PFC/IR-95-1

DOE/ET-51013-315

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

PLASMA FUSION CENTER

1994 - 1995

REPORT TO THE PRESIDENT

JULY, 1995

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This work was supported by the U.S. Department of Energy Contract No. DE-AC02-78ET51013.

Reproduction, publication, use and disposal, in whole or part, by or for the United States government, is permitted.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

The primary objective of the Plasma Fusion Center (PFC) is to provide research and educational opportunities to develop a basic understanding of plasma behavior, and to exploit that knowledge by developing useful applications. The central focus of the activities at the PFC has been to develop a scientific and engineering base for the development of fusion power. Nevertheless, nonfusion applications involving plasmas at the PFC are numerous and diverse. A recent example is the significant growth of programs in hot and cold plasma processing of waste materials.

The Plasma Fusion Center is recognized as the leading university laboratory in developing the scientific and engineering aspects of magnetic confinement fusion and related plasma science and technology. 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 compact high magnetic field, diverted plasmas), (b) the basic physics of energetic plasmas (plasma theory, theoretical support of ITER, TPX and IGNITOR, new confinement concepts, nonneutral plasmas, coherent EM wave generation, development of high-temperature plasma diagnostics, basic laboratory and ionospheric plasma physics experiments, and novel diagnostic of inertial fusion experiments), (c) a broad program of fusion technology and engineering development that addresses problems in several areas (e.g., magnetic systems, superconducting materials, fusion environmental and safety studies, advanced millimeter-wave sources, system studies of fusion reactors, including operational and technological requirements), and (d) the growing activity of plasma waste treatment using plasmas.

Approximately 40 percent of the Center's activities are associated with the Alcator C-Mod tokamak experiment, 40 percent with the research on superconducting magnet system components for future fusion devices, and the remaining 20 percent with the many other R&D activities.

The Plasma Fusion Center R&D programs are supported principally by the Department of Energy's Office of Fusion Energy. There are approximately 305 personnel

associated with PFC research activities. These include: 23 faculty and senior academic staff, 61 graduate students and 20 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 40 visiting scientists; 33 technical support personnel; and 32 administrative and support staff.

The Plasma Fusion Center's high-field tokamak, Alcator C-Mod, started full operation in May 1993. It was designed with the capability to address a range of issues, foremost including ITER-relevant research topics, as well as 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. Alcator C-Mod has an advanced divertor design, unique among presently operating tokamak experiments, incorporating many of the key elements in the present ITER design approach. Thus, the critical issues of particle and power exhaust are a central program focus.

PFC programs also 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, the PFC leads the US ITER-Home Team magnetics effort in 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 experience.

Earlier this year Prof. Miklos Porkolab was chosen to replace Prof. Ron Parker as Director of the PFC. Dr. Bruce Montgomery will remain Associate Director for Engineering and Technology, while the Director for Research position remains to be filled. Mr. Willie Smith (previously of the Provost's Office) has been appointed as the new Administrative Officer.

ALCATOR DIVISION

The Alcator Division, led by Prof. Ian Hutchinson, carries out experimental research on the Alcator C-Mod tokamak. The experiment has been operational since 1993. A sustained campaign of experimentation was conducted during November 1994 through June 1995, during which a variety of important results were obtained. The capabilities of the tokamak were further enhanced and its operating space was broadened. Details are outlined in the succeeding sections.

Alcator C-Mod is now established as one of the "big five" divertor tokamaks in the world. Two of the others, JET and JT-60U are the large "flagships" of their national programs, whereas ASDEX-U and DIII-D are medium sized, lower field devices. Alcator C-Mod is the only high-field compact experiment of the group and therefore plays a unique role in providing critical tests of scaling and fusion theory at high power density. Alcator C-Mod is extremely well placed to contribute to solving problems of ITER and future fusion reactors. Its vertical plate divertor geometry has been adopted as ITER's reference design, and its shape is essentially the same as ITER's. It also is presently unique in having high-Z metallic plasma facing components. Such components are planned for ITER.

Alcator C-Mod is thus extremely favorably placed to contribute vital information to fusion research, and to do so in a highly cost effective way because of its compact, high field approach. Nevertheless, serious concern exists about the continued funding of the project because of the large cuts in the fusion program presently being proposed in Congress. We believe that even in a restructured fusion program, Alcator C-Mod has a uniquely important role to play. Alcator C-Mod, with its total staff in excess of 100 people, including 18 full-time research physicists, 2 faculty members, and 20 graduate students, makes a unique and essential contribution to the MIT educational program. Naturally, PFC staff are sparing no effort to point out the opportunities that Alcator C-Mod represents and to argue for its continuation and expansion.

OPERATIONS AND ENGINEERING SECTION

The operations and engineering section, led by Dr. James Irby, is comprised of more than 50 engineers, supervisors, and technicians. This group is responsible for operation and maintenance of the tokamak facility and also for most facility upgrades. During the past year we have been engaged primarily in making the changes needed to obtain higher performance operation. Improvements in cryogenics, power supplies, and alternator control electronics and diagnostics have been made. Near the end of the last run period C-Mod operated at toroidal field of 8 Tesla, more than twice the field of any other divertor tokamak. Plasma currents up to 1.2 MA have also been obtained. A total of 2,324 plasma pulses were achieved during the 94-95 campaign.

RF HEATING AND ADVANCED TOKAMAK SECTION

This section, led by Prof. Miklos Porkolab and Dr. Yuichi Takase, implements and analyzes plasma heating using radio frequency (RF) power, including investigation of advanced tokamak physics (APT) scenarios. In the past year, up to 3.5 MW of RF power was coupled into the plasma using two dipole antennas. Successful plasma heating was obtained from 2.6T to 8.0T using different heating schemes. Electron and ion temperatures, $T_{e0} = 5.8$ keV and $T_{i0} = 4.0$ keV were obtained at a density of $n_e = 10^{20} \text{ m}^{-3}$. Efficient heating of plasmas at densities up to $3 \times 10^{20} \text{ m}^{-3}$ has also been demonstrated because of the very high power densities in our compact tokamak, ten times higher than JET, for example. This substantial auxiliary heating enables us to perform detailed studies of core transport and divertor physics with independent power control. An enhanced confinement mode, PEP (Pellet Enhanced Performance) is obtained in combination with Li pellet injection and intense RF heating, and fusion neutron rates of up to $9 \times 10^{13} \text{ sec}^{-1}$ have been observed. Highly localized electron heating was observed at 6.5T using the mode converted ion Bernstein wave. This mode of operation will be utilized for future advanced tokamak experiments. Theoretical modelling of "advanced tokamak" modes of operation predict that with additional RF current drive power, C-Mod is particularly well-

suited to test the "reversed-shear" mode of high performance operation recently advocated for TPX, the "Tokamak Physics Experiment."

PLASMA SECTION

The Plasma Section, led by Dr. Stephen Wolfe, is involved in advancing the understanding of the tokamak configuration in the areas of transport (coordinated by Dr. Martin Greenwald) and MHD physics (Dr. Robert Granetz), as well as for developing and implementing optimized control procedures for tokamak operation.

A systematic technique for controlling the plasma shape using orthogonal controllers has been developed and successfully implemented. This technique has improved the robustness of our plasma control system, and facilitated development of new equilibria, including limited, as well as lower and upper single null divertor geometries; elongations have been varied from 0.9 to 1.85.

In a series of experiments with potential significance for future fusion facilities, remote operation of a tokamak was demonstrated for the first time. A team of M.I.T. scientists, in collaboration with a team from LLNL, operated Alcator C-Mod from a remote control room in Livermore, California, with control and shot data as well as interpersonal communications being transmitted over the Internet.

Studies of disruptions have continued, with special attention to halo currents, which flow partly in the plasma and partly through the conducting vessel. The ratio of halo current to plasma current has been shown to be proportional to $1/q$. Toroidal asymmetries and rotation of the halo currents have been measured, and a correlation between halo currents and the occurrence of integral values of an effective rotational transform, including the current path through the wall, has been observed.

Transport experiments have been carried out with ICRF heating up to 3.5 MW. The L-mode plasmas have confinement close to the empirical ITER-89P scaling. H-mode operation, with improved particle and energy confinement, has been achieved at fields up to 8 Tesla, with a range of plasma and surface power density spanning those characteristic of

ITER or a reactor. The threshold power density for transition to H-mode is found to scale with density and field, similar to observations on other experiments. However, in C-Mod the observed threshold values are up to a factor or two lower than those obtained elsewhere, while the surface power density in C-Mod exceeds that in other machines by a factor of ten.

Experiments have begun to test the principles of dimensionless scaling of tokamak transport by running discharges with identical geometry, collisionality, and gyro-size in C-Mod and DIII-D, a larger, lower-field tokamak at General Atomics. These experiments should help validate projections to future devices by extrapolations in gyro-size from current facilities.

EXPERIMENTS SECTION

This section, under the leadership of Dr. Earl Marmor, focuses on studies of edge physics (Dr. Bruce Lipschultz), advanced plasma diagnostics and other experimental techniques for understanding and improving plasma performance.

In the last 12 months excellent progress has been made at Alcator C-Mod both in terms of experimental capabilities and in divertor physics R&D for ITER. In particular, the present divertor diagnostic complement delivers more detailed information about divertor characteristics (radiation, density, temperature) than is available from any other tokamak. Tomographic inversion techniques have been applied to divertor bolometry and visible imaging to determine the strength and spatial distribution of total radiated power and of particular species in the divertor region. We routinely have complete between-shot Langmuir probe density and electron temperature profiles at the divertor plate and in the tokamak edge plasma SOL (scrape-off layer). Important studies of divertor detachment have shown that the detachment threshold can be modified through the controlled addition of impurity gases (methane and neon) as well as by changing the divertor geometry. The flat-plate divertor geometry has a significantly higher detachment threshold (factor of ~ 2) compared to the vertical plate or slot geometry. This result, which is consistent with the

finding that Alcator C-Mod typically has a lower detachment threshold (compared to the "Greenwald density" limit) than other tokamaks, all of which had operated with flat-plate divertors, has important implications for the design of the ITER divertor.

The diagnostics for Alcator C-Mod have reached a mature level of development, with accurate measurements of the majority of important plasma parameters available on a routine basis. In the area of advanced diagnostic development, we are concentrating on upgrading our divertor diagnostic capabilities, along with providing enhancements to interferometry and fluctuation measurements. Much of the diagnostic development proceeds through collaboration with outside groups, including Princeton Plasma Physics Lab (spectroscopy, divertor Thomson scattering, interferometry, reflectometry), Oak Ridge National Lab (CO₂ scattering, faraday polarimetry), Johns Hopkins University (spectroscopy, atomic physics), and the University of Maryland (spectroscopy).

PHYSICS RESEARCH DIVISION

This section discusses progress made on smaller scale physics-oriented experiments, novel diagnostic development, new initiatives and fusion theory research.

FUSION THEORY AND COMPUTATIONS

The PFC Edge Physics and Divertor group (Drs. Dieter Sigmar, Peter Catto and Serguei Kracheninnikov) has intensified its focus on the theoretical exploration of the edge ("divertor") plasma in a tokamak with high power fusion burn such as ITER. This was done through a combination of analytical and numerical modelling studies, the latter using the NERSC supercomputer as well as a local high end HP workstation provided by DOE. A systematic analytic study of various divertor models has been performed to determine the key dimensionless parameters and associated divertor scaling laws which will be used to interpret output from large 2D fluid codes. This information can be used to extrapolate results from present diverted machines, such as Alcator C-Mod, to the operating regimes of

larger tokamaks, such as ITER. Results from Alcator C-Mod are shown to be more ITER relevant than those from other current machines.

A particle-in-cell code being developed through a collaboration between the PFC and Keldysh Institute in Moscow is running and able to model the scrape-off layer of diverted tokamaks. Kinetic codes are capable of modelling behavior far from equilibrium where distribution functions are highly non-Maxwellian. Such non-equilibrium behavior occurs near material walls of such divertor target plates and regions of strong spatial variation of plasma parameters. This unique code is the only kinetic code able to model detachment of the edge plasma from the target. The PFC theory group has been recognized for its leadership and is charged by DOE to lead the national Divertor Task Force.

In the MHD area of theoretical studies (Prof. Jeffrey Freidberg and Dr. Jesus Ramos) the quest for a steady state, advanced tokamak operating regime has been advanced through collaboration with numerical specialists from the Keldysh Institute for Applied Mathematics in Moscow who provided several MHD stability codes with the capability of dealing with diverted tokamaks. Collaborations to apply the codes to Alcator, ITER, and TPX-like tokamaks, in search of stabilization of the external kink modes in plasmas with high self-generated ("bootstrap") current fractions are in place. Work is also being carried out to investigate effects of the plasma toroidal rotation on tokamak equilibrium and stability. A collaboration with the Plasma Research Institute in Ahmedabad, India has been initiated in this area.

Theoretical research into the cause of disruptions and its relationship to halo currents has been initiated by Prof. J. Freidberg and graduate students. Avoidance of disruptions would be of great potential benefit to ITER. Prof. Freidberg has also continued to expand his research activities in the area of superconducting magnet design. The problems of interest involve the development of an explanation for the phenomenon of "thermal hydraulic quench back" and basic theoretical studies of the important operating restrictions associated with "ramp rate limits" (with post-doc Ali Shajii and graduate students). A new research activity involving the vitrification of high level nuclear waste by

means of an electrodeless melter has also been undertaken. By using the principles of MHD in combination with well established ideas from magnetic fusion, it should be possible to design and construct a high efficiency, high reliability, induction melter even though the molten glass has an electrical conductivity comparable only to sea water. (with Prof. Kevin Wenzel and Dr. A. Shajii).

The RF Theory Group (Prof. Abraham Bers and Dr. Abhay K. Ram) has continued and extended its studies on their original work of high-efficiency mode conversion from fast Alfvén waves (FAW) to ion-Bernstein waves (IBW) for plasma heating and current drive. The (ideal) possibility of achieving 100% mode conversion, as reported last year, was shown to correspond to a critically coupled, internal (to the plasma) resonator containing the mode conversion layer. An extended analysis, including the coupling to an external antenna, has brought into evidence a global resonator system that encompasses the internal one with the mode conversion layer. This new model analysis has been used successfully to understand recent experiments on Tore-Supra (Cadarache, France), that show intense electron heating in the presence of high efficiency mode conversion from FAW to IBW. Our one-dimensional model results also compare favorably with (and explain!) the computational results obtained from the three-dimensional, full-wave, toroidal code ALCYON (France) applied to these experiments.

HIGH ENERGY PLASMA THEORY GROUP

Professor Bruno Coppi and his group (Drs. Linda Sugiyama, Stefano Migliuolo and students) have continued their studies of ignition in magnetically confined plasmas. The recent PCAST (President's Committee of Advisors on Science and Technology) report has agreed that the next major step in fusion research is the demonstration of ignition. In addition, it has become clear that the most suitable and cost effective way to pursue this goal is the line of machines that operate at high magnetic field employing cryogenically cooled normal conducting magnets, represented by the Alcator series of machines at MIT and the FT machines in Frascati, Italy. The technological feasibility of this kind of machine

has been demonstrated recently in Italy by the completion of full size prototypes of the key components of the IGNITOR device, which is being designed under the leadership of Prof. Coppi.

On the theoretical side, the pioneering work on internal collective modes that can destroy locally the magnetic field confinement configuration have been recognized by the international community. This is a particularly serious issue for the stated objectives of the ITER project. The theoretical transport model that Prof. Coppi proposed in the 1970's, involving the excitation of the so-called ITG modes (toroidal ion temperature gradient driven modes) and trapped electron modes, has found wide acceptance and has been incorporated recently in several transport codes that are used to interpret present experiments. Other theoretical ideas of importance to experimental studies include the so-called "isotopic effect" on plasma confinement (confinement is observed to improve with heavier isotopes of hydrogen). It has also been found to be present in the transport of angular momentum in rotating plasmas. Finally, in the past year significant progress was made in understanding transport in high field devices, such as C-Mod and FTU.

RF INTERACTIONS AND MODELLING GROUP

A state of the art simulation code has been developed by Dr. Paul Bonoli (in collaboration with Prof. Miklos Porkolab) to compute self-consistent MHD equilibria in the presence of non-inductively driven currents. This simulation model has been coupled to an MHD stability code at Princeton Plasma Physics Laboratory (collaboration with Dr. C. Kessel) and has been interfaced with an MHD stability code ported from the Keldysh Institute in Russia (collaboration with Dr. J. Ramos at MIT). These combined codes have been used to identify MHD stable, advanced physics operating modes in the proposed Tokamak Physics Experiment (TPX) and in the proposed ITER device. The emphasis in these studies has been on the use of off-axis lower hybrid (LH) current drive and on-axis fast wave current drive to create profiles of the safety factor which exhibit magnetic shear reversal. More recently, this comprehensive model has been used to demonstrate the

possibility of achieving MHD stable, advanced physics operating modes in the Alcator C-Mod device through a combination of ICRF heating and off-axis LH current drive (for shear reversal). Theoretical and computational studies have also been initiated to assess the feasibility of a novel scheme for off-axis current drive in a tokamak using mode converted ion Bernstein waves (IBW). Significant mode conversion of fast ICRF waves to IBW has been predicted for D-³He plasma parameters characteristic of the TPX and Alcator C-Mod devices. This work is being done in collaboration with Drs. L. Sugiyama and A. Ram at MIT.

PHASE CONTRAST IMAGING ON DIII-D

A CO₂ laser phase contrast imaging (PCI) diagnostic, installed in previous years on the DIII-D tokamak at General Atomics (San Diego, California), has been employed in the study of low-frequency density fluctuations in the edge plasma region (Prof. Porkolab and graduate student Stefano Coda). Thanks to its unexcelled sensitivity, fast time response, and access to the long-wavelength region of the spectrum, this diagnostic has permitted an investigation of turbulence at an unprecedented level of detail, generating results that are posing new challenges to theory. One MIT Physics Department graduate student (Mr. Stefano Coda) is in residence at General Atomics and is completing his thesis research on this project. The project will terminate sometime in FY96, and a continuation is planned on C-Mod.

Studies have concentrated on two specific physics areas. The first is the evolution of turbulence during the transition from the low (L) to the high (H) mode of confinement. The transition is found to be accompanied by a reduction in the average amplitude of the line-integrated fluctuations. In the frequency domain, two distinct spectral features were identified: a low-frequency (≤ 20 kHz) band, which is generally unaffected by the transition, and a broad high-frequency region, which is strongly suppressed in H-mode. In addition, it was determined that the L-mode fluctuations have a nonzero average group velocity in the inward direction. The second area of interest is a periodic H-mode

instability known as edge localized mode (ELM), which plays a critical role in the ongoing design of the demonstration reactor ITER. This phenomenon is accompanied by a burst of turbulence whose spatial and spectral structure can be studied by the PCI diagnostic. In particular, the so-called type--III ELM is seen to be characterized by fast coherent modes propagating in the outward direction.

THE VTF COMET EXPERIMENT: A NEW PROPOSAL

Dr. Jay Kesner and Prof. M. Porkolab have recently submitted a proposal to DOE to test an exciting and new tokamak confinement approach in the VTF facility: a comet-shaped cross-section that features an oblate plasma with negative triangularity. It has been suggested [R. Miller, et al, Comments Plasma Phys. Controlled Fusion, 12, 125 (1989).] that comet shaping would reduce, or reverse, the curvature driven precessional drift of ions and electrons, and is therefore expected to improve confinement with respect to these modes. This may be particularly important in high temperature reactor grade plasmas.

PFC researchers have shown that a comet-shaped tokamak is expected to have improved MHD properties in addition to improved confinement. Furthermore, the oblate shape tends to form an inner x-point, and a divertor design could incorporate a much larger divertor slot length than is possible in the ITER-type geometry. The comet optimizes at low aspect ratio. A reactor based on this concept has a relatively low plasma current and the center post can be shielded. Thus a comet-shaped tokamak may lead to a low aspect ratio reactor, with low plasma current, good confinement and improved reactor features. A three-year experimental program has been developed in detail at the \$1.5 - 2.0M per year level. A review of this proposal is in progress.

X-RAY AND GAMMA-RAY EXPERIMENTS GROUP

Having developed a new technology to measure the charged particle spectrum of energetic particles, the X-ray and Gamma-ray and Experiments Group (Dr. Richard Petrasso and coworkers) is poised to apply this technology to the laser fusion experiments

at the University of Rochester (the Omega Upgrade). The technology is based on charged-coupled devices (CCDs) that have about one quarter of a million individual picture elements. Each of the individual picture elements is used as a complete detector. In the past CCDs have been used to detect photons but, to the best of our knowledge, this is their first demonstration as charged particle detectors. This latter capability is extremely important for experiments that generate different kinds of massive particles (i.e., protons, deuterons,...), each with its own distinct energy spectrum. It is this novel capability that we will utilize in the laser fusion experiments at the University of Rochester. We also anticipate that a similar set of experiments will be performed at the Lawrence Livermore National Laboratory on the NOVA laser fusion facility. Finally we are also exploring the applicability of this technology to other venues, such as the space physics environment. In particular, it could be applied to measuring the spectrum and particle identity of energetic particles from solar flares. This work is being lead by graduate student Damien Hicks, Research Scientist Dr. Chikang Li, and Group Leader Dr. Richard Petrasso.

Finally, Visiting Scientist Dr. Fredrick Seguin is developing a new class of small, radiation resistant x-ray detectors based on photoconductors that could comprise the individual picture elements needed for future x-ray imaging arrays of reactor-based systems.

The group also expanded its work in theoretical physics. For example, two *Physical Review Letters* were recently published by C. Li and R. Petrasso wherein some of the basic properties of moderately coupled plasmas were delineated (plasmas that occur in the interior of stars and in inertially confined fusion). Such plasmas have relatively high electron densities ($n > 10^{23} \text{ cm}^{-3}$) and low electron temperatures ($T < 10^4 \text{ eV}$). Theoretical effort is now directed at enhancing our understanding of the properties of moderately coupled plasmas through improved calculations of characteristic relaxation times and transport coefficients (e.g. the thermal conductivity). This work was also recently featured in an article entitled "Simply Plasma" in *Science News* (1994). In two review articles in

Nature, Richard Petrasso summarized the progress and challenges that confront both laser and magnetic confinement fusion.

IONOSPHERIC PLASMA RESEARCH

The PFC Ionospheric Plasma Research Group (Visiting Scientist Prof. Min-Chang Lee and students) has been collaborating with the MIT's Haystack Observatory and Lincoln Laboratory at Millstone Hill and the Air Force Phillips Laboratory at Hanscom AFB to conduct radar experiments on lightning-induced plasma disturbances in the ionosphere. Among several mechanisms, the lightning produced whistler waves can parametrically excite a daughter whistler wave and an ion acoustic wave (investigated in laboratory experiments in the 1970's by Professor Porkolab and coworkers) that may give rise to false satellite signals. Further investigation of lightning-induced ionospheric plasma effects will be carried out with the upgraded NSF radio facilities at Arecibo, Puerto Rico in the winter. Laboratory experiments with the Versatile Toroidal Facility (VTF) have greatly contributed to the understanding of ionospheric plasma turbulence that occurs in the auroral region. Furthermore, the thesis research of Dan Moriarty, a Ph.D. student in Nuclear Engineering and Suzanne Murphy, an M.S. student in Electrical Engineering has showed that the VTF experiments can complement the active plasma experiments in space.

SMALL TOKAMAK AS SOURCE OF RADIATION FOR X-RAY LITHOGRAPHY AND MICROSCOPY

In the past year we revived operation of the moth-balled Versator II tokamak in RLE. [Prof. Miklos Porkolab, Visiting Scientists Drs. Jesus Villasenor of UCLA and Jared Squire of General Atomics in collaboration with Prof. Symon Suckewer and Dr. Charles Kinner of Princeton University.] In a new series of experiments we wish to test the feasibility of using tokamak plasmas as the source of nano-meter radiation for x-ray lithography. The PPPL scientific staff took responsibility for the preparation and installation of the radiation detection system. The detector uses a multilayer mirror as a

selective wavelength reflector (around 13 nm), and acts as a balometer for monitoring the total radiation.

In the series of experiments in December 94 and January-February 1995 we obtained information on total plasma radiation from Versator as a function of different impurity injection. These data were analyzed and results indicated, as expected, the strong impact of impurity concentration on total plasma radiation. However the most important data on radiation in the region near 13 nm were not obtained due to the low sensitivity of the detector. Presently we are bench-testing a much more sensitive detector which should allow us to measure time depended radiation in a narrow bandwidth near 13 nm. Our main goal is to obtain data for radiation near 13 nm as a function of impurity concentration and plasma parameters (primarily electron temperature and density). We will use these data for calculating radiation fluxes in a tokamak specially designed as a radiation source. We plan to prepare a proposal for submission to various government agencies.

TECHNOLOGY AND ENGINEERING DIVISION

The Technology and Engineering Division is headed by Dr. Joseph Minervini and comprises 35 engineers, scientists and administrative and support staff. It supports graduate and undergraduate students in the Nuclear Engineering, Mechanical Engineering, Electrical Engineering and Computer Science, and Materials Science and Engineering departments.

This year the majority of the Division's work continued to focus on magnetics R&D for the two main Department of Energy, Office of Fusion Energy supported next step tokamak projects, namely the International Thermonuclear Experimental Reactor (ITER), and the U.S. Tokamak Physics Experiment (TPX).

In-house research for both programs concentrates on superconductor development, subscale testing, and magnet design and analysis. Significant results have been obtained in understanding the stability limitations of fast ramping the superconducting coils as well as in a new area of developing fiber optic instrumentation for superconducting coil

diagnostics. Fabrication of a moderate sized, new test facility, called the Pulse Test Facility (PTF), was begun for pulse testing of large size superconductors and joints for both the ITER and TPX projects. Prof. Ronald Ballinger's Materials Science and Technology Group has begun a new ITER task for detailed mechanical characterization of the superalloy Incoloy 908 which was initially developed in his laboratory for superconducting magnet applications.

Extensive collaboration with U.S. industries continued under the ITER program for fabrication of the U.S. contribution to the model coil program, including sub-contracts with Lockheed Martin, INCO Alloys International, Teledyne Wah Chang, and Intermagnetics General Corp., among others.

Recent congressional actions on the fusion energy budget for next fiscal year indicate substantial reductions are likely. Although, at this time, the main ITER program funding appears secure, the Technology and Engineering Division has begun actively seeking new programs outside the Department of Energy supported fusion program. New initiatives have resulted in funding through INEL (Idaho National Engineering Laboratory) for a large scale, electromagnetic seismic simulator platform, and from Paramag for design of a superconducting magnetic separation magnet. The Basic Energy Sciences Department of South Korea has expressed interest in MIT assisting them in the development of a new superconducting tokamak called StarX. This is a good match to our relevant experience from the TPX and ITER programs. The Division also has active proposals in several other areas of magnet technology which are likely to result in near level personnel support into the next fiscal year.

PLASMA TECHNOLOGY AND SYSTEMS DIVISION

The Plasma Technology and Systems Division, headed by Dr. Daniel R. Cohn, investigates plasma processing for environmental and industrial applications; develops new diagnostic technology for environmental and fusion applications; and investigates advanced fusion reactor systems designs and magnet concepts. Current research areas include arc

plasma treatment of solid waste (Daniel R. Cohn, Paul P. Woskov, Charles H. Titus, and Jeffrey E. Surma); process diagnostic development (Paul P. Woskov and Daniel R. Cohn); cold plasma processing of gaseous waste (Daniel R. Cohn and Leslie Bromberg); plasma manufacturing of hydrogen (Daniel R. Cohn and Leslie Bromberg); millimeter wave and infrared diagnostic development (Paul P. Woskov); system studies (Leslie Bromberg); high temperature superconducting magnet development (Leslie Bromberg); and fusion safety and environmental studies (Mujid S. Kazimi). Some highlights of our research in the past year are listed below.

ARC PLASMA FURNACE TREATMENT OF SOLID WASTE

A pilot-scale arc plasma research furnace to study treatment of simulated solid waste has been operated with continuous feed. Power levels in the 250 kW range were used with a material feed rate of 200 pounds per hour. Soil characteristic of the Idaho National Engineering Laboratory (INEL) has been converted into a stable glass. The furnace has also been used for extensive testing of process diagnostics. Future objectives include studies of vitrification of a range of simulated wastes; development of predictive models and their applications to control systems (with Prof. Julian Szekey of the Materials Science and Engineering Department); and component testing.

PROCESS DIAGNOSTICS FOR WASTE TREATMENT

An active millimeter-wave pyrometer has been developed to measure furnace and material temperatures in a hostile environment. The device has been successfully tested in the Mark 2 furnace. A 1994 R&D 100 Award was received for this work. A microwave plasma analyzer for continuous monitoring of metals in smoke stack emissions has also been successfully tested on the Mark 2 furnace. A 1995 R&D 100 Award for this technology has been announced recently. In addition to application to waste treatment in plasma furnaces, the capability for continuous monitoring of metals emissions could be applied to incinerators, waste to energy plants, and fossil fuel power plants.

LOW TEMPERATURE PLASMA TREATMENT OF GASEOUS WASTE STREAMS

We have shown in the laboratory that low temperature plasmas generated by moderate energy (100-300 keV) electron beams can be used to selectively destroy dilute (1-1000 ppm) concentrations of volatile organic compounds (such as carbon tetrachloride and trichloroethylene) in air streams. The high degree of selectivity results in a highly efficient relatively low cost process. This system is attractive to DOE for on-site treatment of solvents pumped out of the ground in remediation activities and is also attractive for air stripping of contaminated water. In 1995, a successful initial field test was carried out at the DOE Hanford site. The test showed fully automated feedback controlled operation.

PLASMA MANUFACTURING OF HYDROGEN

Support from the DOE Hydrogen Research Program has been received in 1995 for investigations of plasma manufacturing of hydrogen. Experiments are underway to determine the effectiveness of arc plasma technology in converting hydrocarbons into hydrogen-rich gas. Potential applications include use with fuel cells. Prof. Simone Hochgreb from the Mechanical Engineering Department is participating in this activity.

PLASMA DIAGNOSTICS DEVELOPMENT

A gyrotron scattering system for alpha particle diagnostics has been tested on the TFTR tokamak at Princeton University. Scattering from relatively high level nonthermal fluctuations was observed, which has prevented a simple interpretation of these results. Meanwhile, collaborative efforts in scattering experiments are also underway with the JET tokamak in Abingdon, England. This activity, which will use a high power Russian gyrotron operates in a different regime, has good prospects for making the first thermal scattering measurements from alpha particles. These measurements are important for understanding ignition physics and could play a key role in ITER.

WAVES AND BEAMS DIVISION

The Waves and Beams Division, headed by Dr. Richard Temkin, conducts research on novel sources of electromagnetic radiation and on the generation and acceleration of particle beams.

GYROTRON RESEARCH

The gyrotron is a novel source of microwave, millimeter wave and submillimeter wave radiation. It uses a helical electron beam in a high magnetic field to generate radiation by stimulated emission at the electron cyclotron frequency. Gyrotrons are under development for electron cyclotron heating (ECH) of present day and future magnetically confined fusion plasmas as well as for high frequency radar. These applications require tubes operating at frequencies in the range 100-300 GHz at steady-state power levels approaching 1 MW. The gyrotron research group is led by Dr. Kenneth Kreischer.

Research has concentrated on investigating the physics issues which affect the efficiency of operation of high power, high frequency gyrotrons. Efficiency is a critical issue because it determines the recirculating power needed to sustain a practical fusion reactor and also greatly impacts the reliability and cost of plasma heating systems. We have begun a program of research to demonstrate a high power, high frequency gyrotron suitable for application to the International Thermonuclear Experimental Reactor (ITER). A prototype experiment at M. I. T. has been built and is now under first testing. The ITER Joint Central Team has approved the research phase of this project for credit as part of the ITER program. The objective is to demonstrate a 1 MW, 170 GHz gyrotron with an efficiency of at least 35%. This work will be carried out in collaboration with Varian Associates, General Atomics, Univ. Wisconsin, Univ. Maryland and Lawrence Livermore National Lab. The MIT gyrotron group has the lead role in this effort.

A program of research is also underway to demonstrate a coaxial cavity gyrotron. This experiment will be carried out at 140 GHz in collaboration with Dr. Michael Read of Physical Sciences, Inc. of Alexandria, Virginia. In principle, the coaxial cavity gyrotron

may be capable of power levels up to 3 MW, significantly higher than the 1 MW power expected from conventional cavity gyrotrons. The experiments will begin in the summer of 1995.

RELATIVISTIC BEAM PHYSICS RESEARCH

The Relativistic Beam Physics Group, led by Dr. 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 klystron and the induction linear accelerator (ILAC).

Research is continuing on a high power, 17 GHz klystron in collaboration with Haimson Research Corp. of Palo Alto, CA. The klystron electron gun is a gun that was previously built for MIT and the klystron cavities were built by Haimson Research. The klystron has now demonstrated power levels of up to 26 MW in 1 μ s pulsed operation using a 560 kV, 95 A beam. These are record power levels for a relativistic klystron operating at such a high frequency in pulse lengths in the μ s range. An efficiency as high as 51% was achieved. Work is continuing on optimizing the klystron performance and applying it to high gradient acceleration experiments.

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 17 GHz klystron power source will drive the electron gun. This electron beam can be directly applied to microwave generation experiments or it can be used as an injector into a 17 GHz, high gradient accelerator. This research supports the program to build new electron accelerators which can reach the TeV range of energies.

The RF gun experiment has been operated with a microsecond pulse length klystron source at power levels of 5 to 10 MW at 17.145 GHz. The power coupled into the electron gun was monitored using the forward and reflected microwave power. A stored field equivalent to an on-axis accelerating gradient as high as 150 MeV/m was obtained, a record high value. Work is also progressing on generating the required laser pulse for the photocathode. This pulse must be timed to an accuracy of 1 ps in order to coincide with the 17 GHz accelerator field at a phase accurate to within 6 degrees.

THEORETICAL RESEARCH

A new research program has been initiated by Dr. Chiping Chen on the topic of theoretical and computational investigation of periodically focused intense charged particle beams. This research will support the U. S. program to construct advanced accelerators for such applications as nuclear waste treatment, heavy ion fusion and free electron lasers. Research will explore self-field-induced nonlinear resonant and chaotic phenomena in intense charged particle beams.

RELATIVISTIC ELECTRONICS DIVISION

This section, led by Prof. George Bekefi, is involved in exploring the physics of novel lasers using relativistic electron beams as the lasing medium.

Free electron laser research in this division spans wavelengths ranging from millimeters to nanometers. At millimeter wavelengths (8.6 mm) we are generating 60MW of coherent radiation, the world's largest power at that wavelength. This device is now being actively used in a collaborative effort with CERN/CLIC in testing novel high gradient RF accelerating structures. The goal is to achieve accelerating gradients in excess of 100 MeV per meter length (the SLAC RF Linac achieves about 17 MeV/m). Since these systems are physically small, such gradients could in principle be achieved with minimal expenditure of RF energy.

At the opposite end of the wavelength spectrum, we are aiming at generating tens of kilowatts of coherent radiation in the X-ray regime for use in medical and biological studies. To this purpose we have designed, built and tested a novel 70 period magnetic microwiggler of 8.8 mm periodicity with unprecedented uniformity ($\pm 0.04\%$). At this level of precision, wiggler errors are sufficiently small to allow operation at X-ray wavelengths. This program is a collaboration with the Brookhaven National Laboratory where the MIT wiggler is being installed on the 80 MeV, Advanced Test Facility, RF Linac. Radiation at a wavelength of 250 nm is expected within 12 months. Achievement of this goal would be the first of its kind in which an X-ray free electron laser is being driven by a linear RF accelerator.

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 under representation. Our success in meeting this objective is dependent on the pool of applicants available at each level. For example, 75% of both the SRS administrative and support staff are women, while 25% 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 14.6% are other minorities, most of whom are Asian Americans. 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 and, in the long term, with a substantial K-12 and undergraduate outreach effort which encourages women and other minorities to pursue careers as scientists and engineers.

EDUCATIONAL OUTREACH PROGRAMS

The Plasma Fusion Center has established an educational outreach program primarily focused on heightening the interest of K-12 students in scientific and technical subjects. The Mr. Magnet Program, headed by Technical Supervisor Paul Thomas, has been particularly successful. Mr. Magnet, with the help of a graduate student, brings a traveling demonstration on magnetism into local elementary schools, inspiring and exciting students with the chance to take part in hands-on experiments with magnets. He stresses that science is a valid pursuit for boys and girls. Over the past year he has worked with over 10,000 students. The PFC also seeks to educate students and the general public by conducting general tours of experiments being done here. Special "Outreach Days" are held twice a year, encouraging high school and middle school students from around Massachusetts to visit the PFC for a day of hands-on demonstrations and tours.

The PFC has also become involved in the Contemporary Physics Education Project (CPEP), a collaborative effort of fusion facilities around the U.S. The goal of this group is to create a fusion-oriented curriculum, along with supporting hands-on experiments and graphics, for use in high schools around the country. Mr. Paul Rivenberg has worked on the "Chart Committee" of this project, which is focusing on creating wall charts that will aid in the understanding of fusion.

FUSION FORUM DAYS IN CONGRESS

The Fusion Forum, held each year on Capitol Hill, is a community-wide effort to show Congress the goals of the national fusion program and its gains over the past year. Fusion fundamentals are also outlined to educate new Congressmen and staff members. In March 1995 Miklos Porkolab, Bruce Montgomery, Dan Cohn and Albe Dawson, together with Tobin Smith of the MIT Washington office participated in the Forum. An exhibit was brought to Washington to show our 1) education and educational outreach programs, 2) Alcator C-Mod and ITER magnetics accomplishments and 3) the PFC's plasma-science-based spin-off technologies including hazardous waste remediation,

microchip manufacture, and cutting tool plasma-spray coatings to increase surface hardness and tool life up to 100-fold at a very small cost increase. A videotape showing plasmas in C-Mod received considerable attention. Bruce Montgomery testified before the House Appropriations Subcommittee on Energy and Water, and Miklos Porkolab and Dan Cohn made visits to several members of the Massachusetts congressional delegation to garner their support for the fusion program. The exhibit was selected to remain on display in the Cannon House Office building for the two weeks following the Forum. Attendance was considerably higher than in previous years.

APPOINTMENTS AND PROMOTIONS

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

Appointments include: Vincent Bertolino (Sullivan and Cogliano) appointed Systems Engineer in the Alcator C-Mod Division; Changheui Jang (MIT, Nuclear Engineer) appointed Postdoctoral Research Staff and Philip Michael (Yokohama National University) appointed Research Engineer in the Fusion Technology and Engineering Division; Eileen Ng (Artificial Intelligence Lab) appointed Assistant Fiscal Officer in the Fiscal Office; Rosaria Rizzo (Earth Atmospheric and Planetary Sciences) appointed Assistant Fiscal Officer in the Fiscal Office; Willie Smith (Provost's Office) appointed Administrative Officer; Robert Vibert (National Magnet Lab) appointed Assistant Fiscal Officer in the Fiscal Office; and Randy West (Diversified Technologies Inc.) appointed Engineer-Temporary in the Fusion Technology and Engineering Division.

Internal promotions in the Plasma Fusion Center during the past year include: Veronica DuLong, promoted to Associate Fiscal Officer in the Fiscal Office; Chenyu Gung, promoted to Research Engineer in the Fusion Technology and Engineering Division; Kamal Hadidi, promoted to Research Scientist in the Plasma Technology and Systems Division; James Irby, promoted to Head of Operations Section of the Alcator C-Mod Division; and

Pei-Wen Wang, promoted to Research Engineer in the Fusion Technology and Engineering Division;

During the past year, there was one Institute research promotion in the Plasma Fusion Center: Prof. Miklos Porkolab, promoted to PFC Director.

The Plasma Fusion Center has also hosted 68 Visiting Scientists, Engineers and Scholars during the past year.

GRADUATE DEGREES

During the past year, the following students graduated with theses in plasma fusion and related areas: Monica Blank, Ph.D., Electrical Engineering and Computer Science; Adam Brailove, Ph.D., Physics; Michael Graf, Ph.D., Nuclear Engineering; Carsie Hall II, M.S., Mechanical Engineering; Christian Kurz, Ph.D., Nuclear Engineering; Chia-Liang Lin, Ph.D., Electrical Engineering and Computer Science; Thomas Luke, Ph.D., Physics; Martin Morra, Ph.D., Material Science and Engineering; Gennady Shvets, Ph.D., Physics; Jesus Villasenor, Ph.D., Physics; and Ali Zolfaghari, Ph.D., Nuclear Engineering. We take this opportunity to wish these graduates success in their future professional endeavors.

MIKLOS PORKOLAB

DIRECTOR

MIT PLASMA FUSION CENTER