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PLASMA FUSION CENTER

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REPORT TO THE PRESIDENT

JULY, 1993

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**PLASMA FUSION CENTER
REPORT TO THE PRESIDENT 1992-1993**

The primary objective of the Plasma Fusion Center is to develop a basic understanding of the behavior of plasmas, and to exploit that knowledge by developing useful applications involving the plasma medium. The most important potential application is the development of fusion power; however, as can be appreciated by scanning the research highlights presented below, applications involving this ubiquitous state of matter are numerous and diverse. A recent example is our new focus on research and development of hot and cold plasma processing of waste materials.

The Plasma Fusion Center (PFC) is recognized as one of the leading university laboratories involved in the physics and engineering aspects of magnetic confinement fusion and plasma research. Its research programs continue to produce significant results on several fronts: (a) experimental confinement research on the Alcator C-MOD tokamak (investigations of the stability, heating, and transport properties of plasmas at high densities, temperatures and magnetic fields), and similar collaborative efforts on other tokamaks in the United States and worldwide, including the International Thermonuclear Experimental Reactor (ITER), (b) the basic physics of energetic plasmas (plasma theory, RF heating, nonneutral plasmas and coherent EM wave generation, development of high-temperature plasma diagnostics, and basic plasma experiments on the Versator II and Versatile Toroidal Facility tokamaks), and (c) a broad program of technology and engineering development (e.g., magnet systems, superconducting materials, fusion environmental and safety studies, advanced millimeter-wave sources, system studies of fusion reactors including operational and technological requirements, and- as mentioned- plasma waste treatment systems).

The Plasma Fusion Center technical programs are supported principally by the Department of Energy's Office of Fusion Energy. There are approximately 340 personnel associated with PFC research activities. These include: 23 faculty and senior

academic staff, 70 graduate students and 40 undergraduate students, with participating faculty and students from Electrical Engineering and Computer Science, Materials Science and Engineering, Mechanical Engineering, Nuclear Engineering, and Physics; 96 research scientists and engineers and 43 visiting scientists; 33 technical support personnel; and 35 administrative and support staff.

Our flagship experiment is Alcator C-MOD, the Plasma Fusion Center's new high-field tokamak which restarted operation in May 1993 after redesign and repair of a set of poloidal magnetic field coil leads. Alcator C-MOD was designed with the capability to address a range of issues, foremost to address ITER-relevant research topics, as well as some physics issues affecting the design of an advanced (long pulse) tokamak fusion reactor. A particularly difficult problem for ITER is the design of a divertor, or heat removal system, which will exhaust several hundred megawatts of thermal power, while limiting the maximum heat load on a material surface to about 10 MW/m². Alcator C-MOD has an advanced divertor design which is unique among presently operating tokamak experiments, and which incorporates many of the key elements in the present ITER design approach. Thus the physics of particle and power exhaust, which are crucial issues for the design of ITER and fusion reactors, have become high priority elements in the Alcator C-MOD research program.

Beyond Alcator C-MOD, PFC programs support ITER in critical technology areas, including superconducting magnets and development of millimeter wave RF sources suitable for heating and driving current near the electron gyrofrequency. In the magnetics area, D. Bruce Montgomery, Associate Director for the Fusion Engineering and Technology Division, leads the US ITER magnetics effort. The PFC is playing a key role in what will be an extensive, internationally coordinated program of superconducting magnet development leading to construction of magnets on a scale and performance level well beyond that of present-day superconducting magnet experience.

At the present time, the international effort on ITER has moved into the Engineering Design Activity (EDA), including the R&D necessary to support the main design approach. A challenging facet of the EDA is that the design work is carried out simultaneously at three co-centers located in Garching-bei-München (Germany), Naka (Japan), and San Diego (USA). The Garching site is responsible for in-vessel components (vacuum vessel, divertor, blanket and shield, RF heating), the Naka site is responsible for ex-vessel components (magnets, power systems, plant) and the San Diego site has responsibility for design integration. PFC personnel have taken on key responsibilities at these sites. In particular, the PFC Director, Ronald R. Parker, has been appointed to head the design team at Garching and Richard J. Thome, Head of the Fusion Technology and Engineering Division, has been appointed to head the magnetics design work at Naka. A young mechanical engineer, Zbigniew Piec, of our Center, has just been chosen by the ITER Joint Central Team to work in the Magnetics Division at the Naka center.

With this as background, we turn our attention to highlights of the past year's research. The remainder of the report is organized to correspond to the six PFC Divisions: Toroidal Confinement, Fusion Technology and Engineering, Physics Research, Plasma Technology (including plasma waste processing), and Coherent Electromagnetic Wave Generation and Relativistic Electronics.

TOROIDAL CONFINEMENT DIVISION

The toroidal confinement division, led by Professor Ian Hutchinson, carries out experimental research on the high-field tokamak Alcator C-MOD. The first full-scale tokamak plasmas on Alcator C-MOD were obtained in May 1993. This constitutes a major achievement after some years of construction and implementation of a redesigned set of coil leads. A major reassessment of the mission of the device was undertaken last summer when it became widely recognized that the international tokamak fusion

experiment, ITER, faces problems with its heat exhaust into the divertor requiring new physics solutions. Alcator C-MOD is predicted to have edge and divertor heat flux and temperatures similar to those of ITER in full operation. In view of these geometric and parametric similarities, a unique opportunity emerged to contribute to what may be ITER's biggest physics problem. Therefore, the divertor aspects of our program have been given our highest priority, although not to the exclusion of other important aspects such as transport studies, RF heating and MHD and control. The state of the art plasma diagnostic complement and ample port access combine with the unique characteristics associated with the high particle-, power-, and current- densities of this relatively small size device to position Alcator C-MOD as a premier research facility in the world tokamak program.

The activities within this Division are organized into four Sections: Operations (Steve Fairfax), Plasmas (Steve Wolfe), Experiments (Earl Marmor), and RF Heating (Miklos Porkolab). Highlights of the recent technical progress made by each of these groups are presented below.

Operations Section

This group is responsible for engineering design and fabrication of the tokamak facility as well as its operation, maintenance, and upgrade. The group includes over 50 engineers, supervisors, and technicians, notably David Gwinn (Project Engineer), Frank Silva (Tokamak Operations), Edward Thibeault (Engineering Services), Joseph Daigle (Power Systems), James Rosati (Facilities Supervisor), and William Burke (Electronic Design). The experiment resumed operation in April following a 12-month shutdown. The hiatus was due to a structural failure of a magnet terminal. Post-mortem analysis revealed that 8 magnets with similar terminal designs were likely to fail. The new design utilizes very high strength electroformed copper to bond the magnet terminals. While electroforming has been used for decades to produce RF cavities, this is the first known example of electroforming highly stressed structural elements. Development of

this technology required an extensive materials testing program coupled with significant process control improvements.

Most of the engineering systems were substantially upgraded during this repair period. The 700 MVA power conversion system was thoroughly tested. Each of the 30 converters was operated at both low and high power into suitable dummy loads. The cryogenic cooling system, used to chill and maintain the 150-ton experiment at liquid nitrogen temperature, was completely redesigned and rebuilt. The vacuum system, vessel heating system, and alternator control systems were overhauled and upgraded. The engineering control system reliability was substantially improved and all system software revised and tested. The performance of the engineering systems in service has been very good. Only 2 weeks of the integrated systems testing were required before plasmas were produced. The experiment is presently operating 4 days per week with 1 day reserved for maintenance access. At present, typical pulses require 90 MJ and peak powers of 150 MVA. The addition of the flywheel, scheduled for early 1994, will increase the available pulse energy to over 500 MJ. The normal problems of learning to operate a large, complex facility have been greatly simplified by the distributed control system, which minimizes unforeseen system interactions. There have been no problems with the magnets and no significant failures in any system.

Plasma Section

The Plasma Section is involved in advancing the understanding of the tokamak configuration in the areas of transport (sub-group headed by Martin Greenwald) and MHD physics (Robert Granetz), as well as for developing and implementing optimized control procedures for tokamak operation. Alcator C-MOD resumed operation in April 1993 and obtained its first tokamak plasmas in May. Plasma currents above 0.3 MA with densities above $1 \times 10^{20} \text{ m}^{-3}$ have been produced; the facility is operating routinely with a toroidal field of 5 Tesla. Initial operation has primarily employed limiter plasmas, but some diverted discharges have been produced. Plasma breakdown is

obtained with a one-turn voltage of approximately five volts, well within the design capability of 20V. The demonstration of reliable breakdown and current rise at low loop voltage in a tokamak with a thick conducting wall and super-structure, like Alcator C-MOD, is important to the design of future devices such as ITER. Work is continuing to characterize and optimize the plasma startup. The hybrid digital-analog control system developed in collaboration with the CRPP of Ecole Polytechnique Federale de Lausanne (Suisse), is being used for feedback control of vacuum fields prior to breakdown and plasma position control after discharge initiation. The multiple-input-multiple-output capabilities of the control system are being employed, and much of the current operation is being devoted to development of control strategies for plasma position and shaping. The magnetics diagnostics and soft x-ray tomography system are being extensively used to evaluate tokamak operation and progress in the plasma control activity.

Experiments Section

This group focuses on studies of edge plasma physics (Bruce Lipschultz), advanced plasma diagnostics (James Irby) and other experimental techniques for understanding and improving plasma performance. Following the coil accident in April, 1992, efforts were divided among all subgroups aiding the operations group effort to effect the repairs, finishing the initial diagnostic set, and planning new diagnostics and experimental strategies. With the advent of tokamak plasma operation in May, 1993, we have been able to commission and bring into full operation many of our diagnostic systems. These include the 10 channel 2 color interferometer (density profiles), soft x-ray/UV arrays (tomography), visible continuum (Z_{eff}) visible/UV spectroscopy (impurity levels, plasma imaging), Electron Cyclotron Emission (electron temperature profiles), high resolution x-ray spectroscopy (ion temperature profiles, atomic processes), the bolometer array (radiated power profiles), neutral pressure gauges (edge pressure), and Langmuir probe arrays (edge plasma parameters). Additional experiments which will come on line shortly include the sophisticated two dimensional multi-pulse

Thomson scattering system (density and temperature), EUV spectroscopy, hydrogen and lithium pellet injectors (fueling, current density profile), reflectometry (density fluctuations), laser ablation impurity injection, laser scattering (fluctuations, ion tail distributions), fast neutral particle energy analyzers, neutron detectors and charged fusion product diagnostics.

Collaborations with groups outside of MIT continue to play an important role in our diagnostic development efforts. These include collaborations with: University of Maryland on UV/visible spectroscopy (H. Griem); Johns Hopkins University on EUV spectroscopy (M. Finkenthal); ENEA, Frascati, Italy, on X-ray spectroscopy (F. Bombarda began a 9 month visit at MIT in June); and Oak Ridge National Laboratory, on polarimetry and coherent scattering (C.H. Ma and R. Richards).

RF Heating Section

This group has responsibility for the implementation and analysis of plasma heating using radio frequency (RF) power. Key physicists are Yuichi Takase, Stephen Golovato, and Paul Bonoli. RF heating requires high wave power to be generated by transmitters at suitable frequencies, transmitted to the tokamak, launched into the plasma by appropriately designed antennas and absorbed by it. Successful RF heating should bring the C-MOD plasma to temperatures of 4-8 keV, well in excess of those obtainable by Ohmic heating alone. During the past year significant effort has been spent on fabricating and testing several antennas and transmission line components, and on upgrading one of our four transmitters.

The present RF transmitters operate at a frequency of 80 MHz (corresponding to the gyroresonance of ^3He at 8.1 Tesla or H at 5.3 Tesla), and will consist initially of two 2.0 MW RF sources (and later a maximum of four such sources). Two of these transmitters are being upgraded to long pulse operation (initially 1 s pulse length and eventually up to 7 s), and installed. The upgrade of the first transmitter and high power tests have been completed. A maximum power of 2.1 MW has been delivered into a

dummy load for 1 s, exceeding specifications. The second transmitter will be upgraded by the end of CY 1993. The first antenna (single strap, movable) for coupling studies has been fabricated, tested and installed in the tokamak. The high voltage power tests in the test stand have been satisfactory (40 kV has been achieved). Two additional antennas, each consisting of two current straps, capable of more flexible phasing and higher power handling, have also been fabricated and the first one is being assembled in the test stand. Both of these antennas will be installed in C-MOD by the end of this year. Meanwhile, initial experiments on C-MOD with the single strap antenna are imminent. Initial scoping studies of advanced tokamak operations with non-inductive RF current drive and profile control have indicated exciting future prospects on C-MOD.

FUSION TECHNOLOGY AND ENGINEERING DIVISION

The Fusion Technology and Engineering Division reports to D. B. Montgomery, Associate Director for Technology and Engineering. R.J. Thorne is the Division Head and J.V. Minervini is Acting Division Head during Dr. Thorne's secondment to the ITER Co-Center in Naka, Japan. The Division provides engineering analysis for advanced electromagnetic systems and carries out research, development and design for a wide range of fusion technology and magnet system applications. During this year a new Materials Science and Technology Group has been formed within the Division under the direction of Prof. Ronald Ballinger of the Departments of Nuclear Engineering and Materials Science and Engineering. In 1992 -1993 funding for Division projects was split between fusion (70%) and other programs (30%). The principal task among other programs (22%) was design of the GEM (Gammas, Electrons, Muons) detector magnet and cold mass for the Superconducting Super Collider.

The principal fusion activity during this period has been the ITER Engineering Design Activities (54%). Dr. R. J. Thorne has been seconded to the ITER Naka Co-Center as Head of the Superconducting Magnets and Structures Division where he is responsible for magnet system design and integration, Division staffing and coordination

with the Home Teams and the other Co-Centers at Garching, Germany and San Diego, CA. D.B. Montgomery serves as the US Home Team Leader for Ex-Vessel Systems which includes Home Team design of the Superconducting Magnets and Structures, Plasma Field Control, and Nuclear Technology activities. J.V. Minervini, together with M. M. Steeves, have major responsibility for in-house research and development of niobium-tin conductor and conduit for the ITER magnets. This group has also coordinated the national conductor R&D efforts for ITER including insulation development, structural materials development and superconductor performance measurements. These are all multidisciplinary undertakings which include participation by several national laboratories including Lawrence Livermore, Brookhaven, and Oak Ridge National Laboratories, the National Institute of Standards and Technology (NIST), the University of Wisconsin and the MIT Department of Material Science and Engineering (Prof. Ballinger).

Through a 5-year Cooperative Agreement with the DOE Office of Fusion Energy, the Division has principal responsibility for the US contribution to magnet engineering for ITER. The scope of this responsibility includes placing subcontracts with US industry for superconductor, model coil conceptual and final design, coil manufacturing technology, conductor development and production. As part of this effort, Dr. Montgomery has been responsible for the initiation of a commercial manufacturing feasibility study for both the model coils and full-scale coils for ITER. These full-scale coils will be the largest magnetic structures ever to be manufactured and it is essential to the future successful development of fusion that these magnets can be fabricated and operated reliably.

During this time the Division has also played a significant role in the TPX Advanced Steady-State Tokamak Project at Princeton Plasma Physics Laboratory. TPX is a proposed very long pulse tokamak which would incorporate superconducting magnet coils wound of the cable-in-conduit conductor developed by the Division and

which will, if constructed, provide a test bed for many ITER concepts. J.H. Schultz, head of the Advanced Projects Group, has had principal responsibility for the PF and TF coils, as Deputy WBS manager for this area. His work has included conductor and magnet design, code development, preparation of the magnetics R&D plan, and more.

The principal nonfusion activity of the Division in 1992-1993 has been design of the GEM detector magnet and structure for the Superconducting Super Collider. This activity is headed by P.G. Marston, leader of the Advanced Magnet Applications Group, with B.A. Smith as Project Leader. This magnet system is a 31 m long by 18 m ID solenoid which has required extensive test of a new superconductor design and critical evaluation of the balance of the cold mass and support systems. During last year, there has been considerable investigation of the superconductor cable manufacturing capabilities of several nations, with a particular emphasis on the Russian Federation. This time period also saw the successful test of the superconducting interconnect bus developed for the SSC dipole and quadrupole magnets. A test of five interconnected magnets was begun in August 1992 which validated the PFC bus design.

From July 1, 1992 through September 30, 1992 the Division completed work on two major MAGLEV system design studies, one with Magneplane International and the other with the Bechtel Company, in conjunction with Prof. R. Thornton of the Department of Electrical Engineering and Computer Science. The results of these, and two other design studies commissioned by FRA, are the basis of future US work on MAGLEV. In 1992 we had projected further growth in work on magnetically levitated high-speed ground transportation. This funding did not materialize because of the Congressional delay in allocating funds to the Department of Transportation Federal Railway Administration, leaving MAGLEV funding at about 5.5% of the Division total. However, the FRA has begun to issue Requests for Proposals in a number of MAGLEV areas in which the Division hopes to compete successfully. A proposal has been submitted by Prof. Thornton to analyze the effect of magnetic fields on rebar in the

MAGLEV guide ways. It is expected that an RFP will be issued for a follow-on to the work completed by the Division on the application of cable-in-conduit conductor to MAGLEV vehicles. J.R. Hale heads the Division's MAGLEV activities.

PHYSICS RESEARCH DIVISION

Fusion Theory and Computations

The Theory and Computations Group has made several succinct contributions to the world fusion plasma physics program. The plasma RF-theory group (under Professor A. Bers) made significant fundamental as well as applied contributions. In a Physical Review Letter the spatio-temporal nonlinear dynamics of three wave interaction showed nonlinear saturation of an unstable wave by chaotic coupling to two damped waves. On the applied side, they have made progress in a theoretical understanding of the recent observations on the JET tokamak in Europe where a synergism between Lower Hybrid- and Ion Cyclotron Wave heating resulted in an apparent ≥ 3 fold enhancement of RF-induced current drive by a fast tail of the electron velocity distribution. The quest for a steady state tokamak reactor with noninductive current drive and profile control at maximally MHD stable plasma pressure has progressed theoretically (Dr. J. Ramos) by delineating more stringent requirements than predicted last year. Recent modeling by Dr. P. Bonoli and Professor M. Porkolab has shown that a Lower Hybrid Wave Heating and Current Drive system can be installed on our Alcator C-MOD (which is capable of pulses lasting 7-10 magnetic skin diffusion times) and thus this theory could be tested at MIT well before its perceived test in the Princeton Tokamak Physics Experiment (TPX) slated to start operation in 2000.

Besides looking to achieve steady state tokamak operation via RF-current drive, tokamak fusion devices have to cope with large fusion power loads in the so-called divertor chamber (attached specifically for power and particle handling). In support of Alcator C-MOD and ITER the Department of Energy has provided additional funding to establish a Divertor Theory Center within the PFC but structured with a strong emphasis

on collaboration with other US theory groups at universities and national laboratories. The focus is on developing the collisional, anomalous (i.e. fluctuation driven), and radiative, transport in the plasma edge in order to reduce the heat load to the divertor plates. Theoretical and computational simulation work has begun (D. Sigmar et al). One original idea (by J. Kesner and S. Luckhardt) is to turbulently broaden the plasma edge layer thickness (and thus the specific heat load) by introducing an electron gun generated edge current. Our continued leadership in alpha particle physics of plasma with fusion burn was evidenced by new analytical and simulation work on Alfvén-wave turbulence excited by alpha particles (F. Gang): The anomalous alpha loss is convective in the core and diffusive in the outer regions of the tokamak. Such losses are shown to reduce the coupling efficiency of the alpha fusion power to the bulk plasma needed to maintain the plasma energy balance (Ph.D. thesis, 1993, R. Gormley, under D. Sigmar).

Theory of Thermonuclear Plasmas

Professor Bruno Coppi and his group has made important contributions to the theory of fusion plasmas, and in the improved design and upgrading of IGNITOR, a compact ignition design concept based on the high magnetic field tokamak configuration pioneered at MIT in 1970. His group proposed an interpretation of the experimentally observed radio-emission at the ion cyclotron harmonics during the tritium phase of the JET experiments (Physics Letters A, 1993). The theory shows that alpha particles with large drift orbits can make Alfvén waves unstable near the plasma periphery. This could become a diagnostic of alpha particle transport in burning plasma experiments. In another area of research, this group has examined novel ways of enhancing the reactivity of D-³He fusion reactions (a so-called "advanced fuel" reactor concept) by using radio-frequency heating of a small fraction of ³He "minority" ions at the ion cyclotron frequency (ICRF). This would allow a study of such reactions in near term experiments, as well as the proposed IGNITOR concept which has recently been upgraded with the

addition of 20 MW of ICRF power. The confinement and thermalization of 14.7 MeV protons and 3.6 MeV alpha particles could be studied in such experiments.

RF Interactions and Modelling Group

A state of the art code has been developed by Dr. Paul Bonoli, to compute self-consistent MHD equilibria in the presence of non-inductively driven currents. The model includes driven currents by neutral beams, lower hybrid waves, fast magnetosonic waves and the bootstrap current effect. This model has been used to study advanced physics scenarios (in collaboration with Professor Porkolab) for the Tokamak Physics Experiment (TPX). Some of the scenarios studied include driving reverse edge currents with lower hybrid waves (i.e., the Ramos-Zakharov proposal to improve MHD stability at high beta); the study of inverted q-profiles with off-axis current drive, which has been found in recent experiments (JET and DIII-D) to result in improved confinement; and to develop a base operating scenario for TPX in which 2 MA of current can be driven by a combination of RF and neutral beam powers. These results were favorably received by an international panel at the recent Conceptual Design Review of TPX at Princeton. Using this code, we have also studied fast wave current drive and heating scenarios in ITER. More recently this model has been used to explore advanced physics operating regimes in the Alcator C-MOD device. In these studies it has been shown that a combination of lower hybrid current drive, ICRF heating, and pellet injection can be used to achieve advanced tokamak physics scenarios with up to 90% bootstrap current fraction.

Collaborations on TFTR and PBX-M in Advanced Tokamak Physics

A critical area for the improvement of tokamak performance involves current profile control. Current profile modification provides a means to improve plasma stability and confinement properties. Drs. J. Kesner and S. Luckhardt collaborated on current profile modification experiments, and modelling and data analysis on the TFTR

and PBX-M tokamak facilities at the Princeton Plasma Physics Laboratory. In the TFTR experiments low-current, high poloidal beta tokamak plasmas were studied. Current profile modification was obtained through inductive current ramp techniques and through the generation of bootstrap and beam-driven plasma current. The current profile modification experiments were carried out under reactor grade plasma conditions (ion temperature >20 keV) in TFTR. Improved MHD stability and confinement were demonstrated, and connection with the generation of negative edge currents was delineated. In the PBX-M experiment lower hybrid current drive is used to provide a more detailed control of the current profiles. This experiment has produced important results in sawtooth stabilization and in understanding supra-thermal electron diffusion (outstanding work by MIT post doctoral fellow S. Jones).

Advanced Tokamak Physics Studies on the Versator II Tokamak

An "advanced tokamak" related area of research at MIT includes the concluding work of three Ph.D. students on the Versator II tokamak. After 15 years, operation of this device has been terminated by the US Department of Energy, and two students (Drs. J. Colborn, EECS, under Prof. R. Parker, and J. Squire, Physics, under Prof. M. Porkolab) have successfully defended their theses in the area of radio-frequency (RF) current drive studies. The last student on this project, Mr. J. Villasenor (Physics, under Prof. Porkolab) will defend his thesis later this summer. Of particular note is the work of Dr. J. Squire, who has unexpectedly discovered a mode of advanced tokamak operation with 70% of the plasma current being carried by the "bootstrap" effect in the presence of lower hybrid heating. Detailed X-ray spectra measurements verified that lower hybrid waves heated a small population of electrons to 10 keV, which is then responsible for the bootstrap current generation at high values of the poloidal beta. For this work he received a Department of Energy Magnetic Fusion Fellowship, tenable at the DIII-D tokamak at General Atomics.

Phase Contrast Imaging Diagnostic on DIII-D

A novel diagnostic to measure long wavelength plasma density fluctuations has been installed and operated on the DIII-D tokamak at General Atomics, in San Diego, by Mr. S. Coda, a graduate student in the MIT Physics Department under the direction of Professor M. Porkolab. This diagnostic is an example of successful technique transfer between different fields of physics, as it applies the well-known Zernike phase contrast method of optical microscopy to the macroscopic realm of thermonuclear plasmas. A 7.6 cm wide CO₂ laser beam, with wavelength 10.6 μ m (infrared), is launched through the outer edge of the DIII-D torus. A 16 point image of the edge region is formed on a detector array, which generates signals proportional to the fluctuating plasma density. Cross-correlation techniques are used to determine wavelengths and correlation lengths. The development of this unique diagnostic was motivated by its potential for superior performance over existing diagnostic systems in terms of sensitivity, wavelength range, and bandwidth. Experimental studies have been performed in a wide variety of plasma conditions, with particular emphasis on the changes in the spatial distribution of plasma turbulence which occur at the onset of the high confinement regime known as H-mode.

VTF Divertor Simulation Experiment

A new plasma confinement concept, called the HELIMAK, is being developed at the PFC by Dr. Stanley Luckhardt and his collaborators. The experimental work is being carried out on the PFC's Versatile Toroidal Facility (VTF) with the aim of developing the HELIMAK concept as a simulator of the edge and divertor plasma of ITER. An accurate simulation of the ITER divertor region requires rather stringent conditions on plasma density and temperature ($n_e \sim 10^{19} - 10^{20} \text{ m}^{-3}$, $T_e \sim 100\text{-}200 \text{ eV}$), on the heat flux parallel to the magnetic field ($P/A \sim 1000 \text{ MW/m}^2$), on the magnetic connection length ($l_{||} > 15 \text{ m}$) and on continuous operation. Inherent in the HELIMAK concept is the capability of efficient non-inductive current drive in the form of electron gun injected beams, toroidal magnet field curvature, and a long parallel connection

length. The near term laboratory experiments on VTF have focused on raising the electron gun heating power so as to exceed the plasma electron temperature range of 10-30 eV, which is necessary to form plasmas with atomic radiative processes dominating thermal transport. At higher temperatures (50-100 eV) thermal transport by conduction and convection becomes dominant as is the case for the plasma entering the ITER divertor. Thus, exceeding this temperature regime will be necessary to prove the validity of the HELIMAK concept as a potential ITER divertor simulator.

X-Ray and Nuclear Experiments Group

A nuclear engineering graduate student Chi-kang Li, under the direction of Dr. Richard Petrasso, delineated, for the first time, the conceptual and physical properties of moderately coupled plasmas (PRL 70, p. 3059 and p. 3063, 17 May 1993; see also the front-page Tech Talk article, Equations Describe Core of Sun -- and More, May 26, 1993). Of the 99% plasma mass in the visible universe, almost all is a moderately coupled plasma. This follows from the fact that most stars in the universe are sun-like, and the sun itself is a moderately coupled plasma from the core to the photosphere (and this includes over 99.9% of its mass). Until the completion of this work, plasmas have usually been categorized as either weakly or strongly coupled. Examples abound in both these categories. For example, the magnetosphere, the solar corona, magnetically confined plasmas, and the interstellar medium are all weakly coupled. Strongly coupled plasmas include white dwarfs, the crust of neutron stars, and the interior of Jupiter. Moderately coupled plasmas comprise not only the interior of Sun-like stars but, in the laboratory setting, short-pulse laser plasmas, inertially confined plasmas, dense plasma pinches and x-ray laser plasmas. We are now able to investigate issues such as the radius at which convective energy transport occurs in Sun-like stars.

Research in Chaos

An understanding of many coupled nonlinear oscillators is important for models of pattern formation and turbulence in fluids such as plasmas. Experiments and theory by Dr. Paul Linsay and students in this area are under way. Once sufficient numbers of oscillators are coupled, there results an exponentially growing number of final states whose basins of attraction become fractal. A model has been developed in the past year that can explain much of the observed dynamics. We have begun to study the question of coupling several small magnetrons by building a nonlinear electronic model of a magnetron and studying its behavior under a variety of conditions. This nonlinear system is quite complex, exhibiting periodic, quasiperiodic and chaotic dynamics depending on the initial conditions and parameters of the system.

Ionospheric Plasma Research

Under the sponsorship of NSF and NPRSC, the PFC Ionospheric Plasma Research Group (Dr. Min-Chang Lee and students) has conducted ionospheric plasma heating experiments at Arecibo, using both vertically and obliquely injected HF waves to investigate the spectral characteristics of the HF excited Langmuir wave turbulence. In the vertical heating experiments, a broad cascading spectrum of Langmuir waves was constantly detected by the ground-based UHF radar. In the case of oblique plasma heating, a broad spectrum of decay modes often overrode the cascading spectrum of the HF excited Langmuir waves. Theoretical studies predict that Langmuir waves originally produced by the parametric decay instabilities (PDI) have a narrow cascading spectrum. Nevertheless, the filamentation instability of Langmuir waves and their subsequent nonlinear scattering by short-scale low frequency density fluctuations can result in a rather broad cascading spectrum. During the oblique heating of ionospheric plasmas at Arecibo, we found that the parametric excitation of upper hybrid waves and lower hybrid waves can compete with the Langmuir PDI process, leading to an intense broad spectrum of decay modes and a rather weak cascading spectrum of Langmuir waves.

Laboratory experiments to simulate the ionospheric plasma heating phenomena can be performed in the Versatile Toroidal Facility at MIT. The goal is to cross-check the experimental results obtained at Arecibo, and to corroborate the proposed theories. These laboratory experiments, jointly sponsored by AFOSR and NASA, are intended to develop radar cloaking schemes. We have evidence to show that the HF heating of ionospheric plasmas at Arecibo can generate field-aligned ionospheric ducts. These ducts (i.e., artificial waveguides) can guide favorably VLF (whistler) waves from the lower ionosphere into the radiation belts, thereby causing particle precipitation in the lower atmosphere. Largely enhanced radar backscatter echoes were clearly received in our Arecibo experiments. These intriguing phenomena will be further investigated in our future experiments at Arecibo (Puerto Rico), Tromso (Norway), and Millstone Hill (Massachusetts).

PLASMA TECHNOLOGY AND SYSTEMS DIVISION

The Plasma Technology and Systems Division headed by Daniel R. Cohn investigates plasma processing for environmental and industrial applications; develops new diagnostic technology for fusion and low temperature plasmas and investigates advanced materials processing approaches. Current research areas include low temperature plasma treatment of gaseous waste streams using compact electron-beam generated plasmas (Leslie Bromberg, Daniel R. Cohn, and Richard M. Patrick); DC graphite electrode arc plasma treatment of solid waste (Daniel R. Cohn, Charles H. Titus, Paul P. Woskov); process diagnostic development (Paul P. Woskov, Daniel R. Cohn); millimeter wave and infrared diagnostic development (Paul P. Woskov); advanced materials processing (Leslie Bromberg); and fusion safety and environmental studies (Mujid S. Kazimi). Some highlights are:

Low Temperature Treatment of Gaseous Waste Streams

Low temperature plasmas produced by compact electron beam technology (electron beam energy around 100 keV) have been used to selectively destroy dilute concentrations of carbon tetrachloride in air streams. Measurements were made on a range of carbon tetrachloride concentrations between 20 ppm and 700 ppm. The experiments indicate large reductions in energy required for decomposition relative to non-selective thermal processing (10 to 100 times lower energy requirements). High levels of destruction (99.8%) have been obtained. The experimental results are consistent with a decomposition process initiated by electron attachment. Selective decomposition has also been measured in air streams with chloroform and trichloroethylene. The work is supported by the U. S. Department of Energy for use in remediation of CCl₄ contaminated soil. We are working with the Pacific Northwest Laboratories (PNL) on the VOC Arid Site Integrated Demonstration project.

DC Graphite Electrode Arc Plasma Treatment of Solid Waste

In collaboration with Electro-Pyrolysis, Inc. (EPI) and PNL, the Plasma Fusion Center is investigating the use of graphite electrode DC arc plasma technology for ultimate use in vitrification of contaminated soil. A 30-kilowatt graphite arc plasma furnace developed by EPI was used to study vitrification of soil-metal mixtures. Vitrification of incinerator ash was also studied. The experiments produced vitrified waste products that passed standard leach tests. A pilot-scale furnace, Mark 2, is under construction. This furnace will have the capability to be operated at power levels approaching one megawatt and also have capability for continuous feed. The furnace design was developed by EPI. The Mark 2 furnace will serve as a facility for a wide range of investigations relevant to solid waste processing. Startup operation is planned by the end of FY93. The work is supported by the U. S. Department of Energy.

Processing Diagnostics

As part of the graphite electrode DC arc plasma furnace program, we are developing a range of new process diagnostics. A millimeter wave radiometer for measuring furnace and melt temperatures has been constructed. Laboratory experiments indicate that this device could provide significant advantages of sensitivity and robustness relative to conventional measurement techniques. The millimeter wave radiometer will be deployed on the Mark 2 furnace by the end of FY93. In addition a special microwave plasma spectrometer for in situ continuous monitoring of metals has been developed, and promising results have been obtained in the laboratory. There has been strong interest in these diagnostics for a range of applications by the U. S. Department of Energy's environmental restoration and waste management technology development community.

Fusion Plasma Diagnostics Development

We are continuing to work on the development of Thomson scattering for measurement of energetic alpha-particle properties. The required mode of Thomson scattering is obtained by using millimeter wave radiation from high power gyrotrons. The diagnostic is being implemented on the TFTR tokamak at Princeton and the JET tokamak in England, and Plasma Fusion Center personnel will continue to be the leading collaborators on this project.

WAVES AND BEAMS DIVISION

The Waves and Beams Division, headed by Richard Temkin, conducts research on novel sources of electromagnetic radiation and on the generation and acceleration of particle beams. Research on novel radiation sources has concentrated on the use of electron beams to generate microwave and millimeter wave radiation, e.g., the free electron laser (FEL) and the cyclotron autoresonance maser (CARM). These devices are promising for plasma heating, industrial heating (for example, ceramics sintering) and

high frequency radar. Theoretical research indicates the possibility of extending the range of wavelengths to the infrared, optical and x-ray regions. Research is also conducted on the generation and acceleration of electron beams. A novel, induction linear accelerator is operated at high repetition rates and its beam quality is under investigation. Research is underway on the use of high frequency microwaves to accelerate electron beams with very high gradients, up to 200 MeV/m. The demonstration of such high gradients is critical to the planning of future electron accelerators such as the Next Linear Collider (NLC). A strong effort in theoretical studies is conducted on the basic equilibrium and stability properties of non-neutral plasmas and intense charge particle beams.

Gyrotron Research

The gyrotron research group is led by Ken Kreischer. The gyrotron is currently under development for electron cyclotron resonance heating of the ITER plasma and high frequency radar. These applications require tubes operating at frequencies in the range 100-300 GHz at steady-state power levels of 1 MW or more. Research has concentrated on investigating the physics issues which affect the efficiency of operation of high power, high frequency gyrotrons. We have measured the velocity spread, $\Delta v/v$, for both the parallel and perpendicular components of a high power gyrotron electron beam. The apparatus consists of beam slits and a drift tube analyzer/repeller. The measured values of velocity spread far exceed the predicted values obtained from electrostatic field codes. At high electron beam currents, the spread in electron velocities leads to mirroring and trapping of electrons and to a significant reduction in the electron beam helicity (the ratio of transverse to parallel beam velocity). This results in reduced gyrotron efficiency. The large velocity spread may also indicate the growth of instabilities on the electron beam (dynamic effects). We have begun research on a high power, high frequency gyrotron suitable for application to ITER. This gyrotron will have a novel mode converter internal to the tube to transform the high order mode of the

gyrotron cavity into a free space, Gaussian-like beam. In a related program, M. I. T. will supervise the national industrial research and development activities for gyrotrons. Industrial groups will manufacture gyrotrons which operate continuously at power levels exceeding one megawatt.

Relativistic Beam Physics Research

The Relativistic Beam Physics Group, led by Bruce Danly, investigates the generation of high voltage electron beams and their application to high power microwave generation. Research programs include investigations of the cyclotron autoresonance maser (CARM), the free electron laser (FEL), the relativistic traveling wave tube, the relativistic klystron and the induction linear accelerator (ILAC). A CARM amplifier experiment at 17 GHz has been built using the induction linac electron beam from the SNOMAD II induction linear accelerator. The electron beam was operated at high repetition rate at 350 kV and 300A in 20 ns pulses. The amplifier was designed to operate in the TE_{11} mode at 17 GHz at the CARM resonance condition. The best results were obtained in gyrotron modes and not in CARM modes. This is most likely the result of a reduced electron beam quality. The gyrotron modes interact with the beam at cyclotron resonance, as do the CARM modes, but the gyrotron modes are close to cutoff in the waveguide and are less sensitive to spread in the electron beam axial momentum. Power levels of up to 5 MW were obtained in the TE_{31} mode at 17 GHz. A relativistic traveling wave tube was designed to operate at a frequency near 10 GHz in microsecond pulse lengths with an output power of up to 20 MW. This device is expected to have a bandwidth of over 10%. A relativistic klystron has been designed by Haimson Research of Palo Alto, CA to operate using the M. I. T. high voltage electron gun and modulator at 500 kV, 125A in 1 μ s pulses. An output power exceeding 20 MW at 17 GHz is expected.

High Gradient Accelerator Research

The High Gradient Accelerator Experiments Group led by Dr. Shien Chi Chen is preparing a novel, 17 GHz microwave driven, photocathode electron injector. This device, sometimes called an RF gun, can generate a 2 ps beam of 2-3 MeV, 50-500 A electrons at high repetition rate. A 5 MW, 17 GHz source will drive the electron gun. This electron beam could be directly applied to microwave generation experiments or it could be used as an injector into a 17 GHz, high gradient accelerator. A laser driver for the RF gun has been designed and fabricated and delivered to M. I. T. by Spectra Physics. The laser produces a 0.2 MJ, 1 to 2 ps pulse in the UV, 200-280 nm, to drive the photocathode. The laser design consists of a mode-locked, CW Ti-sapphire laser and a pulsed Ti-sapphire laser amplifier. This laser eliminates the need for pulse chirping in a fiber and pulse stretching and compression by gratings. A laboratory space is being converted for use as a laser laboratory. The RF gun cavity and the transmission line from the 17 GHz source to the RF gun have been constructed and are under test. The 17 GHz source has demonstrated the 5 MW of power needed to drive the RF gun but the source phase stability must still be measured. The first tests of the RF gun are expected this year.

Theoretical Research

The Intense Beam Theoretical Research Group led by Professor Jonathan Wurtele has contributed very significantly to our understanding of coherent radiation generation and particle acceleration. Topics covered include coherent radiation sources (CARM, FEL, gyrotron, relativistic klystron, relativistic TWT), beam-beam interactions, cyclotron resonance accelerators, two-beam accelerators, photocathode design, and other topics. Multimode codes have successfully predicted new phenomena in both the cyclotron autoresonance maser and free electron laser amplifier. Separately, research on nonneutral plasmas has been reported in two Physical Review Letters and an invited paper in The Physics of Fluids, in close collaboration with an experimental group led by

Professor Joel Fajans at UC Berkeley. In standard, symmetric equilibria, the electron plasma is circular and axis-centered. Because the plasma is charged, the ensuing electric field interacts with the axial magnetic field to produce EXB drifts leading to biased patches on the conducting wall which generate a non-axisymmetric potential. The plasma equilibrium responds by becoming asymmetric. The demonstration of asymmetric, stable equilibria in pure electron plasmas is a surprising result which contradicts one of the most strongly held beliefs in the field.

RELATIVISTIC ELECTRONICS DIVISION

The main interest of this division, headed by Professor George Bekefi, is the generation of coherent electromagnetic radiation using intense relativistic electron beams as the lasing medium. In addition to studying experimentally and theoretically the basic physical characteristics of devices such as the free electron laser, the cyclotron maser and the relativistic klystron, we began implementing more novel concepts, e.g., the two-stream relativistic klystron, the double stream cyclotron maser and the now operating and highly successful "Reversed Field FEL" (patents applied for). In addition to the above we have two ongoing collaborative efforts. One is with the Brookhaven National Laboratory where we are presently installing the MIT Microwiggler (period 8.8 mm) in the beam line of a high brightness 50 MeV RF LINAC. The purpose is to generate coherent radiation at a wavelength of $\sim 5000 \text{ \AA}$. The other is a collaboration with CERN/CLIC in which our "Reversed Field FEL" will be used as a high power (60 MW) high frequency (33 GHz) driver for a novel high gradient accelerating (HGA) section built and designed at CERN and brought to MIT. The primary objective is to achieve accelerating gradients in excess of 100 MeV per meter length of system. A successful outcome of such experiments could lead to the realization of the next generation of linear colliders for particle physics.

AFFIRMATIVE ACTION

The Plasma Fusion Center is committed to increasing the number of women and minorities at those levels of the work force where there is significant underrepresentation. Our success in meeting this objective is dependent on the pool of applicants available at each level. For example, 80% of both the SRS administrative and support staff are women, while 16.2% of both support and service staff are African Americans. In these categories, we have found that our search procedures, which utilize both internal and external resources, have turned up an excellent supply of highly qualified candidates. On the other hand, at the SRS technical level, our success is more modest: approximately 3.1 % of SRS technical staff are women, while 13.5% are other minorities, slightly more than half of whom are Asian Americans. These numbers reflect the applicant pool which, for the 6 month period October, 1992 through March, 1993 was .2% women and 11.7% identified as other minorities, primarily Asian American. We are attempting to enlarge the reservoir of qualified underrepresented applicants in the near term by more intensive dissemination of job postings to organizations specifically concerned with opportunities for women and other minorities. To serve in the long term, we are maintaining a substantial K-12 and undergraduate outreach effort which encourages women and other minorities to pursue careers as scientists and engineers.

APPOINTMENTS AND PROMOTIONS

During the past year, there have been several important appointments and promotions in Plasma Fusion Center program areas:

Appointments include: Deirdre Dow-Chase (MIT, Francis Bitter National Magnet Lab), appointed Assistant to Director for Administration in the Office of Resource Management; Jeffrey Colborn, (MIT, Department of Electrical Engineering and Computer Sciences) appointed SRS - Temporary in the Physics Research Division; Veronica DuLong (MIT, Property Office) appointed Assistant Fiscal Officer in the

Office of Resource Management; Ronald Englade (MIT, Research Lab of Electronics) appointed SRS Technical -Temporary in the Office of Resource Management; Chen-Yu Gung (MIT, PFC and Department of Nuclear Engineering) appointed Postdoctoral Research Staff in the Fusion Technology and Engineering Division; Sangkwon Jeong (MIT, Department of Mechanical Engineering) appointed Postdoctoral Research Staff in the Fusion Technology and Engineering Division; Michael Pelletier (MIT, Brain and Cognitive Sciences) appointed Assistant Fiscal Officer in the Office of Resource Management; Shahin Pourrahimi (MIT, Francis Bitter National Magnet Lab), appointed Mechanical Engineer in the Fusion Technology and Engineering Division; Alexander Rabinovich (Lab of Plasma Processes, Russia), appointed Research Engineer - Temporary in the Plasmas Technology and Systems Division; and Mary Young (MIT, Division of Toxicology) appointed Assistant Fiscal Officer in the Office of Resource Management.

During the past year, internal promotions in the Plasma Fusion Center have included: Christine Augello, promoted to Payroll and Travel Administrator in the Office of Resource Management; Rejean Boivin, promoted to Experimental Research Scientist in the Toroidal Confinement Division; Jacqueline Granville, promoted to Personnel Administrator in the Office of Resource Management; Thomas Hrycaj, promoted to Engineering Coordinator in the Fusion Technology and Engineering Division; John Machuzak, promoted to Experimental Research Scientist in the Plasma Technology and Systems Division; L. Thomas McCallum, promoted to Associate Fiscal Officer in the Office of Resource Management; Lissa Natkin, promoted to Fiscal Officer in the Office of Resource Management; Richard Patrick, promoted to Research Engineer in the Plasma Technology and Systems Division; Patricia Stewart, promoted to SRS-Administrative Assistant to the Director in the Office of the Director; Andrew Szczepanowski promoted to Engineer - Temporary in the Physics Research Division; Leonardo Toma, promoted to Engineer - Temporary in the Fusion Technology and

Engineering Division; Reich Watterson, promoted to Research Scientist in the Toroidal Confinement Division.

During the past year, Institute research promotions in the Plasma Fusion Center include: Dr. Daniel Cohn, promoted to PFC Acting Assistant Director; Dr. Dieter Sigmar, promoted to the PFC Acting Director; and Dr. Paul Woskov, promoted to Principal Research in the Plasma Technology and Systems Division.

During the past year, the Plasma Fusion Center has also hosted many Visiting Scientists, Engineers and Scholars in the various research programs. They are: Dr. Mohammed Afsar (Tufts University), millimeter wave research; Dr. William Aitkenhead (Magneplain International Inc.), ITER magnetics design and R&D Program; Dr. Stefano Alberti (Ecole Polytechnique Federale, France), high frequency gyrotrons, free electron lasers, and cyclotron autoresonance masers; Dr. Masanori Arata (Toshiba, Japan) stability and protection of high performance superconducting magnets; Dr. Daniel Birk (Science Research Laboratory), induction linear accelerator work; Dr. Francesca Bombarda (Frascati, Italy), high resolution x-ray spectroscopy; Ms. Cristina Borrás Senabre (CIEMAT, Spain), x-ray and charged particle diagnostics; Prof. Bastiaan Braams (Courant Institute), Braams code; Dr. Jeffrey Casey (AZTEC), laser scattering diagnostics; Dr. Franklin Chang-Diaz (NASA), plasma propulsion; Dr. Xing Chen (Science Research Laboratory), radiation-hardened detectors; Mr. John Citrolo (Princeton Plasma Physics Lab), mechanical design of PPX magnets; Dr. Dennis Clarke (Science Research Laboratory), induction linear accelerator work; Dr. Jeffrey Colborn (MIT, Department of Electrical Engineering and Computer Sciences), current drive near cyclotron frequency; Mr. Jean-Paul Dionne (Centre Specialise de Technologie Physics, Canada), Plasma Arc Technology and VTF projects; Mr. Paul Evans (Cornell University), refinement of simple mode for the SOL layer in the divertor chamber; Dr. Joel Fajans (University of California, Berkely) non neutral plasma physics; Prof. John Davies (Clark University), theory of free electron lasers; Dr. Hideshi Fukumoto (Hitachi

Ltd., Japan), computational analysis of magnet systems; Mr. Eric Giguet (Thomson Tubes Electroniques, France), free electron laser and cyclotron autoresonance maser; Mikhail Gershteyn (Research and Development Co. Success, Russia), Russian work on microwaves and fusion energy; and translator; Mr. Jerome Gonichon (University of Paris, France), RF gun experiments; Dr. Daniel Goodman (Science Research Laboratory), induction linear accelerator work; Dr. Keith Groves (Phillips Lab, Hanscom Air Force Base), non linear wave propagation and interaction with ionospheric plasma; Mr. Richard Hamilton (Electro-Pyrolis, Inc.), Plasma Vitrification Project; Dr. Gong-He Han, (Chinese Academy of Science, PRC), diagnostic measurements and plasma characterization; Prof. Akira Hasegawa (Osakawa Univeristy, Japan), nonlinear wave phenomena and dielectric fiber; Dr. Jung Hur (Integrated Applied Physics Inc.), pulsed power for microwave; Dr. Yuri Iglikhanov (IPP, Garching, Germany), divertor physics; Dr. Pallavi Jha (University of Lucknow, India), applications or design of FELs; Dr. George Johnston (MIT, PFC), modeling RF gun cavity for coupling; Dr. George Kirkman-Amemiya, (Integrated Applied Physics), high power modulators and high brightness electron beams; Dr. Robert Kirkwood (Hanscom Air Force Base), VTF plasma experiments; Mr. Daniel Kominsky (The Cambridge School), Alcator C-MOD electron cyclotron emission diagnostics; Dr. Barton Lane (Plasma Dynamics), Toroidal ECR Reactor project; Prof. Ming-chang Lee (Boston University), Ionospheric Plasma Research Group Leader and thesis supervisor; Mr. Ping Liu (Southwestern Institute for Physics, PRC), source design; Mr. Guishi Luan (Academia Sinica of China, PRC), gas divertor physics analysis; Dr. Juan Moreno (University of Maryland), Alcator C-MOD spectroscopy; Prof. William Marable (Hampton University) advanced lasers and free electron accelerations; Mr. Mark May (John Hopkins University) spectroscopy; Mr. Robert McKenney (Drexel University), metallographic examination of Incoloy 908; Dr. Takahide Mizuno (Hitachi Ltd., Japan), high power microwave and millimete wave sources; Mr. Scott Nicol (Worcester Polytechnical Institute), stress rupture testing for

magnet technology; Dr. Alexander Rabinovich (Lab of Plasma Process, Russia), plasma chemical processing; Mr. Robert Randall (Supercon Inc.) R&D for ITER involving extrusion work; Dr. Dennis Reilly (Avco Research Lab), plasma processing programs; Dr. Nicholas Reinhardt (Integrated Applied Physics, Inc.), high power modulators; Mr. Jean-Luc Rullier (CEA/CESTA, France), free electron laser and CARMs; Mr. Frank Sabelli (General Electric), AC power system; Mr. Jesper Sallander (Royal Institute of Technology, Sweden), scanning Thomson scattering experiments; Dr. Frederick Seguin (American Science and Engineering), γ -ray and X-ray research; Ms. Vera Talanker (Cobe Labs Inc.), numerical procedures for solving transport problems; Mr. Charles Titus (Electro-Pyrolisis, Inc.), Plasma Vitrification Project; Mr. Gil Travish (University of California, Berkely), FEL simulation; Dr. Alan Wan (Lawrence Livermore National Lab), data analysis of retarding grid energy analyzer; Dr. Reich Watterson (Science Research Laboratories), novel laser scattering diagnostics; Dr. Benjamin Welch (University of Maryland), spectroscopy; Mr. Fredrick Wising (Chalmers University, Sweden), tokamak fusion plasma; Dr. Kenneth Wittle (Electro-Pyrolisis, Inc.), Plasma Vitrification Project; Dr. David Whittum (University of California at Berkeley), advanced accelerators and novel radiation sources; Mr. Qun Yao (College of William and Mary), SUN workstation; Dr. Leonid Zakharov (Kurchatov Institute of Atomic Energy, USSR), MHD theory for tokamak applications; Dr. Glen Zeiders Jr. (The Sirius Group), gyrotrons and CARMs; and Ms. Ge Zhang (Clark University), theory of free electron lasers.

GRADUATE DEGREES

During the past year, the following students graduated with theses in plasma fusion and related areas: Mark Basten, M.S. in Physics; Robert Bellis, M.S. in Mechanical Engineering; Hei Wai Chan, Ph.D. in Electrical Engineering and Computer Science; Ronson Yiu-Yuen Chu, Ph.D. in Physics; Jeffrey Colborn, Ph.D. in Electrical Engineering and Computer Science; Manoel Conde, Ph.D. in Physics; Raghav Gorur,

M.S. in Nuclear Engineering; Terry Grimm, Ph.D. in Nuclear Engineering; Gaspar Gulotta, M.S. in Nuclear Engineering; Chen-Yu Gung, Ph.D. in Nuclear Engineering; Steven Lund, Ph.D. in Physics; David Rhee, Ph.D. in Nuclear Engineering; Jared Squire, Ph.D. in Physics; Christopher Teixeira, Ph.D. in Nuclear Engineering; Edward Thomas, M.S. in Physics; Kenneth Vilece, M.S. in Nuclear Engineering; Jesus Villasenor, Ph.D. in Physics; Ling Wang, Ph.D. in Nuclear Engineering; and James Wei, Ph.D. in Nuclear Engineering.

We take this opportunity to congratulate these candidates on their accomplishments at the Plasma Fusion Center and thank them for enriching the science enterprise of our Center in many important ways beyond their research topics, (e.g., through exemplary contributions to the PFC's outreach program). We wish them success in their future professional endeavors.

DIETER J. SIGMAR
ACTING DIRECTOR
MIT PLASMA FUSION CENTER

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