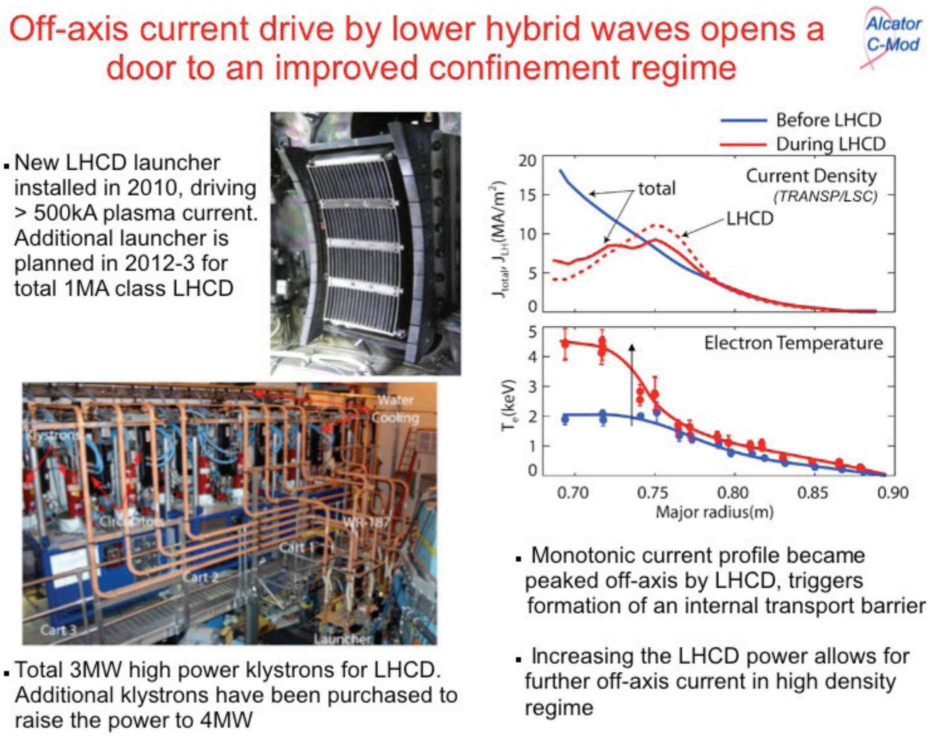
Recent Research Achievement Highlights

One focus of the 2010–2011 research campaign was extension of the I-mode operational regime to quasi-steady conditions (pulse length much longer than the characteristic times for energy and particle confinement in the hot plasma). Additionally, we are beginning to explore the detailed physics of the fast particle and reduced energy transport seen near the edge of I-mode plasmas. Finally, I-mode operation has been accessed over a significantly broadened range of plasma parameters. All of these advances are important in evaluating the prospects for applying the regime to US International Thermonuclear Experimental Reactor (ITER) and fusion reactors.

As part of a nationally coordinated joint research program, C-Mod is studying the detailed physics of the high confinement (H-mode) pedestal, the region of suppressed turbulence and enhanced confinement near the edge of the tokamak plasma. In combination with complementary studies on the DIII-D and NSTX facilities, and focused collaborations with theorists and computational modelers, these experiments will be used to test numerical models of the plasma behavior, and to aid in extrapolations to make predictions for ITER.

Recent investigation of spontaneous peaking of the central plasma density in Alcator C-Mod has found a link between the ion temperature of the plasma, the rotation of the plasma in the toroidal direction and increased stability in the core. The most damaging instability in this region is driven by steep gradients in the ion temperature, and its effects can be mitigated by using shear to limit its ability to grow and drive transport. This has been demonstrated in tokamaks where the plasma rotation and resulting shear can be controlled through neutral beam injection. In Alcator C-Mod, which has no neutral beams, this rotation rises spontaneously as a result of heating the plasma with ICRF waves at the halfway point, and is sufficient to control the instability, and allow peaking of the central density. Experimental results are backed up by extensive computer modeling of the plasma. Since neutral beam injection is expected to be of limited value in reactor plasmas such as ITER and even more so beyond, understanding how to utilize the spontaneous rotation for instability control is important.

One of the key tools available for non-inductive current drive, required to maintain the tokamak configuration in a steady state, is the use of high-powered microwaves that can be injected into the torus with phase velocity strongly directed along the toroidal direction. This is done with an advanced phased-array launcher that couples the microwave power into the plasma (figure 2). Under the right circumstances of wave frequency, plasma temperature and density, and magnetic field, the waves will penetrate into the hot plasma, and preferentially damp on suprathermal electrons (i.e. those with energies about a factor of 7–10 higher than the average thermal energy). The resulting transfer of momentum to the electron distribution is primarily toroidal, causing a net current drive. While at ITER relevant densities and magnetic fields the current drive efficiency on C-Mod was found to be in good agreement with theoretical predictions, at higher densities, such as necessary in a fusion power plant, unexpectedly low current drive efficiency has been observed. Recently significant strides have been made in increasing our understanding of the physics behind this phenomena. Using that information, we are formulating plans for additional investigations, as well as


Off-axis current drive by lower hybrid waves opens a door to an improved confinement regime

Alcator C-Mod

- New LHCD launcher installed in 2010, driving > 500kA plasma current. Additional launcher is planned in 2012-3 for total 1MA class LHCD
- Total 3MW high power klystrons for LHCD. Additional klystrons have been purchased to raise the power to 4MW
- Monotonic current profile became peaked off-axis by LHCD, triggers formation of an internal transport barrier
- Increasing the LHCD power allows for further off-axis current in high density regime

Figure 2: Lower hybrid phase array launcher microwave system and results.

possible hardware design upgrades to improve the current drive efficiency in C-Mod. It is also possible that at the much higher electron temperatures expected in reactor grade plasmas the current drive efficiency will increase once more to theoretically predicted levels due to the much stronger "single pass" absorption of the injected waves.

Physics Reseach Division

The goal of the Physics Research Division, headed by professor Miklos Porkolab, is to improve the theoretical and experimental understanding of plasma physics and fusion science. This division maintains a strong basic and applied plasma theory and computational program that focuses on tokamak and stellarator confinement devices while developing novel plasma physics diagnostic experiments and investigating general plasma mechanisms, such as reconnection. 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 the DOE-OFES, focuses on basic and applied fusion plasma theory and computational plasma physics research. It supports Alcator C-Mod and other tokamak experiments, as well as stellarator research worldwide. The PSFC theory effort is about to be enhanced by the addition of Dr. Felix Parra, who has been hired as an assistant professor by the Nuclear Science and Engineering (NSE) Department. Felix will bring with him Dr. Michael Barnes who has won a DOE Oak Ridge Institute for Science and Education (ORISE) postdoctoral fellowship. Michael will be joining our impressive group of postdoctoral fellows who include: Dr. Antoine Cerfon, who will become a professor at the Courant Institute at New York University in the fall of 2012; Dr. Matt Landreman, who also won a DOE ORISE postdoctoral fellowship (our group won two out of the four awarded this year and PSFC won three out of four); and Dr. Bo Li, who is supported by the DOE's Scientific Discovery Through Advanced Computing (SciDAC) Center for the Study of Plasma Microturbulence.

The division's high-performance, 600 processor computer cluster is the main computational resource for PSFC experimental and theory research and is heavily utilized by students, staff, and collaborators. The cluster has been in operation for almost four years. We have initiated a long-range planning process for examining technologies that might provide for our future needs.

Tokamak and Stellarator Confinement and Transport

Gyrokinetic descriptions are used throughout the magnetic fusion program to simulate turbulence in tokamaks. They retain gyromotion and magnetic drift departures from constant pressure surfaces and extent drift kinetic descriptions by retaining arbitrary perpendicular wavelengths. Recent work by Dr. Darin Ernst, PSFC research staff member, and his postdoctoral fellow, Dr. Bo Li, has shown how to rigorously retain the full linearized Fokker-Planck collision operator in an implementable manner in gyrokinetic simulations. The technique avoids the approximations and ad hoc nature of previous treatments of collisions that, for example, yield classical ion transport 50 percent in error relative to the full Landau operator even for the best model operators preserving the Boltzmann H-theorem. The improved treatment is important because of the collisional sensitivity of the nonlinear transition to a fully turbulent plasma state.

Dr. Felix Parra, our former student who is about to return to MIT, has won the 2011 Marshall N. Rosenbluth Outstanding Doctoral Thesis Award from the American Physical Society's Division of Plasma Physics. The citation reads as follows: "For demonstrating limitations in the gyrokinetic theory of the radial electric field for plasmas in an axisymmetric magnetic field and formulating an alternative procedure-insights that have inspired research around the world." Felix's revolutionary thesis and follow-up work on momentum transport in tokamaks with Dr. Catto continues to gain more acceptance within the international fusion program and is in the process of being implemented by Dr. Michael Barnes in the GS2-Trinity-Neo codes.

Dr. Matt Landreman completed his thesis with Dr. Catto on transport in optimized or omnigeneous stellarators and the role of radial electric field effects in such devices. Omnigenous stellarators (like tokamaks) confine all collisionless orbits in the absence of turbulence. Even though omnigenous stellarators (unlike tokamaks) are fully three dimensional, we were able to derive concise, explicit expressions for the gradient driven ("bootstrap") current, the ion flow, and the radial electric field in the long mean free path regime, as well as the collisionality independent, geometry driven Pfirsch-Schluter current and ion flow.

Magnetohydrodynamics and Extended MHD Simulations

Dr. Jesus Ramos, PSFC principal research scientist, through his participation in two SciDAC projects, the Center for Extended Magnetohydrodynamic (MHD) Modeling (CEMM) and the Center for Simulation of Wave Interactions with MHD (CSWIM), has been examining weakly collisional tokamak plasmas with near Maxwellian distribution functions. The motivation is to develop a theoretical model to analyze slowly growing macroscopic instabilities (such as the neoclassical tearing mode) in a high temperature, magnetically confined plasma. Using a small mass ratio ordering, the electron part of this description was completed. It features a finite Larmor radius drift kinetic equation for the non-Maxwellian perturbation to the Maxwellian that guarantees consistency between the fluid, particle, momentum and energy conservation equations, and the density, mean velocity and temperature of the Maxwellian. It also features rigorous Fokker-Planck collision operators and recovers the neoclassical results for the electrons in the long mean free path limit. Thus it includes the bootstrap current physics in general magnetic geometry, as needed for a realistic simulation of dynamic, three-dimensional magnetic fields.

The solution of a second order, nonlinear, elliptic partial differential equation known as the Grad-Shafranov equation fully determines plasma equilibria in toroidally axisymmetric magnetic confinement devices. Analytic solutions are desirable and useful for studying equilibrium, stability and transport properties as well as for benchmarking equilibrium codes. Professor Jeff Freidberg (NSE) and his former student, Dr. Antoine Cerfon, found extended analytic solutions to the Grad-Shafranov equation using more realistic profiles than previous treatments. The solutions are very versatile since they describe standard tokamaks, spherical tokamaks, spheromaks and field reversed configurations for arbitrary plasma shaping and plasma pressure.

Heating, Current Drive, Advanced Tokamaks, and Nonlinear Dynamics

In a variety of magnetically confined plasmas, radio frequency waves in the electron cyclotron and lower hybrid range of frequencies have been and are being used to modify the current profile and control the growth of the neoclassical tearing mode (NTM) instability. These waves, coupled into the plasma from an external excitation structure, have to propagate through the turbulent edge region of a tokamak where the waves can get scattered. Dr. Abhay Ram, PSFC principal research scientist, along with professor Kyriakos Hizanidis and Dr. Yannis Kominis of the National Technical University of Athens, Greece, have been studying the refraction and diffraction of radio frequency waves by edge turbulence in tokamak plasmas. They find that the electron cyclotron waves could be scattered in real space and wave vector space so as to be of concern in ITER. The electron cyclotron waves in ITER are used for controlling the deleterious NTM instability and require precise localization of the wave absorption.

SciDAC Center for Simulation of Wave-Plasma Interactions and Center for Simulation of Wave Interactions with MHD Fusion Simulation Project

PSFC conducts an active research program in the area of wave-particle interactions in fusion plasmas in the ion cyclotron range of frequencies (ICRF) and the lower hybrid range of frequencies (LHRF), through it's participation in the SciDAC Center for Simulation of Wave-Plasma Interactions (CSWPI) and the Center for Simulation of Wave Interactions with MHD (SWIM). In the past year, the CSWPI SciDAC Center secured funding for five more years with MIT senior research scientist Dr. Paul Bonoli serving as the lead principal investigator for the multi-institutional center. In collaboration with research staff member and graduate, Dr. John Wright, the MIT SciDAC research focused on the validation of predictive models for the evolution of non-thermal ion distributions generated by ICRF waves and the evolution of non-thermal electron distributions generated by LHRF waves. These simulations models self-consistently combine either an electromagnetic field solver or ray tracing code for the wave propagation with a Fokker-Planck code to evolve the distribution function. Detailed comparisons between the measured and simulated spectra produced by fast ions charge exchanging with background boron in the Alcator C-Mod tokamak have shown that the ICRF simulation model works well when the non-thermal ion distribution is no longer evolving in time, but that non-linear "kicks" in energy imparted by the ICRF waves to ions may be important during the transient formation phase of the fast ion tail. Simulated and measured hard x-ray spectra produced by LHRF-generated fast electrons in the Alcator C-Mod tokamak have also been compared in detail. It has been found that full-wave effects such as focusing, diffraction, and interference, not included in ray tracing treatments may be needed to correctly describe LHRF wave absorption in weak damping regimes, where the LH waves can propagate many times between the plasma core and vessel wall before being absorbed either by electron Landau damping or collisional dissipation.

Experimental Research

Termination of the Levitated Dipole Experiment (LDX)

LDX was a basic physics experiment that explored the confinement of plasmas in the magnetic field of a floating dipole ring. As such, it provided a unique magnetic geometry: a toroidal plasma without a toroidal field, where the coil producing the magnetic field floated within the plasma as opposed to having the plasma within a torus of coils such as in a tokamak (figure 3). The US DOE terminated this experimental effort in November 2010 as the DOE narrowed its research focus in favor of projects that directly support the international ITER effort. LDX was a joint collaborative project with Columbia University that was located in Building NW21 at MIT and was headed by Dr. Jay Kesner of MIT and Professor Michael Mauel of Columbia University. Beginning in 2007, LDX operated in the fully levitated configuration with the 1,200 pound coil floating for up to two-and-a-half hours. Plasmas were heated by electron cyclotron resonance heating (ECRH) with up to 25 kW of power including sources at five different frequencies, which permitted a spatial control of the heating profile. Levitation eliminated field-aligned losses to supports that were seen to be present in supported-mode operation. LDX also had a substantial diagnostic capability.

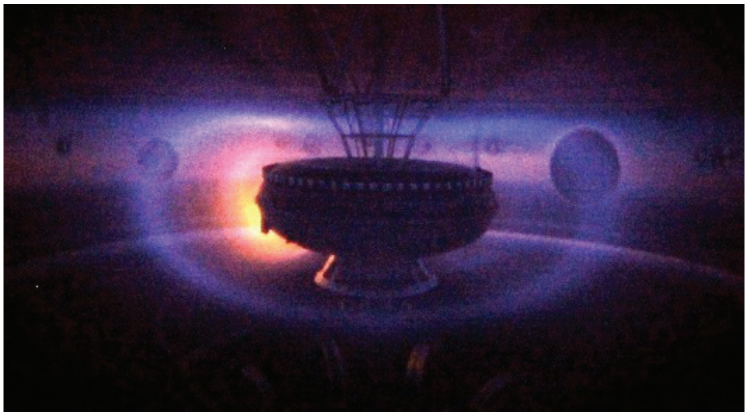


Figure 3: Color picture of Levitated Dipole Experiment. This helium discharge underwent a large scale instability which resulted in the injection of molten steel into the plasma which backlights the ½ ton, 1.2 million amperes, superconducting levitated coil.

During levitation a strong particle pinch was observed, which was reported in a Nature-Physics article (Boxer et al., *Nature Physics*, 3 (2010) 207). The pinch appeared to be the result of plasma turbulence, which is observed in LDX. That plasma turbulence can improve plasma confinement was a counter-intuitive result that supported similar observations seen in magnetospheric plasmas. Such a turbulent pinch may have been observed in other confinement devices but the effect was seen to be much more dramatic in a dipole. The pinch is observed to produce stationary density profiles with a peak-to-edge density ratio of up to 30. A new proposal is being prepared and will be submitted to secure funding from the NSF-DOE plasma science activity.

Plasma Science Center on Plasma-Surface Interactions

Professor Dennis Whyte is the director of the multi-institutional Plasma Science Center on Plasma-Surface Interactions (PSI), a collaboration among MIT, University of California, San Diego, University of California, Berkeley and Sandia National Labs, which seeks to advance PSI science through an approach that equally emphasizes material exposure to fusion-relevant conditions, cutting-edge plasma and surface

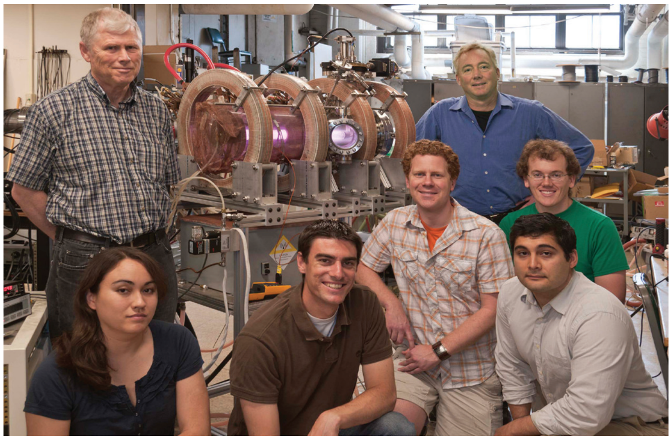


Figure 4: The operating DIONISOS experiment showing a hydrogen plasma (glowing pink horizontal column). Left to right: (standing) Research Engineer Pete Stahle, Prof. Dennis Whyte, (kneeling) Postdoctoral Associate Regina Sullivan, Graduate student Brandon Sorbom, Research Scientist Graham Wright, Graduate students Harold Barnard and Kevin Woller.

diagnosis, and high-fidelity surface and material modeling. At PSFC, Professor Whyte's research group has successfully established operation of the DIONISOS experiment which has the unique combination of high-intensity continuous plasma bombardment with in-situ material diagnosis using high-energy ion beams from an accelerator (figure 4). Initial experiments on DIONISOS are examining the mechanisms that produce surface nano-tendrils when refractory metals such as tungsten are exposed to helium plasma ions. Tungsten is considered the leading candidate as a protective armor material for future fusion devices. A particularly significant breakthrough was the very first observation of tungsten nano-tendrils forming in a tokamak divertor in a collaboration between the PSI Center and the Alcator C-Mod tokamak. It was previously believed that the intense heat and particle conditions of an actual tokamak divertor would preclude the formation of nano-tendrils. However our experiments clearly demonstrated their formation in just a short period of time in about 10 to 20 seconds in the Alcator divertor (figure 5). This clearly indicates that such strong surface modification of the tungsten will occur in ITER and reactors, increasing the urgency to understand the mechanisms causing the tendrils to grow.

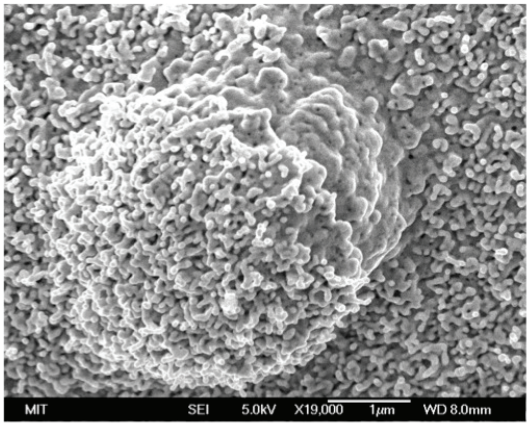


Figure 5: A scanning electron microscope image of tungsten surface after exposure to high intensity helium plasmas in the Alcator tokamak divertor. The appearance of nanometer scale tendrils being extruded from the surface indicates first observation of their formation in a tokamak divertor.

Magnetic Reconnection Experiments on the Versatile Toroidal Facility

Magnetic reconnection plays a fundamental role in magnetized plasmas as it permits rapid release of magnetic stress and energy through changes in the magnetic field line topology. It controls the spatial and temporal evolution of explosive events such as solar flares, coronal mass ejections, and magnetic storms in the earth's magnetotail, driving the auroral phenomena. Magnetic reconnection is studied in VTF (figure 6) under the leadership of professor Jan Egedal, who leads the effort of half a dozen undergraduate and graduate students. The magnetic geometry of VTF is providing insight into what controls the onset of the explosive magnetic reconnection event observed in nature. In a recent issue of *Physical Review Letters* important details of the three-dimensional nature of the magnetic reconnection event was published. The spontaneous onset is facilitated by a global mode that breaks the axisymmetry that enables a localized reconnection onset.

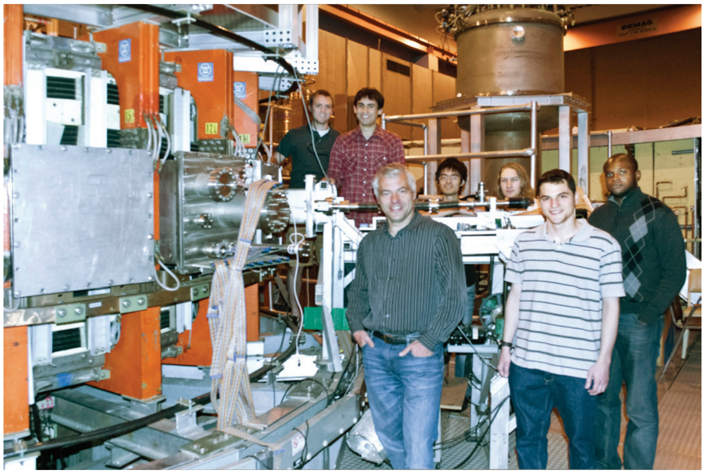


Figure 6: The VTF magnetic reconnection experiment, showing (front, left to right) Professor Jan Egedal, UROP student Dustin Katzin and graduate student Obioma Ohia, and (rear, left to right) graduate students Arturs Vrublevskis and Ari Le, and UROP students Jonathan Ng and Evan Lynch.

In most theories for reconnection, the electrons are approximated by Maxwellian isotropic distribution. However, based in part on VTF experimental results obtained during the past three years, members of the VTF group have derived a new analytic model for the electron pressure tensor during reconnection. This theory accounts for the highly anisotropic pressure near the reconnection region observed by spacecraft and in kinetic simulations. In fact, the pressure anisotropy is the driver of the highly structured electron distribution function that is characteristic of electron jets observed in the central reconnection region. We note that a strong collaboration exist between the VTF group, and eminent theorists and computer modelers at universities and National Labs (Los Alamos), who develop some of the largest 3D codes to properly describe magnetic reconnection in the earth's magnetotail and solar coronal mass ejection phenomena. The VTF group activities are part of a larger national—and, in fact, international effort—to understand the physical processes responsible for magnetic reconnection under different conditions in nature and in the laboratory.

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

Professor Porkolab leads this project from MIT, with significant participation by Dr. Paul Woskov, PSFC senior research engineer. This program supports 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 have been installed in JET during the past two years. These studies are expected to 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 which may drive Alfvén waves unstable. A new proposal was submitted recently to the DOE for continuing financial support of this project for another three years and at press time for this report we are awaiting a response by the referees.

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 the DIII-D tokamak 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 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 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 turbulence related to energy transport, and various instabilities in the Alfven wave regime during plasma current evolution. Ongoing comparisons with state of the art gyrokinetic codes (see description in the section of theory research) have provided a critical insight into the physics of electron transport, which is key to understanding energy transport in ITER scale burning plasma experiments in the presence of intense alpha particle heating of electrons. In addition, in Alcator C-Mod, mode converted ion cyclotron waves have been detected during flow drive (both toroidal and poloidal) associated with intense ICRH heating (see earlier Alcator C-Mod section). Two students (one on Alcator and one student on DIII-D) have successfully defended their PhD theses in the past year and publication of relevant results are in preparation. A new postdoctoral associate [We need to query on whether this is a postdoctoral fellow or associate. I put in “associate” as a placeholder, though because it is a hire, that probably implies an associate. I haven’t come across an example like this, which is why I am flagging it.]has been hired on the DIII-D project who will help with the ongoing experiments, including the upgrade of the cryogenically-cooled detector array.

Spinoff Research in the Physics Research Division

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 circulates the fluid to heat exchangers. The economical and technical feasibility of EGS depends very much on drilling costs to create the wells and the formation of reservoir heat exchangers. At present, the well costs can account for 60 percent or more of the total capital cost. A significant advance in rock penetration rates over conventional rotary drilling systems at lower cost could enable exploitation of sustainable geothermal energy on a larger scale than at present. Such an advance in rock penetration systems may now be possible with efficient (>50%) high energy millimeter-wave (MMW) gyrotron sources originally developed for fusion energy research. During FY2011, Dr. Woskov, sponsored by the MIT Energy Initiative, experimentally studied MMW rock ablation using the 10 kW, 28 GHz gyrotron at PSFC. The experiments succeeded in melting and bringing hard crystalline rock specimens (granite) to the vaporization point and showed good coupling of MMW directed energy to rock melt (emissivity ~ 65%). For FY2012 Dr. Woskov is working with Impact Technologies, LLC on a proposal to DOE to advance the experiments and MMW system design toward a field test. Proposed Phase I FY2012 effort at MIT will involve more extensive rock ablation experiments, modeling MMW drilling and MMW component design. PSFC will also partner with professor Herbert Einstein at the MIT Rock Mechanics Laboratory, Civil Engineering Department, to study the strength of MMW exposed rocks and resulting vitrified forms that could be used as borehole casing.

Thermal Analysis of GEN IV Nuclear Reactor Materials

The development of Generation 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 FY2011, Dr. Woskov, along with Dr. S. K. Sundaram, of Pacific Northwest National Laboratory and now with Alfred University, carried out experiments funded by the DOE Nuclear Energy University Program on the development and use of novel MMW thermal analysis tools to address VHTR materials needs. An MIT Undergraduate Research Opportunities Program student is also participating in this work. A pair of 137 GHz heterodyne receivers with orthogonal polarization has been set up to view specimens inside a furnace for high temperature materials studies. This makes possible the real-time non-contact observation of material temperature, emissivity, displacement, and anisotropy. Experiments have been done with graphite and silicon carbide samples to demonstrate the unique thermal analysis capabilities of millimeter-waves. The ability to observe anisotropic material behavior in real time was shown by tilting a test sample to simulate anisotropy. Results were reported at the Materials Research Society Fall 2010 meeting in Boston. In FY2012, materials studies will continue with reactor-grade graphite materials, silicon carbides, and composite ceramics.

High-Energy-Density Plasma Physics Division

The High-Energy-Density Physics (HEDP) Division, led by Dr. Richard Petrasso, has carried out pioneering and important studies in the areas of Inertial Confinement Fusion (ICF) physics and HEDP. The division designs and implements experiments, and performs theoretical calculations, to study and explore the non-linear dynamics and properties of plasmas in inertial fusion and those under extreme conditions of density (~1,000 g/cc, or 50 times the density of gold), pressure (~1,000 billion atmospheres, or 5 times the pressure at the center of the sun), and field strength (~1 megagauss, corresponding to 2.5 million times the earth's magnetic field).

HEDP collaborated extensively with the Lawrence Livermore National Laboratory (LLNL), where the huge National Ignition Facility (NIF) is expected to achieve ignition (self-sustaining burn) by imploding fuel capsules with a 2-MJ, 192-beam laser. The NIF is being tuned for an ignition campaign, and MIT has developed and provided several diagnostic instruments for studying the compression, symmetry, timing, and nuclear

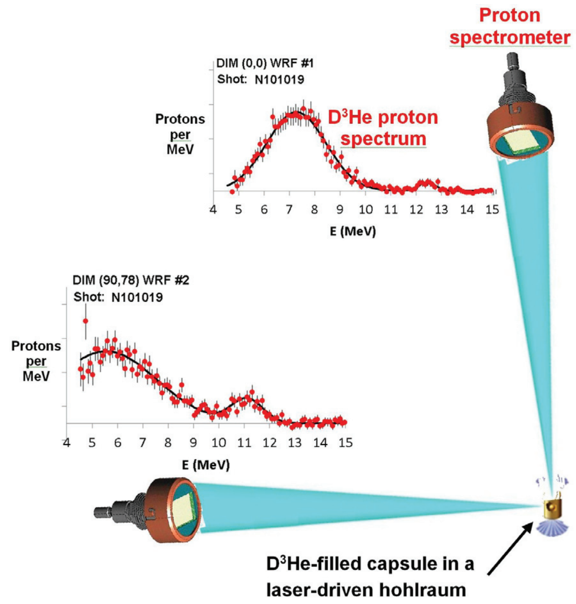


Figure 7: Two proton spectrometers measure the spectra of fusion protons leaving a NIF fuel capsule in different directions for purposes of studying implosion symmetry and areal density.

yields of NIF ICF. The Magnetic Recoil Spectrometer (MRS) is used to measure high-resolution spectra of 16-30 MeV DT neutrons. The spectra of primary 14.1 MeV neutrons give information about fusion yield and plasma temperature, while spectra of downscattered neutrons that have lost energy through interactions with fuel ions provides a measure of the compression of the fuel. Compact proton spectrometers are used to measure the energy and yield of protons born at 14.7 MeV during fusion in fuel capsules containing D and 3He. The measured energy reflects capsule areal density, which causes the protons to slow down while leaving a capsule. The spectrometers record two separate proton lines (the first generated when shock waves coalesce at the capsule center, the second at the time of maximum fusion yield) and thus determine areal densities at two different times. Spectrometers utilized simultaneously at different directions around the capsules provide a measure of the symmetry of capsule compression both at shock coalescence time and at compression bang time (figure 7). A third diagnostic is being developed to measure the precise times corresponding to shock and compression bang. This is a particle time-of-flight detector, which utilizes a special kind of diamond to measure the time evolution of the fusion product yield at a detector location. The MIT-developed instruments collectively form an essential part of the ignition diagnostics set for studying implosion dynamics. In addition to ICF physics, division scientists are collaborating with colleagues at LLNL and at the Laboratory for Laser Energetics (LLE) at the University of Rochester, in defining other science that can be studied at NIF, which will offer unique opportunities to explore the properties of matter under extreme pressures and densities.

The division also collaborated and did its own original research at LLE, where the 30-kJ, 60-beam OMEGA laser provides an important test bed for ICF experiments. The MIT-LLE collaboration works to provide (using novel diagnostic techniques) comprehensive diagnostic information about ICF plasmas by making spectral, spatial, and temporal measurements of fusion products. MIT diagnostics and experiments on the OMEGA laser facility support programmatic objectives of both LLE and LLNL, MIT's own scientific goals, and research programs of other external users of the OMEGA laser facility from universities and national laboratories around the world. A particularly important series of MIT experiments on OMEGA involved the use of monoenergetic, charged-particle radiography to study electric and magnetic fields and plasma flow in indirect-drive ICF experiments that are scaled-down versions of those to be performed at the NIF (laser beams incident on the inner walls of a small container called a hohlraum generate x-rays that cause an ICF fuel capsule to implode). MIT also undertook a major effort to organize all external OMEGA researchers for the third time in the now-annual OMEGA Laser Users' Group Workshop. This workshop brought together scientists and students from all over the world to discuss current research and to help LLE enhance its facility and procedures for outside scientists.

Besides research results themselves, HEDP places equal importance on the training and accomplishments of its seven PhD students and its postdoctoral associate. They are all intensely involved in all division projects at LLNL and LLE, and they perform major work on the division's accelerator, where they calibrate MIT-developed diagnostics and do other basic research (figure 8).

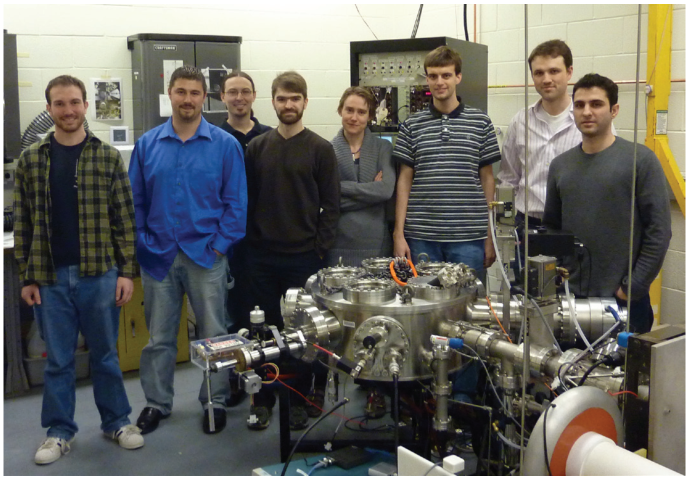


Figure 8: Shown behind the target chamber of the Division's Cockroft-Walton Accelerator are seven of the Division's PhD students and Post-doctoral Associate Maria Gatu Johnson. From left to right are Mike Rosenberg, Mario Manuel, Dan Casey, Hans Rinderknecht, Dr. Johnson, Alex Zylstra, Caleb Waugh, and Nareg Sinenian. The accelerator was used for a wide range of purposes in the development and calibration of ICF diagnostics for experiments at OMEGA and at the National Ignition Facility.

Waves and Beams Division

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

Gyrotron and Accelerator Research

Gyrotrons are under development for electron cyclotron heating of present day and future plasmas, including: the ITER plasma; for the purposes of high-frequency radar; and for the purposes of spectroscopy. These applications require gyrotron tubes operating at frequencies in the range of 90–500 GHz at power levels up to several megawatts. The Gyrotron Group, headed by Dr. Michael Shapiro, is conducting 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 used for heating large-scale plasmas in the fusion energy research program. Research on the MIT 1.5-MW-power-level gyrotron is needed to help plan the upgrade of the heating system of the DIII-D tokamak at the General Atomics Corporation in San Diego, CA; that system now uses 1-MW-power-level gyrotrons. In 2010–2011, experimental research was conducted on measuring the gyrotron cavity modes excited during the start-up, as the voltage increased, of the pulsed gyrotron operating at 96 kV and 42 A. We found that at the operating point corresponding to the highest output power in the TE22,6 design mode, a high order axial TE21,6 backward wave mode was excited during start-up and persisted up to a voltage of 70 kV. This surprising result does not agree with previous theoretical predictions that higher frequency modes are the most dangerous competitors during start-up. These results are an excellent test of nonlinear gyrotron theory. We are collaborating with the University of Maryland on the use of their code to explain these unexpected results. The gyrotron group is also using the 1.5 MW, 110 GHz power-level pulsed gyrotron to study breakdown in air and in other gases, including the discovery of arrays of filaments in microwave air breakdown. In 2010–2011, we measured the optical emission spectrum of light from the air breakdown and compared it with theory. We also measured the delay time in plasma formation and found very good agreement with theory. These results are of great interest in planning future radars.

We are continuing research on low-loss microwave (170 GHz) transmission lines in collaboration with the US ITER project headquartered at Oak Ridge National Lab. In 2010–2011, we investigated methods for measuring the unwanted higher order modes in the transmission line. We compared two separate measurement techniques: phase retrieval from amplitude measurements on a series of planes and direct measurement of phase. The latter technique was found to be superior. We continued research on techniques for converting the unwanted higher order modes of the transmission line back into the fundamental (HE11) mode. We proposed using two miter bends of the line, with mirrors either shaped or tilted, for accomplishing this mode conversion. Elimination of the higher order modes is needed to properly steer the microwave beams at the exit of the transmission line and to avoid damaging the launching structures.

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 headed by Stanford University's SLAC National Accelerator Laboratory that includes major labs in the US as well as the CERN and KEK labs. In 2010–2011, we tested a novel photonic bandgap accelerating structure at the 11.4 GHz test set at SLAC. The tests were focused on measuring the breakdown rate in the structure as the accelerating gradient was increased from 50 to 120 MV/m. The tests were conducted over a four-month period to study the exceedingly low rates, less than one breakdown per hour in some cases. We are upgrading our facilities at MIT PSFC in order to conduct similar tests at 17.1 GHz. These results are important for planning future accelerators.

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 has broad experience in all aspects of engineering research, design, development, and construction of magnet systems and supporting power and cryogenic systems. The division's major emphasis is on support of the US national fusion program and international collaboration, where PSFC provides leadership through the Magnets Enabling Technology program.

During the past year, division efforts were focused in three major areas: research and development of very compact, high field superconducting cyclotron accelerators for detection of Strategic Nuclear Materials (SNM); application of High Temperature Superconducting (HTS) materials and systems to fusion magnet systems; application of HTS materials increasing power grid efficiency, reliability, and stability.

Led by Dr. Timothy Antaya, a principal research engineer in the division, a strong program and capability is being developed in very high field, superconducting cyclotrons for medical, security, and research applications. Foremost among these applications, the division is now working on four different projects funded by the Defense Threat Reduction Agency (DTRA). A basic research program called the "Frontier Studies Program" is aimed at understanding the physics and technology for sensing fissile materials at long range. This program is lead by Dr. Antaya and supports two graduate students in fundamental topics applied to this technology. This includes both theoretical and experimental research.

More directed research is supported using DTRA funds through awards from the Los Alamos National Laboratory (LANL) and the Pennsylvania State University Applied Research Laboratory (PSU-ARL). This work is aimed at developing a new type of inspection system that will result in a rapidly relocatable system for the active interrogation of objects at a distance for concealed SNM. Under the LANL project we successfully completed a conceptual design study for the construction of a 250 MeV, 1 mA, high-extraction-efficiency, superconducting, isochronous, cyclotron proton accelerator. In December 2010, this project leadership was assumed by PSU-ARL, and MIT has, under contract to them, continued into the final design and fabrication stage of this device, referred to as the Megatron. MIT is also under contract to PSU-ARL to develop a proof-of-principle device called the Nanotron, a small-scale superconducting cyclotron proton accelerator for portable deployment in various operational scenarios.

A fourth project, also using DTRA source funds, has been received from Raytheon for the Integrated Standoff Inspection System, or ISIS. This is an active interrogation nuclear radiation detection system that will provide the government with an accurate and reliable inspection system that is fully integrated and automated.

Under the fusion magnets base program, our efforts are now directed at developing magnet technology for devices beyond ITER, and toward the era of a DEMO. We are doing this by development of very high current cables and joints using YBCO second-generation high temperature superconductors (HTS).

Over the last decade, significant worldwide efforts have been devoted to development of HTS wires of the first generation BSCCO-2223, BSCCO-2212 and the second generation YBCO for various electronic device applications such as transformers, fault current limiters, energy storage systems, magnets and power transmission cables. Most HTS tape devices have been using configurations employing single tape or only a few tapes in parallel. Few cabling methods of HTS tapes have been developed. Fusion magnet applications require development of high current density cables capable of carrying high currents, at high magnetic fields. We have developed a new cabling approach to achieve these goals, and this year performed various, small-scale lab experiments and performance analyses.

We have also continued to promulgate the application of similar scale HTS cables, to applications in superconducting DC power distribution and transmission, with particular emphasis on microgrids, and integration of time fluctuating renewable power sources such as solar, wind, and others into the grid.

Other smaller research grants have been awarded through one phase-I SBIR from the fusion program, and a Princeton Plasma Physics Laboratory funded project to develop the In-Vessel-Coils for the ITER project.

The division now has a relatively large portfolio of funding for different applications from several different sources. The growth in these programs has led us to hire new staff, and, in several cases, rehire former PSFC staff members. The division personnel roster now includes a broad and deep interdisciplinary team in science, technology, and engineering that should allow for stable program growth in the future.

Educational Outreach Programs

The Plasma Science and Fusion Center's educational outreach program is planned and organized under the direction of Mr. Paul Rivenberg, communications and outreach administrator of PSFC. The program focuses on heightening the interest of K–12 students in scientific and technical subjects by bringing them together with scientists, engineers, and graduate students in laboratory and research environments. Hopefully, this kind of interaction encourages young people to consider science and engineering careers. Tours of our facilities are also available for the general public.

Figure 9: Senior Research Scientist Martin Greenwald (right) discusses the importance of fusion research with Florida Senator Bill Nelson in front of the Alcator C-Mod Tokamak.

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.

PSFC has received some attention from lawmakers this year, facilitated by MIT alumnus Reiner Beeuwkes ’67. These included US Senator Bill Nelson (D-FL) (figure 9), US Senator Jon Tester (D-MT), Massachusetts State Senator Benjamin Downing, and US Representative Peter Welch (D-VT). All were guided around the Alcator C-Mod control room and cell to learn more about the benefits of fusion energy.

The Mr. Magnet Program, headed by Mr. Paul Thomas, was well known for bringing lively demonstrations on magnetism into local elementary and middle schools for 17 years. In 2009, the program was scaled back to focus entirely on in-house educational outreach, such as Outreach Days. Although Paul has retired his truck, he has not retired his vision of bringing science into elementary school classrooms.

Knowing that his large hands-on experiments were becoming a logistical challenge, requiring hours to install and break down, Paul decided to move in the opposite direction, designing demos that could be easily handled and transported by anyone. Originally motivated by a desire to bring some new demonstrations to his niece’s school, Paul built three tabletop experiments for grades K–4, focused on measuring voltage, building circuits, and testing electromagnets. He had hoped he could make them so user-friendly that PSFC employees and alums would want to borrow them for presentations at their children’s schools. These have become the foundation of the Portable Elementary Physics Program.

Thomas has used the equipment in his niece’s classroom, and has loaned the materials to alumni. Any PSFC employee interested in bringing science into the K–4 classroom is welcomed to sign out the equipment (or pieces of it). Paul Thomas will provide training, which will also address safety issues involved with bringing MIT equipment into a school.

For the first time, PSFC has had the opportunity to participate in the NuVu Studio program. This innovative educational collaboration between MIT and a local high school, welcomed PSFC graduate student Istvan Cziegler to coach a two-week studio on fusion energy. The result was judged to be one of the best studios NuVu had presented.

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 a variety of interactive plasma demonstrations to their very successful Energy Night at the MIT Museum in October, and the MIT New England Energy Showcase at the Kendall Marriott in March. 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. This year the laboratory also participated in the MIT150 Open House, providing tours of the center, as well as magnet and plasma demonstrations from Mr. Magnet. These events were filled to capacity.

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; see figure 10) has become a tradition at each year's APS-Division of Plasma Physics meeting.

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 overseeing the production of a short video about plasma. 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.

Figure 10: Senior Research Scientist Paul Bonoli engages children with a "plasma sword" at the APS-DPP Chicago 2010 Plasma Sciences Expo.

Awards, Appointments, and Promotions

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

Awards

Associate professor in physics Jan Egedal was honored as an APS Fellow at the American Physical Society's Division of Plasma Physics meeting, held in Chicago in November 2010.

Assistant professor Anne White was selected by the DOE Office of Science to receive an Early Career Research Award. Professor White's project is entitled Electron Temperature

Fluctuation Measurements and Transport Model Validation at Alcator C-Mod. The five-year awards are designed to bolster the nation's scientific workforce by providing support to exceptional researchers during the crucial early career years, when many scientists do their most formative work.

Alternator supervisor Mike Rowell and Alcator Project technician Frank Shefton were selected to receive 2011 Infinite Mile Awards by the Office of the Provost along with the Office of the Vice President for Research and Associate Provost.

A number of PSFC graduate students were also recognized for their work:

Elizabeth Kowalski and Christian Haakonsen received 2010 US Department of Energy Office of Science fellowships. Kowalski is an Electrical Engineering and Computer Science student in the Waves and Beams Division; Haakonsen is an NSE student working with the Alcator Project. Incoming NSE student Mark Chilenski also received an award.

Matthew Reinke was honored twice by NSE. He received the Manson Benedict Award, for excellence in academic performance and professional promise by a graduate student. His poster, Impurities in Tokamak Plasmas, was also honored as Best Poster at the second annual Doctoral Research Expo.

Brian Munroe was a winner of a Best Student Paper award at the 2011 Particle Accelerator Conference in March 2011.

Appointments

Alcator Division: Ms. Roza Tesfaye was appointed Power Electronics Systems Engineer; Dr. David Pace was appointed postdoctoral fellow.

Physics Research Division: Dr. Bo Li was appointed postdoctoral associate; Dr. Maria Gatu Johnson was appointed postdoctoral associate; Dr. Antoine Cerfon was appointed postdoctoral associate; Dr. Alessandro Marinoni was appointed postdoctoral associate.

Technology and Engineering Division: Dr. Andre Berger was appointed postdoctoral associate; Dr. Alexey Radovinsky was appointed Leader, Analysis and Codes Group; Mr. Bradford Smith was appointed project manager, Magnet Design Group.

Waves and Beams Division: Dr. Alan Cook was appointed postdoctoral associate; Dr. Sudheer Jawla was appointed postdoctoral associate.

Promotions

Headquarters: Jane Jackson was promoted to associate fiscal officer.

Alcator Division: Mr. T. Brandon Savage was promoted to IT and network administrator; Mr. Joshua Stillerman was promoted to data systems manager; Dr. Shunichi Shiraiwa promoted to research scientist; Dr. Brian LaBombard was promoted to senior research scientist.

High Energy Density Physics Division: Dr. Chikang Li was promoted to senior research scientist.

Graduate Degrees

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

- NSE: Mr. Antoine Cerfon, PhD; Mr. Haruhiko Kohno, PhD; Mr. Robert Block, MS
- Physics: Mr. Matthew Landreman, PhD; Ms. Andrea Schmidt, PhD; Mr. Istvan Cziegler, PhD

Miklos Porkolab
Director
Professor of Physics