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MIT’s Plasma Science and Fusion Center is known internationally as a leading university research center for the study of plasma and fusion science and technology. Plasmas (ionized gas) are a rich area of basic and applied research. The PSFC seeks to provide research and educational opportunities for expanding the scientific understanding of the physics of plasmas, the “fourth state of matter,” and to use that knowledge to develop useful applications.

The study of plasmas relevant to fusion power is the major focus of the PSFC research program. Thermonuclear fusion occurs naturally in the sun and other stars, releasing the energy that keeps them “burning.” The plasma that makes up a star is held together by gravity because of the star’s large mass. In laboratory devices, magnetic fields may be used to confine the hot deuterium and tritium (isotopes of hydrogen) long enough for fusion reactions to occur. In another approach, powerful laser beams may be used to compress pellets or special capsules of deuterium and tritium gas, to achieve “inertial fusion” for short time durations. Plasmas in magnetic confinement devices are usually heated by energetic particle beams or high-power radio frequency waves or microwaves. Most successful magnetic confinement devices use a plasma in the shape of a “torus” (a doughnut shape), which prevents the particles following the magnetic field lines from escaping the plasma. The most advanced of these toroidal configurations is called the “tokamak,” an acronym of the Russian words for “toroidal magnetic chamber.” However, the PSFC has research activities not only in magnetically confined plasmas, but also in high-energy-density, inertially confined plasmas, both relevant to the production of fusion power.
Founded in 1976, the Center consolidated research carried out in MIT’s academic departments, the Francis Bitter Magnet Laboratory, and the Research Laboratory of Electronics (RLE). The laboratory was originally known as the Plasma Fusion Center. However, given the Center’s broad range of plasma and fusion science related research and its educational mission, more than 10 years ago the name was changed to Plasma Science and Fusion Center, or PSFC. Located on the MIT campus, the PSFC is integrated into the university community, where it provides research opportunities not only to research scientists, but also to both graduate students and undergraduates, helping them fulfill the research requirements for their academic degrees. In addition, faculty members associated with the Center are actively involved in teaching plasma physics and fusion-oriented courses in various academic departments. Nearly all research staff members are employees of MIT, and the Institute provides and maintains the laboratory and office facilities and infrastructure.

Administratively, major research areas are organized by Divisions, each with its Division Head who reports directly to the PSFC Director. The PSFC’s research divisions are the Alcator Project, Physics Research, High-Energy-Density Physics (HEDP), Waves and Beams, and Fusion Technology and Engineering. The newest of these divisions, HEDP, was formalized this past year to recognize the growth of inertial confinement fusion (ICF) research at the PSFC during the past decade. The Division of Plasma Technology, another area of active research in previous years was phased out very recently due to loss of funding. In summary, the following are the key research activities at the PSFC at the present time:

- The science of magnetically confined plasmas in the development of fusion energy, in particular the Alcator C-Mod tokamak project
- The basic physics of plasmas, including magnetic reconnection experiments on the Versatile Toroidal Facility (VTF), new confinement concepts such as the Levitated Dipole Experiment (LDX), development of novel high-temperature plasma diagnostics, basic laboratory experiments, and importantly, theoretical plasma and fusion physics
- The physics of high-energy-density plasmas (HEDP), which includes the PSFC’s activity on inertial confinement laser-plasma fusion interactions, mostly through collaborations on the OMEGA laser at the University of Rochester; future activities will also include the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory
- The physics of waves and beams (gyrotron and high gradient accelerator research, beam theory development, non-neutral plasmas, and coherent wave generation)
- A broad program in fusion technology and engineering development that addresses problems in several areas
(for example, both normal and superconducting magnets for fusion and accelerator devices, superconducting materials, and system studies of fusion reactors)

- Research into plasma technologies, such as plasma-assisted conversion of hydrocarbon fuels into hydrogen, and the development of environmental monitoring and remediation techniques based on plasma technology has been phased out very recently due to lack of funding.

PSFC research and development (R&D) programs are supported principally by the Department of Energy. Total research volume in the past year from all sources was approximately $32 million. There are approximately 252 personnel associated with PSFC research activities. These include 9 faculty and 11 senior scientists and engineers; 56 graduate and 6 undergraduate students from MIT and 3 visiting students; 76 research scientists, engineers, postdoctoral associates, and technical staff; 37 visiting scientists, engineers, and research affiliates; 31 technical support personnel; and 23 administrative and support staff. The PSFC is affiliated with 7 academic departments, including (in alphabetical order) Aeronautics and Astronautics, Chemical Engineering, Electrical Engineering and Computer Science, Materials Science and Engineering, Mechanical Engineering, Nuclear Science and Engineering, and Physics. The majority of the PhD students are from the departments of Nuclear Science and Engineering (NSE) and Physics.

Meanwhile, over the past decade student interest in plasma and fusion sciences and engineering has remained strong, and a steady stream of highly qualified student applicants ensures healthy graduate student participation in research projects at the PSFC. The PSFC has also been sponsoring a strong K-12 educational outreach program, including on-site demonstrations of science and experiments by "Mr. Magnet," both at local schools and at MIT, where graduate students also help guide school visits. We have been also actively participating in the Plasma Expo at the Annual APS Plasma Physics Division Meeting.

In view of recent dramatic increases in the cost of nearly all forms of energy, we are optimistic that because of fusion’s promise for an unlimited and clean energy source, funding of fusion research will continue in the United States at a healthy level, and MIT’s PSFC will continue to contribute in important ways to realize fusion’s promise in the future.

**Miklos Porkolab**
**Director**
**Professor of Physics**
The Alcator C-Mod tokamak uses extremely strong magnetic fields, an approach that makes it possible to produce very dense, very well-confined plasmas in a relatively compact device.

**Background**

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.

Alcator C-Mod, like its MIT predecessors Alcator A and Alcator C, operates with extremely strong magnetic fields, an approach that makes it possible to produce very dense and well-confined plasmas in a relatively compact device. C-Mod’s big difference is its D-shaped cross-section with a poloidal divertor. Information from Alcator C-Mod provides important contributions to the ITER Project, a world-wide collaborative facility to be built in France. ITER will be the world’s largest tokamak. It is designed to be the first tokamak to study the science of burning plasma, where the power from the fusion reactions is the dominant plasma heating source.

For fusion to occur, hot plasma must be kept away from the walls of the vacuum vessel. The insulation is never perfect, however, and plasma heat and particles slowly leak across the confining magnetic fields. These diffusion and convection processes are turbulent, and predicting the rates at which heat and particles are lost presents major experimental and theoretical challenges. To estimate energy losses in future machines, “scaling laws” are developed using experimental results from many different tokamaks operating over a wide range of conditions. A range of heating and fueling techniques, plasma shapes and variations in toroidal and poloidal magnetic fields is used to increase understanding.
of energy, particle and momentum transport in high-temperature plasmas, by carefully comparing theory and experiment.

Tokamak plasmas have a cross-section that is naturally circular. However, an elongated plasma, taller than it is wide, favors efficient “cleansing” by a vertical divertor system like the one in Alcator C-Mod. The plasma’s elongated shape also allows superior plasma stability and confinement. To optimize performance, experimenters control the plasma’s detailed shape. Fast feedback systems control the magnetic fields during each pulse. Localized heating and fueling help to control the temperature and density profiles. The plasma current profile is indirectly affected by these parameters, and currents can also be directly controlled using microwaves.

Alcator C-Mod has an advanced “divertor system” that uses specially shaped magnetic fields to scrape away the cooler, outer edge of the plasma and draw it into an isolated channel on the bottom of the vacuum vessel. This is necessary because ions escape from magnetically confined plasmas and collide with the walls of the vacuum vessel, where they deposit their energy and become neutralized. Efficient divertor systems will be key elements in future fusion plants. Alcator C-Mod employs divertor channels with a baffle design that sets the standard for the next generation of tokamaks.

The C-Mod team includes Full Time Equivalent Staff at MIT of approximately 50 scientists and engineers, (including 8 faculty and senior academic staff), plus 27 graduate students and 25 technicians. In addition we have collaborators from around the world, bringing the total number of scientific users of the facility to about 200.

**RECENT RESEARCH ACTIVITIES**

Research on C-Mod continued during the past year in high-performance, compact magnetic plasma confinement. Experiments this year were carried out in the topical science areas of transport, wave-plasma interactions, pedestal physics boundary physics and magneto-hydrodynamic stability, as well as in the integrated thrust areas of H-Mode Inductive Scenarios and Advanced Scenarios aimed eventually at non-inductive steady-state operation.

Facility operation for research in the current fiscal year (FY2008) is 15.7 weeks, slightly exceeding the planned 15 weeks. Details of the
day-by-day operation can be found on http://www-cmod.psfc.mit.edu/cmod/cmod_runs.php, which includes links to run summaries, mini-proposals and engineering shot logs.

Recent research activities on Alcator C-Mod have addressed many issues important for the success of ITER and future reactors. A study of density peaking in C-Mod plasmas at low collisionality, enabled after the installation of a divertor cryopump, has broken the covariance between collisionality and density limit fraction that wasn’t separable from observations on other devices; it now appears that the collisionality is the relevant control parameter, and density peaking factors of ~1.5 may be expected for ITER. There is some uncertainty about the H-mode (high confinement regime) power threshold at low density and recent experiments have shown that this low density limit for H-mode does not depend on the plasma density normalized to the empirical density limit, also known as the Greenwald limit. For discharges with unfavorable B field drift direction, there is a slowly developing L-H (L for low confinement regime) transition, which can be studied with a comprehensive set of diagnostics to unravel the role of radial electric field and velocity shear in the dynamics of the edge pressure pedestal formation in plasmas without external momentum sources. Pedestal width remains one of the crucial uncertainties for the ITER H-mode scenario, despite the substantial leverage the quantity has on performance. C-Mod H-mode pedestal density profiles exhibit a remarkable stiffness, with resiliency to core fueling and magnitude of the plasma current, suggesting an edge-critical gradient regulated by transport, similar to what is seen in the plasma core. There is also evidence for a critical gradient in the near scrape-off layer (SOL) profiles.

Important progress was made using the lower
hybrid microwave system, which is a key tool for control of plasma current density profiles in advanced scenarios. The long term goals of this research are to: demonstrate and develop predictive models for current profile control, leading to full non-inductive current drive for pulse lengths long compared to current profile relaxation times; produce, understand and control core transport barriers with strongly coupled electrons and ions; attain and optimize plasma pressure up to the no-wall beta (plasma pressure to magnetic pressure ratio) limits, with normalized $\beta_N$ approaching 3. Lower Hybrid RF power has been coupled into ion-cyclotron heated plasmas, including plasmas operating in the H-mode regime. Current drive experiments at ITER-relevant magnetic field and density on C-Mod have already demonstrated off-axis current drive, with good agreement between hard x-ray diagnostic profile measurements, and code modeling. As much as 800 kilo-Ampere of the plasma current has been driven by lower hybrid waves in these experiments, corresponding to 80% of the total current. Microwave current drive has also been used to manipulate plasma instabilities, alternately stabilizing or destabilizing magneto-hydrodynamic modes through control of the phasing of the launched power. The lower hybrid project is under the direction of Professor Ronald Parker.

Major disruptions are potentially risky events in tokamaks because the escaping pressure caused by the plasma instability can damage the containment vessel. Rapidly injecting inert gas into the unstable plasma greatly lowers the risks by making the thermonuclear plasma lose its pressure by releasing a relatively uniform emission of photons. Recently this mitigation technique has been experimentally demonstrated on Alcator C-Mod at plasma and magnetic pressures comparable to those expected in ITER. The instability was detected and the disruption “caught” in a few thousandths of a second by real-time computer monitoring of the plasma, and the gas mitigation system was automatically triggered in time to ameliorate the effects of the disruption. For the first time, a state-of-the-art 3D instability numerical model (NIMROD) of these experiments has shown how the plasma “helps itself” by mixing around the injected gas particles via the plasma instabilities themselves, a key insight into projecting this method to ITER and ultimately to reactors.

C-Mod is a unique high-power diverted tokamak with molybdenum refractory metal armor. Research on C-Mod has shown that its molybdenum walls have the surprising ability, in some cases, to retain about 30% of the hydrogenic (deuterium) gas fuel injected into the device. Large fractions of retention are not tolerated in a burning plasma device because they affect the tritium (hydrogen isotope) inventory available for burning. Refractory metals are typically favored for
1. Shown in blue, the poloidal field magnets control the plasma’s shape and position. Molybdenum tiles protect the vacuum vessel’s plasma-facing wall.

2. Shown in yellow are three of the 20 toroidal field magnet arms, which join in the tokamak’s central core. The horizontal windings around the core are used to establish the plasma current. The peak toroidal field inside these windings is 20 tesla. (1 tesla = 10,000 gauss. The earth’s magnetic field is about 0.4 gauss. A toy bar magnet is about 100 gauss.)

3. The wedge plate forms channels which support the toroidal field magnet arms.

4. Twenty vertical legs complete the magnet, which can produce a 9 tesla toroidal field.

5. The top and bottom covers, made of solid stainless steel, are 10 feet in diameter and 26 inches thick. Each cover weighs 35 tons, and bulges 1/8 inch during a maximum performance pulse.

6. Draw bars, made of a super-strong alloy, hold the covers in place.
ITER and future reactors due to their high melt temperature and strength, and usually, their low capacity for H storage as compared to graphite (the material commonly used in many present day tokamaks). The research has identified new mechanisms by which exposure to the harsh, high heat and particle flux environment of a burning plasma tokamak can actually modify the metal properties to allow it to retain more of the fuel. These new experiments, and related modeling, could be critical to the successful use of refractory metals in ITER and beyond, where fuel retention must be about a factor of 100 lower than is seen in present fusion devices.

The Cooperative Agreement with the Department of Energy, Office of Fusion Energy Sciences, which funds the C-Mod project, was renewed effective November 1, 2003 for a five-year period. A formal proposal for the next five-year grant period was submitted to the Department of Energy in March, and it has been very favorably peer-reviewed.
Background

The Physics Research Division, headed by Professor Miklos Porkolab, seeks to improve our theoretical and experimental understanding of plasma physics and fusion science. This Division develops basic plasma physics experiments, new confinement concepts, novel plasma diagnostics, and is the home of a strong basic and applied plasma theory and computations program. Members of the Physics Research Division include theoretical and experimental plasma physicists, faculty members, graduate and undergraduate students and visiting collaborators, all working together to better understand plasmas and to extend their uses.

Recent Research Activities

Fusion Theory and Computations

The theory effort, led by Dr. Peter Catto and funded by the DOE Office of Fusion Energy Sciences (OFES), focuses on basic and applied fusion plasma theory research. It supports Alcator C-Mod and other tokamak experiments worldwide, the Levitated Dipole Experiment and the Versatile Toroidal Facility. In support of these efforts, PSFC theorists are developing improved analytical and numerical models to better describe plasma phenomena, both in the laboratory and in nature.

In addition to basic plasma theory, the PSFC pursues research on radio frequency heating and current drive, core and edge transport and turbulence, and magnetohydrodynamic and kinetic stability. MIT theorists also investigate concepts to improve tokamak performance. One promising approach to advanced tokamak operation uses radio frequency waves to control pressure and current profiles in
order to control instabilities and achieve steady state operation in high-pressure plasmas.

During the past year major advances were made in the area of gyrokinetic simulations of trapped electron mode (TEM) turbulence. During studies of the impact of collisions on the zonal-flow-induced upshift of the TEM threshold it was discovered that the zonal-flow-dominated states arise from nonlinear secondary instability. This mode is thought to be one of the main candidates to explain electron heat and particle transport in tokamaks. Regarding new code development, finite gyroradius effects and energy scattering was implemented in the collision operator of the GS2 gyrokinetic code (only pitch angle scattering had been previously included). The finite gyroradius terms strongly stabilize short wavelength TEM’s, while energy scattering greatly reduces resolution requirements.

Tokamak turbulence levels are regulated by plasma flow shear referred to as zonal flow. Analytical evaluation of the residual zonal flow level was found to be in good agreement with the GS2 code predictions for the zonal flow residual (i) at arbitrary perpendicular wavelengths, confirming that the level is larger for electron temperature gradient drive than for ion temperature gradient drive; (ii) for non-circular flux surfaces, demonstrating that the residual increases more strongly with ellipticity than triangularity; and (iii) with arbitrary collisionality, confirming an improved estimate of the poloidal flow damping rate.

Members of the Theory Group participated in two SciDACs, “Center for Extended MHD Modeling” and “Center for Simulation of Wave Interactions with MHD,” with the purpose of implementing an advanced fluid description of magnetized plasmas in large-scale nonlinear simulations. During FY07-08, previous collisionless two-fluid systems were generalized to a fusion-relevant low collisionality regime, and a finite-Larmor-radius drift-kinetic equation compatible with these fluid moment equations and suitable for their closure was derived. Also, as part of an ongoing collaboration with members of the National Institute for Fusion Science in Japan, basic properties of the equilibrium equations for axisymmetric plasmas with flows were obtained within the reduced-MHD framework that applies to plasmas in a strong background magnetic field with weak curvature.
Existing nonlinear gyrokinetic and extended MHD codes are unable to predict the evolution of tokamak plasma on transport time scales that require a simultaneous knowledge of the global axisymmetric radial electric field and its associated flow. To predict long-time-scale plasma evolution along with the superimposed zonal flow established on shorter time scales and at shorter radial scale lengths, hybrid fluid - kinetic descriptions are required. The PSFC Theory Group, in collaboration with Los Alamos theorists, developed such descriptions for arbitrary collisionality by closing moment equations with solutions to kinetic equations. Descriptions have been developed with (i) a Maxwellian lowest order distribution function and a drift kinetic equation closure, and (ii) an arbitrary lowest order distribution with a full gyrokinetic Fokker-Planck closure. In addition, a gyrokinetic technique has been developed and applied to analyze pedestal and internal transport barrier (ITB) regions in a tokamak. In contrast to typical gyrokinetic treatments, the new approach allows strong radial plasma gradients to be treated conveniently, while retaining zonal flow and neoclassical (including orbit squeezing) behavior and the effects of turbulence.

The Theory Group also has a strong participation in the multi-institutional SciDAC “Center for Simulation of Wave Plasma Interactions,” where Dr. Paul Bonoli serves as the Principal Investigator of this entire SciDAC Project. During this year they successfully implemented a full-wave electromagnetic field solver for waves in the ion cyclotron and lower hybrid (LH) range of frequencies on the new 256 core parallel computing cluster at the PSFC. This has allowed simulations of LH waves to be performed at unprecedented spectral resolution (see above), thus satisfying an important

The 256 core parallel computing cluster.

LH wave simulation with full wave code TORIC, showing partial wave penetration and absorption.

Paul Bonoli is the Principal Investigator of the SciDac “Center for Simulation of Wave Plasma Interactions.”
theory (JOULE) milestone of the US Department of Energy. They also worked extensively on simulating the radial and velocity space structure of non-thermal fast electrons produced in LH current drive experiments on Alcator C-Mod. The simulated profiles of current density have been found to be in quantitative agreement with measurements from a Motional Stark Effect (MSE) diagnostic on the experiment, but the predicted profiles of hard x-ray emission have been found to be narrower than the measured profiles. Physics explanations for the broader measured emission include fast electron diffusion or broader deposition than what is predicted from ray tracing, perhaps due to diffraction effects. These effects are under investigation. PSFC theorists are also participating in the Fusion Simulation Project “Simulation of Wave Interactions with MHD (SWIM),” where they have completed work on coupling a full-wave field solver to a general framework known as the integrated plasma simulator.

An analytical description correctly including relativistic effects on the propagation and damping of electron Bernstein waves was formulated for the first time by collaborative work between PSFC theorists and their counterparts in Cadarache, France. They have recently shown that the physics of electron Bernstein wave propagation and damping in spherical tori is similar to that of ordinary electromagnetic wave propagation and damping in ITER plasmas. Thus, the results for electron Bernstein waves (EBW) may be useful in understanding electron cyclotron current drive in ITER. In addition, a model for mode conversion to EBWs in the presence of sharp gradients in the edge region of the plasma was developed for the first time.

The MHD interchange mode is thought to set the pressure limit in dipole confinement devices like LDX. A Z-pinch provides a large aspect ratio approximation to a dipole and in this limit finite beta nonlinear modeling indicates the development of a stiff pressure gradient limit accompanied by convective cells that reduce particle, but not necessarily energy, confinement. Recent theoretical work indicates that toroidal flow has only a weak effect on the MHD stability limit. A quasi-linear MHD theory developed showed that the density as well as the pressure may be expected to attain a stiff profile. Finally, PSFC theorists have completed a study of equilibrium beta limits in dipole configurations with toroidal rotation and pressure anisotropy. The existence of an equilibrium limit was proven with the use of numerical and analytical tools. They are continuing their analytic study of magnetic confinement devices in the presence of flow and resistive walls, with the purpose of formulating the problem in a form attractive for code development.

**LEVITATED DIPOLE EXPERIMENT (LDX)**

Physicists at the PSFC are exploring novel magnetic confinement configurations that are fundamentally different from the tokamak. These may lead to alternate reactor concepts, and in addition may provide insights into space and astrophysical plasma phenomenon. One such approach, which uses a levitated current-carrying superconducting ring, is being pursued as a collaboration with Columbia University. Such a current ring generates a dipole type magnetic field geometry, which in
Dipole confinement is observed in nature to be robust (e.g., in the magnetosphere around the planet Jupiter). This Levitated Dipole Experiment (LDX) will improve our understanding of dipole confinement in a laboratory setting.

LDX is a joint collaborative project with Columbia University at MIT. The principal investigators of this project are Dr. Jay Kesner (MIT) and Professor Michael Mauel (Columbia University).

During the initial experimental campaign, which began in 2004, the dipole coil was mechanically supported within the LDX vacuum chamber. These experiments provided a database for supported operation to be compared with future levitated experiments and have provided an opportunity to test the coil operation, the diagnostic set and the control system. During the supported experiments plasma was primarily lost to the supports.

The experiments with the floating coil fully levitated began in 2007. The loss channel to the supports was eliminated by the levitation...
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 under the leadership of Dr. Jan Egedal, appointed Assistant Professor of Physics in 2005. The new magnetic geometry of VTF is providing insight into what controls the onset of the explosive magnetic reconnection event observed in nature. In January 2007 a Physical Review Letter was published detailing the first observation of a spontaneous reconnection event in a toroidal geometry (figure, left). The focus of the experiment is now to explore the physics of the three-dimensional mechanism that initiates these events.

Magnetic Reconnection Experiments on the Versatile Toroidal Facility (VTF)

Novel Diagnostics for Fusion Research

The PSFC is developing two novel diagnostics for fusion research:
a. Phase Contrast Imaging on DIII-D and C-Mod

It is now widely believed that microturbulence in magnetically confined fusion plasmas results in excessive loss of particles and heat. To better understand such turbulence, PSFC researchers have developed a new diagnostic using CO₂ lasers and a special imaging technique widely used in microscopy—Phase Contrast Imaging (PCI). This diagnostic, which provides detailed measurements of the density fluctuations with extraordinary sensitivity and fine spatial and temporal resolution, is being used to study turbulence and RF waves on the DIII-D tokamak in San Diego, and on the Alcator C-Mod tokamak at the PSFC. Recent upgrades will allow tests of some of the latest theoretical predictions regarding the stabilization of microturbulence, leading to improved confinement and RF wave propagation.

The Phase Contrast Imaging (PCI) diagnostic is able to detect short wavelength (cm to mm), 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. These experiments are providing important new information on short wavelength instabilities related to transport, and various instabilities in the Alfvén wave regime (Reversed Shear Alfvén waves, or RSA). New turbulence data has been obtained on both machines and data analysis is in progress.

b. Collective Thomson Scattering

An international partnership consisting of the PSFC, Risø National Laboratory (Denmark), Institut für Plasmaphysik (Jülich, Germany), and Max-Planck-Institut für Plasmaphysik, (Garching, Germany) is pursuing the development of fast ion collective Thomson scattering (CTS) diagnostics. CTS experiments have been implemented at the TEXTOR (Jülich) and ASDEX-Upgrade (Garching) tokamaks using the available high power gyrotron infrastructure at these facilities with the addition of sensitive scattered signal receiver systems.

In FY2007 several CTS diagnostic campaigns were carried out at TEXTOR with neutral beam heating of the plasma. Measurements of fast ion dynamics were obtained during neutral beam turn on and off, and during sawtooth activity. Initial comparisons of these measurements with Fokker Plank modeling calculations appear to be in agreement. At ASDEX-Upgrade, initial CTS plasma measurements will begin in FY2008. The higher performance plasmas of ASDEX-Upgrade are expected to provide a more definitive test of CTS for fast ion studies. The development of fast ion diagnostics is considered essential for the advancement of fusion burning science to study energetic product alpha particles during fusion burn. This activity also involves the design and application of CTS to ITER fusion alpha product diagnostics.
INTERNATIONAL COLLABORATION ON JET

This program conducts collaborative experiments among PSFC (MIT), CRPP (Lausanne, Switzerland) and UK scientists at the Joint European Torus (JET) in England, the world’s largest tokamak and the major experimental tool of the European Fusion Development Agreement. In these experiments researchers study Alfvén wave propagation and instabilities driven by high-energy particles, such as radio frequency-driven energetic ions, injected neutral (ion) beams, and fusion-generated alpha particles.

Importantly, waves are launched by specially built antennas, the most recent of which has just been installed in JET. Studies of wave propagation and damping processes have been carried out in the past year. A large database has been obtained in recent experiments and it is presently being analyzed. Further antenna components will be installed next year to improve on the spectral resolution of launched waves. In addition, instabilities driven by high-energy particles, such as neutral beam ions, RF-driven energetic ions and ultimately, alpha particles, are studied. These studies lead to an improved understanding of plasma stability and transport that will be important in future burning plasma experiments where the fusion process generates a substantial alpha particle component.
The High-Energy-Density Physics (HEDP) Division has carried out pioneering and important studies of Inertial Confinement Fusion (ICF) physics. 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 (~1000 g/cc, or 50 times the density of gold), pressure (~1000 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).

The 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. This 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 experiments on the OMEGA laser facility support both programmatic objectives of LLE and MIT's own scientific goals. They have provided information about fusion yield, plasma temperature and density, implosion symmetry, implosion dynamics, burn symmetry and burn history, electromagnetic fields generated by imploding plasmas, fuel capsule compression, stopping power of hot plasmas, and laser-plasma interactions.

The Division also works closely with the Lawrence Livermore National Laboratory, where the huge National Ignition Facility (NIF)
under construction will host the next generation of ICF experiments expected to achieve ignition (self-sustaining burn and net energy gain) by imploding fuel capsules with a 2-MJ, 192-beam laser. Fusion ignition experiments will commence in 2010. With colleagues at Lawrence Livermore National Laboratory (LLNL) and LLE, Division scientists are active in defining the science that can be studied at NIF, which will offer unique opportunities to explore the properties of matter under extreme pressures (~1000 billion atmospheres) and densities (~1000 g/cc). Division scientists have developed two novel diagnostics for NIF that could be used in addition to the many nuclear diagnostics they have developed for OMEGA. The first diagnostic would use MIT-developed proton spectrometers to study the amount of material ablated during capsule compression, a quantity critical to implosion dynamics and ignition. The second diagnostic, discussed in greater detail in the next paragraph, would measure the energy spectra of fusion neutrons that are downscattered by the compressed capsules, in order to determine the amount and symmetry of capsule compression.

**Recent Research Activities**

A major initiative in the last years was the development of a diagnostic instrument for OMEGA and the NIF (called the Magnetic Recoil Spectrometer, or MRS) that will measure high-resolution spectra of 16 - 30 MeV DT neutrons. This is accomplished by measuring the spectra of protons or deuterons scattered by the neutrons in a special foil. The spectra of primary 14.1 MeV neutrons will give information about fusion yield and plasma temperature, while spectra of “down-scattered” neutrons that have lost energy through interactions with fuel ions will provide a measure of the level of compression of the fuel. A first-generation instrument has been built and installed on OMEGA, and is now providing preliminary data. It will enable workers to make the first measurements of fusion products under the extreme density conditions – 200 g/cc or greater – achieved in fusion implosions.

MIT scientists have done a wide range of important experiments at LLE this year utilizing charged fusion products to study the dynamics of imploded ICF fuel capsules, including cryogenic fuel capsules. MIT-developed diagnostics provided the key information allowing LLE scientists to verify the achievement of a major milestone in direct-drive ICF research: compressing fuel capsules to an areal density of 200 mg/cm². In addition, proton radiography utilizing MIT-developed methods with monoenergetic proton sources has been used for the first time to study magnetic reconnection in
laser-plasma interactions and to observe and quantify the spatial structures of compressed ICF capsules and the electric and magnetic fields that form around and within them during implosions.

The figure on page 23 shows the MIT-developed monoenergetic (15-MeV) proton radiography system and a sample image of an imploding “cone-in-shell” ICF fuel capsule, showing exciting features never before observed. The image, recorded at the OMEGA laser facility, shows proton fluence vs. position at the detector over a field of view that corresponds to 2.7 mm at the location of the object being imaged; darker areas have higher proton fluence. The light lower left quadrant of the image shows the shadow of the expanding gold cone, and the light circular region near the center shows the shadow of the spherical plastic capsule shell. The dark region at the center shows that protons were focused at the detector center, indicating the presence of a radially-directed electric field resulting from the radial pressure gradient in the compressing fuel. The filamentary structure outside the capsule shows the presence of a complex electromagnetic field.

Several papers about this work were published in Physical Review Letters, and one was also recently published in the journal Science.
This schematic drawing shows the system HEDP physicists are using to study tiny implosions of hydrogen fuel. On the left, protons streaming away from the far-left implosion travel through magnetic and electric fields generated by the other implosion. On the right is the resulting image of the fields, with the compressed hydrogen pellet in the center. These results were recently published in *Science*. 

15-MeV proton backlighter (imploded D²He-filled capsule)

Imploding cone-in-shell capsule

Protons focused by a radial electronic field

Filamentary magnetic or electric field

Protons per unit area on detector

2.7 mm

Shadow of the spherical plastic capsule shell

Shadow of the expanding AU cone

Imaging detector

15-MeV proton backlighter (imploded D²He-filled capsule)
BACKGROUND

The Waves and Beams Division, headed by PSFC Associate Director Dr. Richard Temkin, conducts research on novel sources of electromagnetic radiation, and on the generation and acceleration of charged particle beams. All research programs within the Division emphasize substantial graduate student involvement. High power microwaves are needed for scientific, industrial, military and medical applications, including: heating high temperature plasmas in nuclear fusion research; accelerating high power beams of electrons; processing materials in the semiconductor and ceramics industries; advanced radar systems; and electron and nuclear resonance spectroscopy. Intense beams of charged particles have scientific, industrial and medical applications, such as high energy and nuclear physics research, heavy ion fusion, cancer therapy and homeland security.

RECENT RESEARCH ACTIVITIES

GYROTRON RESEARCH

Gyrotrons are under development for electron cyclotron heating of present day and future plasma devices, including the ITER and DIII-D tokamaks; for high frequency radar; and, for spectroscopy. These applications require gyrotron tubes operating at frequencies in the range 90-500 GHz at power levels of up to several megawatts. In 2007, the Gyrotron Group conducted research on the efficiency of a 1.5 MW, 110 GHz gyrotron with an internal mode converter and a depressed collector. New theoretical research, in collaboration with the University of Maryland, identified that the gyrotron efficiency may be limited to 50% or less by an unwanted interaction that occurs after the gyrotron cavity. Experimental results on the limits of the voltage that can be reached...
with the depressed collector agree with this theory. The observed efficiency of gyrotrons built and tested at many laboratories around the world is now being investigated to see whether the same efficiency-reducing effect is present in those gyrotrons. An intensive program of theoretical research is being undertaken to design a new gyrotron that will have substantially higher efficiency. The goal is to achieve at least 60% overall efficiency in the near term. This research is funded by the US DOE Office of Fusion Energy Sciences and is a collaborative effort with General Atomics, CPI, Calabazas Creek Research, University Maryland and University Wisconsin.

**ITER Transmission Line Research**

The US is responsible for designing, building and fabricating the transmission line system for electron cyclotron heating and current drive on ITER. MIT is conducting research on the losses in transmission line components in collaboration with the US ITER Project Office, Oak Ridge National Lab; General Atomics; and the JAEA Laboratory in Japan. The transmission lines will be carrying 24 MW of power over more than 100 meters of path length, so that losses in the lines must be kept to the absolute minimum. The largest loss in the line occurs at the 90 degree miter bends, where 0.6% loss is expected theoretically. This is a small fractional loss, but represents 144 kW of power lost from a 24 MW microwave heating system! MIT is now attempting to measure this loss in individual miter bends and to derive theoretically the nature of conversion to high order waveguide modes.
that occurs at these bends. Recently PSFC researchers have measured, for the first time, the conversion from the fundamental HE11 waveguide mode to the next highest mode, which is the HE21 mode. Future research will concentrate on more exact measurements of this mode conversion and estimates of power lost in a complete 100 meter system. This research is funded by the US ITER Project Office at Oak Ridge National Laboratory.

**Accelerator Physics Research**

The research effort on high gradient accelerators is focused on high frequency linear accelerators for application to future multi-TeV electron colliders. In 2007, the Accelerator Research Group continued operation of the Haimson Research Corporation 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. We have recently installed our photonic bandgap accelerator cavity to measure the wakefields generated when the intense electron beam passes through the structure. Wakefield radiation into parasitic modes is not predicted by ordinary theoretical calculations, due to the lack of high order modes in a photonic structure. However, 3D simulations have been carried out by collaborators at the SLAC Laboratory at Stanford and at STAR, Inc. These simulations show that small amounts of wakefield power can be radiated by the electron beam passing through the cavity. These theoretical calculations have been compared with the data, but theory predicts larger wakefields than have been observed in the laboratory. Improvement of the theory is expected in the next few months and the new results will be compared with experiment. This research is funded by the US DOE Office of High Energy Physics.
Background

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 emphasis is on support of US and international (ITER) Fusion Programs, and further development along the lines of the Magnets Enabling Technology program.

The Fusion Technology and Engineering Division has broad experience in engineering research, development, and construction of magnet systems. It has applied its expertise in large and small project management, and its outstanding computational skills to a wide range of projects. These include development in structural and electromagnetic analysis, unique magnetic field mapping and field and force computations.

Areas of interest include: conventional and superconducting magnets for fusion and other advanced power systems; compact superconducting cyclotrons for medical and security applications; superconducting cable-in-conduit conductor analysis and development; high strength, long fatigue life materials development for electromechanical devices; advanced superconducting materials; stability, quench and protection systems for superconducting magnets; high gradient magnetic separation (HGMS) systems for water treatment and biological materials separation; high field magnet design and development; magnet safety analysis; pulsed energy storage in conventional, nitrogen-cooled and superconducting magnets; and magnet design for high-speed ground transportation, space, and naval applications.
The US ITER TF Conductor test sample was shipped to SULTAN Superconductor Test Facility.

The Pulse Test Facility (PTF) is a state-of-the-art facility designed to test large superconductors, and especially superconducting joints developed for ITER, under conditions that simulate ITER’s actual operating environment. The PTF can be used to test conductors carrying currents up to 50 kA in background magnetic fields perpendicular to the test sample’s principal axis at strengths up to 8.4 tesla (one tesla is equal to 10,000 gauss; Earth’s magnetic field is about 0.4 gauss) and in parallel magnetic fields up to 6.6 tesla. Among the most important features of PTF is the ability to change its background field rapidly from one level to another. This rapid “ramp rate” change is important in determining superconductor performance in a fusion reactor, since certain coils are “pulsed” on and off. The ITER device will operate with ramp rates up to 1.5 tesla/second for several seconds, or with field change rates of 0.3 tesla/second for extended periods. The PTF also has a 200-channel data acquisition system that allows ITER partners worldwide to review data as it is collected without actually being at the PTF site.

As part of the ITER Engineering Design Activities, a model coil was built in the late 1990’s to verify the magnet system design and performance, and to develop actual fabrication techniques to be used in ITER magnet...
construction. This Central Solenoid Model Coil (CSMC) was a joint US-Japan project. The coil contributed by the US program is about 3 meters tall and about 3 meters in outer diameter, and is wound from two grades of superconducting cable-in-conduit conductor. The coil is the world’s largest Nb₃Sn magnet and most powerful pulsed superconducting magnet, storing over 640 MJ of energy at 13 tesla.

Recent Research Activities

From 2007 until the present a major part of the Division’s activities have been focused on CS magnet and TF Conductor related research and development for the US contributions to ITER, under a contract from the US ITER Project Office at Oak Ridge National Laboratory. A conductor test sample 3 meters long was fabricated from 2 full-size-legs of US designed TF Cable-in-Conduit-Conductor. The sample was prepared with test instrumentation, a mid-joint between the two legs and terminations at the other end for current transfer. In January 2008, it was shipped to the SULTAN Superconductor Test facility in Villigen, Switzerland for performance testing. Other work was focused on optimizing the quench detection system and the structural design and analysis of the CS magnet system.

Last year the FT&E Division completed its collaboration with Brookhaven National Laboratory, Princeton University, ORNL, and other institutions in developing mercury jets as targets for a muon-collider or neutrino factory. The MERIT magnet and cryostat developed at the PSFC was installed in the TT2/TT2A tunnel at CERN, coupled with the ORNL-developed mercury jet target system and successfully tested during its first experimental scientific campaign.
In a different area of research, work on a privately funded project to develop a 250 MeV synchrocyclotron for proton beam radiotherapy was completed in CY 2007. The Clinatron-250 is a synchrocyclotron with the capability of accelerating protons to 250 MeV and delivering a continuous current of up to 100 nA to a cancer patient. The system is now in the manufacturing phase by Still River Systems, Inc. of Littleton, MA.

Very recent work has been further developing tools for beam dynamic simulations to be applied to the design of highly compact, high magnetic field cyclotrons for advanced applications in sensitive nuclear materials detection and other medical applications.

A proposal that PSFC engineers submitted to the MIT Energy Initiative Seed fund was accepted for funding in 2008. The topic, “Superconducting DC Power Transmission and Distribution,” is focused on developing a superconductor-based DC power distribution system for data server centers. Data server centers consume more than 1.5% of all electric power in the United States, and this use is growing fast every year. The goal of this initial study is to determine the configuration of a superconducting DC power distribution system, compare the efficiency with standard AC power distribution systems, and identify the key technologies requiring further development.

The Division has had some discouraging news. Congressional cuts of the ITER project funding in FY 08 necessitated the termination of our main work project, namely contributing to the US ITER magnet R&D program. As a result, many members of the Division are on a "work termination" notice. At the same time, the multimillion dollar Still River Project contracts have been completed in FY 07, and no further work is anticipated from this source. Division personnel are actively involved in writing proposals and searching for alternate projects.
The objectives of the Plasma Technology Division, led by Drs. Daniel Cohn and Paul Woskov, are to develop new spin-off applications from plasma science and related technologies in areas that include clean, high efficiency vehicles, homeland-security-relevant monitoring devices and nuclear waste treatment. The Division also seeks to develop new environmental sensors.

In previous years the Division has received six R&D 100 Awards for environmental and process monitoring devices, and a Discover Award for transportation technology. It has adapted and applied plasma technology expertise to a variety of environmental and energy applications, such as clean and efficient fuel technologies, and diagnostics for environmental monitoring, nuclear waste processing and national security work. The plasmas used for these applications are at or near atmospheric pressure, and range from approximately room temperature to 10,000°C. Plasmas in the high temperature end of this range have been used to investigate the treatment of solid wastes, monitor hazardous metals pollution, and chemically change hydrocarbon fuels to make them burn more cleanly. Room temperature ‘cold’ plasmas have been used to treat, selectively and efficiently, dilute concentrations of hazardous substances in air streams.

The R&D 100 Awards and Discover Award for Technological Innovation were given to the Division for work in the following areas:

- A microwave plasma continuous emissions monitor for hazardous metals monitors the gas emitted by plasma furnaces, incinerators and
other waste treatment technologies. It can be mounted in the furnace exhaust stack, where it continuously samples a portion of the off-gas and analyzes it by atomic emission spectroscopy. It is sensitive to approximately one part per billion for most metals considered toxic or carcinogenic. This monitor uses an innovative method for real-time calibration of unpredictable exhaust conditions. This ensures monitoring accuracy for compliance with pollution regulations.

- An active millimeter wave pyrometer measures the temperature and emissivity at many different places inside a furnace, which is crucial to safe and efficient operation. Conventional methods using visible light and infrared detection lose effectiveness because of smoke, and cannot measure the emissivity properties of the material.

- A refractory corrosion monitor evaluates in real-time the insulation thickness in high-temperature furnaces, such as those used in steel and glass industrial incinerators, and in plasma arc furnaces for waste processing. This device uses microwaves to monitor unobtrusively the thickness of the inner refractory layer without requiring access into the furnace. It eliminates the need to shut down a multimillion-dollar furnace for refractory inspections, and helps control operations to minimize refractory wear and improve safety.

- A MilliWave Viscometer measures high-temperature viscosity inside process reactors/melters of hot molten materials, such as those used in glass manufacture and in metals refining. It is the only viscosity measurement technology that uses millimeter-wave electromagnetic radiation to probe the movement of molten glass inside a melter is shown in the background.
liquids. The MilliWave Viscometer fills a need for a high temperature on-line viscosity sensor that can make possible real-time process control in the manufacture of glass, metals, and other melter-produced materials.

- A MilliWave Thermal Analyzer uses millimeter waves for integrated non-contact, real-time measurements of temperature, emissivity, and physical changes of materials under extreme temperatures or in corrosive environments. The MilliWave Thermal Analyzer is currently the only thermal characterization technology that can monitor the properties of materials in the extreme conditions inside a glass melter or high-temperature process reactor. This technology was designed to withstand previously inaccessible conditions created by high temperatures, corrosive fluids, melting materials, and radioactive or biologically contaminated environments.

The Division received the 1999 Discover Award for Technological Innovation in Transportation for its work on the on-board plasmatron reformer as a means to reduce vehicular-generated air pollution.

Another major research area in the past was plasma-enhanced conversion of hydrocarbon fuels into hydrogen, using the “plasmatron” reformer device. The plasmatron, a compact plasma arc device, was developed to enhance hydrogen-rich gas production from gasoline and other hydrocarbon fuels. This gas has the potential to be used in fuel cells to create electricity efficiently and with greatly reduced pollution. Fuel-cell generation of electric power using hydrogen gas produced in this manner could be applied to either stationary sources, such as an electric power plant, or to hybrid electric vehicles. In addition, hydrogen-rich gas could be used to reduce smog-producing pollutants in present internal combustion engine vehicles. The MIT intellectual property related to the plasmatron was licensed by Arvin Meritor, a major automotive parts supplier, to develop and commercialize this invention, and work at MIT was terminated.

From 1999 – 2007 the Division has worked with Pacific Northwest National Laboratories (PNNL) on a variety of millimeter wave diagnostics for improving the capabilities for vitrification of radioactive waste. This work was supported by the DOE Environmental Management and Science Program.

The Division continues to explore novel applications of plasmas and related technologies for near term environmental and energy needs. Ongoing topics range from the application of fusion energy spin-off technologies to new approaches for nuclear waste vitrification and deep drilling to access earth’s fossil and non-fossil energy resources. Other activities include the development of more efficient vehicle propulsion technologies.

Funding in these areas has not materialized yet. Nevertheless, we are continually searching for funding opportunities in the above areas as long as expertise remains at the PSFC.
The Educational Outreach 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.

Paul Rivenberg, Educational Outreach Administrator.

**BACKGROUND**

The Plasma Science and Fusion Center’s educational outreach program, under the coordination of Mr. Paul Rivenberg, 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.

**RECENT ACTIVITIES**

In 2007 the PSFC was part of the citywide Cambridge Science Festival, offering a tour to the general public, and a general seminar about some of the PSFC’s recent environmental research. Annual visitors include participants from the Keys to Empowering Youth and the National Youth Leadership Forum.

Outreach Days are held twice a year, encouraging high school and middle school students from around Massachusetts to visit the 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 Mr. Paul Thomas, has been bringing lively demonstrations on magnetism into local elementary and middle schools for 15 years. This year Mr. Magnet presented the program to nearly 30,000 students at over 55 schools and other events, reaching kindergartners through college.
As Mr. Magnet, Paul Thomas brings a truckload of magnetic demonstrations to area schools.

Graduate student Arturo Dominguez fields questions about fusion while students use a video game to learn how magnets confine plasma in the Alcator C-Mod tokamak.

freshmen. In addition to his program on magnetism, he is offering an interactive lecture about plasma to high schools. The “Traveling Plasma Lab” encourages students to learn more about plasma science while having fun investigating plasma properties using actual laboratory techniques and equipment. The Plasma Lab is offered two weeks during the academic year. In April 2007, at the request of the U. S. Department of Energy, Paul traveled with his truckload of equipment to Washington, DC, for the DOE-sponsored National Science Bowl. Paul has made this trek annually for the past eight years, to present his magnet and plasma demonstrations to high school teams from across the nation.

The PSFC organizes many educational events for the MIT Community, including the PSFC’s annual IAP Open House. The PSFC has continued its educational collaboration with the MIT Energy Club, bringing interactive plasma demonstrations to their autumn “Energy
Night” at the MIT Museum, and their spring MIT New England Energy Showcase at the Kendall Marriott. 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.

The PSFC continues to collaborate with other national laboratories on educational events. An annual Teacher’s Day (to educate middle school and high school teachers about plasmas) and Plasma Sciences Expo (to which teachers can bring their students) has become a tradition at each year’s APS-Division of Plasma Physics meeting.

The PSFC also continues to work with 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. The goals of this group include requesting support from Congress and funding agencies, strengthening appreciation of the plasma sciences by obtaining endorsements from industries involved in plasma applications, and educating the government, the schools and the general public about plasma, its presence in the universe and its many possibilities. Among other contributions, the PSFC has been instrumental in designing and editing their publications and their web site.
Recent Awards

During the past year, a number of PSFC staff have received awards.

Associate Division Head, Paul Woskov, has been honored with his sixth R&D 100 Award for his work on the MilliWave Thermal Analyzer. Principal Research Scientists Chikang Li (High-Energy-Density Physics) and John Rice (Alcator), and Associate Professor Dennis Whyte (Alcator) were awarded Fellowship by the American Physical Society (APS).

Mr. Andrew Pfeiffer, Engineering and Diagnostics Shop Supervisor, and Mr. Thomas Toolland, Project Technician Electro-mechanical, received 2007 MIT Infinite Mile Awards for their contributions to the Alcator Project. In 2008, PSFC System Programmer/Analyst Mr. Mark London, and Senior Fiscal Officer Ms. Katherine Ware, were honored with this award.

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

Professor Jeffrey Freidberg was awarded Fellowship by the American Association for the Advancement of Science (AAAS).