MASSACHUSETTS INSTITUTE OF TECHNOLOGY

PLASMA FUSION CENTER

TECHNICAL RESEARCH PROGRAMS

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MIT's Plasma Fusion Center is recognized as one of the leading university research laboratories in the physics and engineering aspects of magnetic fusion energy development. Its research programs have produced significant results on four fronts: (a) the basic physics of high-temperature fusion plasmas (plasma theory, RF heating, development of advanced diagnostics, and small-scale experiments on the Versator tokamak and Constance mirror devices), (b) major confinement results on the Alcator A and C tokamaks, including pioneering investigations of the equilibrium, stability, transport and radiation properties of fusion plasmas at high densities, temperatures and magnetic fields, (c) development of a new and innovative design for axisymmetric tandem mirrors with inboard thermal barriers, with initial operation of the TARA tandem mirror experimental facility scheduled for 1983, and (d) a broadly based program of fusion technology and engineering development that addresses problems in several critical subsystem areas (e.g., magnet systems, superconducting materials development, environmental and safety studies, advanced gyrotron development for RF heating, preconceptual design studies of torsatrons and stellarators, and advanced tokamak design and reactor studies). This report gives an overview of Plasma Fusion Center technical research programs and staffing and objectives at the individual Research Group level.

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I. INTRODUCTION

The primary responsibility of the Plasma Fusion Center (PFC) is to provide the strong technical and administrative leadership required for effective implementation of all fusion research and development activities sponsored by the Department of Energy at the Massachusetts Institute of Technology. Outstanding technical excellence is the primary cornerstone for all PFC research programs, and a major emphasis is placed on providing the intellectual environment that fosters and encourages independent creativity both at the individual researcher level and on the scale of major fusion projects such as Alcator C and TARA. A major strength of the Plasma Fusion Center, and more broadly speaking, of the Massachusetts Institute of Technology as an institution, is the ability to evolve new ideas and concepts in critical technical areas required for the development of fusion energy, and to train professional researchers. Therefore, in the years ahead, there will be necessarily a continued increase in emphasis on the involvement of additional faculty, students, and research scientists and engineers in both new and existing PFC program areas. The Plasma Fusion Center, through the training of students and professional researchers, makes a major contribution both to MIT's goal of excellence in technical education and to the scientific and engineering manpower needs of the national fusion program.

By way of background, the Plasma Fusion Center technical programs are supported by the Department of Energy's Office of Fusion Energy at a funding level of approximately $20 million in FY82. Moreover, there are approximately 315 personnel associated with Plasma Fusion Center research activities. This includes: 25 faculty members, 70 graduate students, and 20 undergraduate students, with participating faculty and students from Aeronautics and Astronautics, Electrical Engineering and Computer Science, Materials Science and Engineering, Mathematics, Nuclear Engineering, and Physics; 125 research scientists and engineers and 10 visiting scientists contributing to numerous physics and engineering aspects of fusion energy development; and 65 support personnel, including technical support staff, secretaries, and administrative staff. At the present time, the Plasma Fusion Center's major experimental and engineering facilities are located at several sites on the MIT campus, including NW13 (Nuclear Engineering), NW14 (National Magnet Laboratory), NW16 (Plasma Fusion Center), Building 36 (Research Laboratory of Electronics), Building 38 (Electrical Engineering and Computer Science), and NW21 (PFC Nabisco Laboratory).

II. PLASMA FUSION CENTER TECHNICAL PROGRAMS

Plasma Fusion Center research activities are carried out in five major Technical Divisions. These are:

- Applied Physics Research
- Toroidal Confinement Experiments
- Mirror Confinement Experiments
- Fusion Technology and Engineering
- Fusion Systems

We briefly outline here the main objectives and subprograms in each of these Divisions. A more detailed summary of associated research activities, facilities, and staffing is given later in this report.

A. Applied Physics Research

Objectives: Develop the basic experimental and theoretical understanding of plasma heating and confinement properties.

The subprogram areas include:

- Experimental Research - Tokamak Systems
- Experimental Research - Mirror Systems

- Physics of Stellarator/Torsatron Systems
- Fusion Theory and Computations
- MACSYMA
- Diagnostic Development and Laser Systems
- Intense Charged Particle Beams

B. Toroidal Confinement Experiments

Objectives: Develop an understanding of the stability, transport and radiation properties of high-temperature toroidal fusion plasmas at near-reactor conditions. Develop methods for heating plasmas to fusion temperatures.

At the present time, the subprogram areas include:

- Alcator C Experimental Program
- Advanced Toroidal Experiment Design

C. Mirror Confinement Experiments

Objectives: Develop an increased understanding of basic tandem mirror physics with emphasis on microstability properties, thermal barrier formation and RF heating. Design, construct and operate the TARA tandem mirror facility.

The subprogram areas include:

- Tandem Mirror Confinement Physics
- TARA Engineering
- Computations and Advanced Concepts

D. Fusion Technology and Engineering

Objectives: Provide critical engineering support for the advanced design projects. Develop advanced superconducting magnet technology for the national fusion program.

The subprogram areas include:

- Advanced Design
- Superconducting Magnet Development
- Superconducting Materials Development
- Divertor Development

E. Fusion Systems

Objectives: Identify and investigate problems in design and operation of fusion reactors and advanced fusion systems. Develop advanced components.

The subprogram areas include:

- Safety and Environmental Studies
- Tokamak System Studies
- Gyrotron and Advanced Millimeter Source Development
- Millimeter and Submillimeter Wave Detector Development

As evident from Figure 1, Page 29, virtually all of the subprograms listed above are at the individual Research Group level.

III. PLASMA FUSION CENTER TECHNICAL STEERING AND ADVISORY COMMITTEES

A. PFC Technical Steering Committee

The PFC Technical Steering Committee, which is composed of the Principal Investigators of all major fusion research activities in the Plasma Fusion Center, meets on a regular basis. This is a very important forum for advising the Director on technical issues and items of special significance to the Plasma Fusion Center and the overall fusion program. As the situation merits, the membership of this committee is expanded to include additional senior scientists and engineers who play a key role in PFC research activities. The present membership of the Plasma Fusion Center Technical Steering Committee is summarized in Appendix A, page 113 of this report.

B. PFC Advisory Committee

The PFC Advisory Committee consists of the Director of the Plasma Fusion Center, the Vice President for Research, and the Deans and Heads of academic departments with faculty affiliated with Plasma Fusion Center research programs. This committee addresses a broad range of important policy issues related to overall program balance and direction, faculty and student participation in PFC research programs, and appointments and promotions. The present membership of the Plasma Fusion Center Advisory Committee is summarized in Appendix A, page 114 of this report.

C. PFC Visiting Committee

The PFC Visiting Committee consists of ten nationally and internationally renowned fusion scientists and engineers, external to the PFC, that meets at approximately eighteen-month intervals to advise the Director and the MIT Administration on a broad range of technical issues related to PFC research programs. Important Visiting Committee feedback is obtained in several key areas, including the scope and technical merit of individual research activities, and the overall balance, emphasis, and future directions of PFC research programs. The present membership of the Plasma Fusion Center Visiting Committee is summarized in Appendix A, page 113 of this report.

D. PFC Executive Committee

Finally, the PFC Associate Directors and Division Heads form an Executive Committee to the Director, and meet with the Director on a frequent basis to address all major program issues and help plan future program directions.

IV. THE NABISCO LABORATORY

Nabisco, Inc., with headquarters in East Hanover, New Jersey, announced on May 31, 1978, that it was donating its property at 184-190 Albany Street, Cambridge, Massachusetts, to the Massachusetts Institute of Technology. The property was conveyed to MIT on April 7, 1980 following completion of Nabisco's move to a new facility. The value of the 71,000 square foot building and property is in excess of $1.5 million. The original building was constructed in 1905. Additions and remodeling were done in 1953. The building is constructed of masonry walls, concrete and rock maple floors, steel and wood columns, steel roof joists, gypsum deck roof, basically single-story with a small second floor area in the central section.

As evident from Figure 2, Pg. 30, the Nabisco Laboratory (NW21) is adjacent to the PFC 220 MW Alternator (NW20) donated by Consolidated Edison Co. of New York, and Plasma Fusion Center research facilities located in the Francis Bitter National Magnet Laboratory (NW14), the Nuclear Engineering Department (NW13), the Nuclear Reactor Laboratory (NW12), and the Plasma Fusion Center research complex (NW16). The close proximity to these facilities and heavy power make the Nabisco Laboratory an ideal location to house the Plasma Fusion Center's major confinement experiments and engineering test facilities, particularly, the TARA tandem mirror experiment, the upgrades/follow-on experimental devices in the Alcator, Versator and Constance programs, as well as new experimental activities that may evolve in the torsatron/stellarator area.

V. HIGHLIGHTS OF 1981 RESEARCH ACTIVITIES

In this section we briefly summarize selected research accomplishments during the past year. A more detailed overview of PFC research programs, facilities and staffing is given later in this report.

A. Applied Physics Research

The primary objective of the Plasma Fusion Center Applied Physics Research Division, with Ronald Davidson as acting head, is to develop the basic experimental and theoretical understanding of plasma heating and confinement properties. Present applied physics research activities include: experimental research on the Versator II tokamak (George Bekefi, Miklos Porkolab and Stan Luckhardt); experimental research on the Constance II mirror device (Louis Smullin); fusion theory and computations (Abraham Bers, Bruno Coppi, Ronald Davidson, Thomas Dupree, Jeffrey Freidberg, Jay Kesner, James McCune and Kim Molvig); development of the MACSYMA symbolic manipulation system (Joel Moses); plasma diagnostics and laser development (Daniel Cohn and Paul Woskoboinikow); development of advanced stellarator/torsatron concepts (Lawrence Lidsky and Jeffrey Freidberg); basic experimental and theoretical research on intense charged particle beams (George Bekefi and Ronald Davidson).

We summarize here the significant progress made during the past year in selected applied plasma physics research areas.

Versator II is a medium-sized research tokamak (major radius = 40.5 cm; minor radius = 13 cm; toroidal magnetic field = 15 kG) with primary emphasis on basic investigations of plasma heating and confinement properties. Lower-hybrid current-drive experiments on Versator II have drawn significant national attention during the past year. In particular, it has been shown that in the vicinity of the lower hybrid frequency it is possible to enhance the toroidal current by injecting unidirectional lower hybrid waves via a set of 4- or 6-phase array of waveguides, thus imparting a net toroidal momentum to the plasma electrons. By injecting 30-50 kW of RF power at a frequency of 800 MHz, a net current increase of up to 15 kA has been observed, implying an RF-generated current of 25-30 kA. Thus, in these experiments, most of the toroidal current is due to the injected RF power rather than the initial ohmic heating current (approximately 30 kA). These results show that an RF driven steady-state fusion reactor might be possible. However, contrary to present theory, the current-drive mechanism operates only at relatively low plasma densities ($n_0 \lesssim 10^{13}\mathrm{cm}^{-3}$), whereas a reactor would operate at densities in excess of $10^{14}\mathrm{cm}^{-3}$. Ways to increase the density limit are presently under investigation, as well as the detailed physical mechanism responsible for RF current drive. The Versator II current-drive experiments are perhaps the most advanced and best diagnosed in the world. Future plans include the lengthening of the RF pulse, and crowbarring the ohmic heating supply to study the equilibrium and stability properties of a fully RF-driven tokamak. In parallel with the above experiments, studies of electron cyclotron resonance heating (ECRH) are underway in collaboration with scientists from the Naval Research Laboratory. ECRH power at a frequency of 35 GHz and 100 kW is injected into the Versator II tokamak using the NRL gyrotron as the microwave source. Preliminary results show electron heating with an efficiency in excess of 60%. Combined ECRH and lower hybrid current-drive experiments are under investigation.

Plans are also underway for designing Versator III, an upgraded version of the present device. Larger-scale RF heating experiments are planned for Versator III and possibly a series of heating studies using intense relativistic electron or ion beams.

Two high-voltage accelerators are available and capable of supplying 20-100 kA of electrons at energies in the 0.5-1.5 MeV range. At the present time, the electron beam accelerators are being used in the study of relativistic electron and ion diodes with emphasis on optimizing the beam quality and current density. The generation of intense coherent radiation is actively pursued using two different approaches. One approach utilizes a relativistic magnetron capable of emitting approximately 1 GW of radiation at centimeter wavelengths. The other approach is a Raman-type free electron laser designed to generate megawatts of coherent radiation at millimeter and submillimeter wavelengths.

<u>Constance II</u> is a moderate-sized mirror research facility with primary emphasis on the basic experimental development of RF and beam-plasma techniques for stabilization of mirror loss-cone instabilities. During the past year, the Constance II mirror facility has been improved by the development of a new hot-cathode plasma gun that generates hotter and denser plasmas than the washer guns used previously. The guide field strength has

been increased from 1.8 kG to 2.8 kG by adding eight coils taken from the Constance I experiment. Moreover, a Thomson scattering diagnostic, including laser and five-channel polychromator, has been fabricated and calibrated, and is now being installed in Constance II. Theoretical and numerical studies are being carried out in a variety of areas: nonadiabatic particle motion in a minimum-B mirror; ray tracing for microwave power at the electron cyclotron resonance frequency; the excitation of transverse modes in a warm plasma by a density modulated electron beam. Wall effects such as lowering of the plasma electron temperature by secondary electrons are being studied. Measurements of secondary electron emission from gas-covered metal targets show anomalously high values compared to clean surfaces.

In the Plasma Theory and Computations area, there has been considerable technical progress during the past year in a variety of important areas. Recent studies include: (a) the development of a self-consistent plasma model which simultaneously includes the effect of neoclassical transport and plasma turbulence, (b) the continued development of self-consistent theoretical models describing anomalous electron energy transport in tokamaks, (c) basic investigations of the MHD stability properties of tokamak plasmas and the determination of stable operating regimes at moderate values of plasma beta (the ratio of plasma pressure to magnetic pressure), (d) the development of a self-consistent kinetic description of the free electron laser instability including the important influence of finite radial geometry, (e) continued basic theoretical investigations of RF heating, including studies of steady RF current drive and computational studies of the nonlinear coupling of microwave power to the plasma from waveguide arrays, (f) studies of the thermal stability of ignited plasmas, (g) basic studies of the MHD stability properties of toroidal fusion systems with external helical windings, (h) fundamental nonlinear studies of the influence of stochastic magnetic fields on turbulent transport in high-temperature plasmas, and (i) basic studies relating to the equilibrium stability and transport properties of high-field tokamak configurations using advanced fuels (e.g., D-He^3).

MACSYMA is a symbolic manipulation program implemented on the MACSYMA consortium PDP-10 at MIT and available to the magnetic fusion community through the National Magnetic Fusion Energy Computer Network. The MACSYMA effort involves the maintenance and development of the MACSYMA system, its underlying MACLISP system, and the ITS operating system which all operate on the MACSYMA consortium PDP-10. A new project is underway to develop a LISP system, called NIL, which is exportable and can support MACSYMA on recently available large-address machines such as DEC VAX-11. In addition to the ongoing algorithm development for the symbolic manipulation of algebraic structures, an effort has also been initiated to implement improved I/O facilities such as a two-dimensional display editor for mathematical expressions.

In the area of Advanced Fusion Concepts, there has been a continued emphasis on the development of stellarator/torsatron reactor designs consistent with the best available models of plasma physics and technological capabilities. Torsatron research activities during the past year have included studies related to ion thermal conductivity and alpha-particle transport, as well as investigations of modular coil structures and MHD stability properties.

B. Alcator Confinement Experiments

The Alcator experimental program constitutes one of the most successful and prominent tokamak confinement programs, both nationally and internationally. The primary objective of the Alcator experimental program, headed by Ronald Parker, is to develop the basic physics understanding of the stability, transport and radiation properties of high-temperature plasmas at near-reactor conditions and to develop methods for heating plasmas to fusion temperatures. The main Alcator experimental areas include: device operations (David Gwinn); confinement studies (Steve Wolfe);

plasma-wall interactions (Earl Marmar); radio frequency heating (Miklos Porkolab and Jack Schuss); and data acquisition and computations (Martin Greenwald). The experimental design activities during the past year have emphasized advanced toroidal facilities with helical features (such as Alcator A Modification) as well as advanced tokamak designs in the high-field Alcator line (Peter Politzer and D. Bruce Montgomery). Ronald Parker and Bruno Coppi are overall Alcator program principal investigators.

Alcator A: During the past year, research activities on Alcator A have terminated, and the primary emphasis of the experimental program has focussed on the operation of the larger, higher field tokamak Alcator C. The Alcator A was a relatively small (minor radius = 10 cm, major radius = 54 cm) tokamak capable of operation at extremely high toroidal field strengths (up to 100 kG). Alcator A has operated for nine years and has proved to be one of the most important and successful fusion experiments in the world during the decade of the 1970's. While Alcator A is principally known for the discovery of an empirical scaling law that relates energy confinement time to plasma density, a result which was exploited to raise the Lawson product $n\tau_E$ by an order of magnitude, many equally significant technical results have been obtained in several key areas. Among important technical results are basic contributions to impurity control and confinement, methods of particle removal and control, and development and testing of techniques for RF heating. These areas of research are critical for the continued development of the tokamak concept for use as a fusion reactor, and research on these problems is being continued on Alcator C as well as tokamaks at other laboratories.

Alcator C: The Alcator C tokamak (major radius = 64 cm, minor radius = 16 cm, toroidal magnetic field up to 140 kG) has been operated intensively during the past year with particular emphasis on the study of ohmically-heated discharges at toroidal fields B_T up to 120 kG. For minor radius a = 16 cm and toroidal field B_T = 105 kG, the "best" parameters produced in the Alcator C device during this period are: line-averaged density $\bar{n} = 7 \times 10^{14} cm^{-3}$, central density $n_0 = 8.5 \times 10^{14} cm^{-3}$, electron and ion temperatures of 3 keV and 1.6 keV, respectively, plasma currents of 750 kA, and energy confinement times of approximately 40 ms. On the other hand, for reduced limiter size with minor radius a = 10 cm, major radius R = 58 cm and toroidal field B_T = 120 kG, the performance of Alcator C has exceeded that of Alcator A. In this case, the best parameters achieved are line-averaged density $\bar{n} = 8 \times 10^{14} cm^{-3}$, central density $n_0 = 1.2 \times 10^{15} cm^{-3}$, energy confinement time $\tau_E \simeq 30$ ms, and corresponding value of the Lawson parameter $n_0\tau_E \simeq 0.35 \times 10^{14} cm^{-3}$-s.

Although Alcator C has performed up to design expectations in most areas, an exception has been in the measured value of energy confinement time τ_E when the minor radius a = 16 cm. The best value obtained for τ_E is about a factor of two below that anticipated on the basis of extrapolation of the results from Alcator A. This can be traced to the observed dependence of τ_E as a function of plasma density. At plasma densities $\bar{n}$ in excess of $2 \times 10^{14} cm^{-3}$, it has been found that τ_E increases only slowly with density rather than continuing to increase linearly with density as found in Alcator A. The main results are consistent with an enhanced (anomalous) ion energy transport that is up to a factor of five times larger than the classical value based on two-body collisions. However, the present experimental uncertainties are such that a departure from an empirically-based scaling law for electron thermal conductivity could also explain the trends in the data. The main significance of these results is that the ion energy confinement time at high densities may be less than expected. This will make the achievement of $n_0\tau_E \simeq 10^{14}$ cm^{-3}-s difficult in Alcator C. However, the present best value of $n_0\tau_E \simeq 0.35 \times 10^{14} cm^{-3}$-s obtained in Alcator C does exceed that obtained in Alcator A, and a value of $n_0\tau_E$ in the range 0.5-0.7 $\times 10^{14}$ cm^{-3}-s is expected to be achieved in Alcator C even with the unfavorable trends discussed above. These experimental studies are receiving continued emphasis with expanded and more accurate diagnostic capability.

RF Heating: The second phase of the Alcator C experimental program, namely, the use of high-power radiofrequency (RF) waves to raise the plasma temperature, has begun with the installation of a single four-waveguide coupler operating at a frequency of 4.6 GHz. This unit enables a maximum of 250 kW to be applied to Alcator C plasmas. During the coming year, more RF tubes and couplers will be added and this will result in an ultimate capability of 4 MW using a total of 64 waveguides. Present low-power studies are concerned with matching the plasma to the RF system, studies of wave propagation effects, and at higher power levels, plasma heating. Significant technological progress has been made during the past year on the development of the RF couplers and vacuum windows. In addition, preliminary low-power (25 kW) results on lower hybrid current drive indicate RF-generated currents in the 1 kA/kW range.

Advanced Toroidal Systems Design: The experimental design activities during the past year have emphasized advanced toroidal facilities with helical features (such as Alcator A Modification) as well as advanced tokamak designs in the Alcator high-field line. For purpose of illustration, the primary objective in the Alcator A Modification design is the development of an experimental facility for the basic study and control of MHD instabilities and disruptions. The important feature of the design is a helical $\ell = 2$ winding capable of producing substantial vacuum rotational transform. Combining this winding with those of a conventional tokamak leads to a device with considerable flexibility in its modes of operation, ranging from operation as a pure tokamak to operation as a pure stellarator, with an intermediate "hybrid" mode that has both tokamak and stellarator features. The present design (minor radius = 30 cm, major radius = 110 cm) is approximately twice the size of Alcator C but has considerably lower toroidal field capability (up to 50 kG). An advantage of the increased size and lower design field is the availibility of substantially increased access, which will be exploited both for additional diagnostics and RF heating capability.

C. Mirror Confinement Experiments

In the fall of 1980, the Mirror Confinement Systems Division, headed by Richard S. Post, prepared a technical proposal to the Department of Energy for construction and operation of a major new tandem mirror experimental facility called TARA. The TARA proposal received very strong technical endorsement by a peer review panel chaired by Grant Logan of LLNL. The construction costs for the TARA device are approximately $13M over a thirty month period, with initial operation scheduled for November, 1983. The principal investigators are Richard S. Post and Jay Kesner, and the TARA device will be sited in the west wing of the Nabisco Laboratory. The TARA experiment will significantly complement the mirror research activities at Lawrence Livermore Laboratory (LLNL) as well as the ongoing PFC research activities in mirror theory and the Constance II experimental program.

The TARA Tandem Mirror configuration is unique and utilizes an axisymmetric confining plug with an "outboard" minimum-B anchor. It has been identified as the most desirable tandem mirror configuration for potential reactor applications. The primary objectives of the experiment will be to test plug microstability, overall MHD stability and beta limits, central cell radial transport and thermal barrier formation. The experiment will provide data for the proposed upgrade of the MFTF-B facility under construction at Lawrence Livermore National Laboratory.

The following is a brief summary of the TARA design. The TARA central cell is a 15 cm radius, 5 m long solenoid with upgrade capabilities to 15 m. When a thermal barrier is present, the projected plasma parameters are $T_e \sim T_i \sim 400$ eV and $n_e = 4 \times 10^{12} \text{cm}^{-3}$. Ions are confined by axisymmetric plugs which eliminate the possibility of enhanced radial transport that is driven by the quadrupole moments of the plugs (so-called "resonant" transport).

The central solenoid is bounded by high mirror ratio plugs (R = 5 to 10) with peak fields of up to 5 T. Neutral beams (20 keV extractor energy) with 150 A current are injected at a 40° angle into the plugs to create a sloshing-ion distribution which is expected to exhibit improved microstability properties and provide a partial thermal barrier. Gyrotrons at 28 GHz will be available with a capability of 200 kW per plug for creating the hot mirror-trapped thermal barrier electron species and the suprathermal ($T_e \sim 700$ eV) warm electron species. Thus, a thermal barrier is expected to form at the midplane of the plugs.

A unique feature of the TARA configuration, and one that provides a substantial reduction in cost and technology requirements is the use of RF-driven MHD anchors. The anchor will be formed in externally located baseball coils that were formerly the plugs in TMX. They will operate steady-state and contain a low-density ($n \sim 5 \times 10^{11} \mathrm{cm}^{-3}$) hot-electron plasma, formed by ECRH heating in the X-band. Additional ion heating utilizing ICRF will be used to augment beta values in the anchor.

D. Fusion Technology and Engineering

The Fusion Technology and Engineering Division, headed by D. Bruce Montgomery, provides engineering support for the advanced design projects, and develops advanced superconducting magnet technology for the national fusion program. Research activities include: advanced design for the TARA tandem mirror experiment and for proposed follow-on experiments in the Alcator/toroidal confinement area; design support for the magnet systems of the Fusion Engineering Device (Joel Schultz); responsibility for construction of a magnetic divertor for the ISX-B tokamak at Oak Ridge National Laboratory (ORNL), and responsibility to develop improved magnetic divertor concepts (Ted Yang); the development of forced-flow superconductors for application to advanced fusion devices (Mitchell Hoenig); basic research on the development of ductile superconducting materials (Simon Foner, Robert Rose and Brian Schwartz).

During the past year, there has been significant progress in each of these activities. We summarize here progress in a few selected areas.

The proposed next major step in the United States fusion program is a 200 MW output, 100-second-burn engineering tokamak device known as the Fusion Engineering Device (FED). A six-member technical management board, of which D. Bruce Montgomery is a member, has been established by DOE to develop the overall concept and objectives for the device, and to develop a parallel engineering feasibility program to supplement the FED and prepare for the first demonstration fusion reactor.

The PFC Fusion Technology and Engineering Division has had responsibility for the Magnetics Branch of the FED Design Center activities during the past two years. This work has been carried out in close cooperation with the FED Design Center Headquarters at ORNL, which has overall responsibility for systems integration. Since the beginning of FY82, General Electric has assumed responsibility for the magnetics branch activities, and the PFC has taken responsibility for critical issues.

The Plasma Fusion Center has been active in developing improved magnetic divertor concepts under the direction of Ted Yang. A long-burning fusion reactor must deal with the buildup and removal of helium "ash" and impurities, and magnetic or mechanical divertors are considered to be an extremely demanding but necessary component. The Plasma Fusion Center has recently completed the major construction of a high-field divertor for the ISX-B tokamak at ORNL. Borivoje Mikić and Neil Todreas and their students have been active during the past year working with Ted Yang on basic divertor studies.

Critical experimental tests are also being carried out in the development of forced-flow conductors for superconducting fusion magnets. The supercritical helium-cooled conductor conceived and developed by the magnet group has been selected by Westinghouse for the 2 × 3 meter niobium-tin coil for the Large Coil Project at the Oak Ridge National Laboratory. The group will also utilize an advanced version of the conductor to build a 40 cm bore, 12 tesla insert for the High Field Test Facility at the Lawrence Livermore National Laboratory.

Basic research on advanced superconducting materials is also a major fusion engineering activity in the Plasma Fusion Center and the Materials Science and Engineering Department. The objective is to develop materials and techniques for producing superconductors capable of generating 15 tesla magnetic fields and sufficiently ductile to be suitable for advanced fusion devices. Materials developed by this group show considerable improvements in mechanical properties and offer significant possible reduction in production costs over conventional industrial preparations.

E. Fusion Systems

The Fusion Systems Division, headed by Daniel Cohn, investigates several aspects of fusion reactor design and develops advanced millimeter and submillimeter wave technology. Research activities include: safety and environmental studies (Mujid Kazimi); reactor system studies (Daniel Cohn); blanket and first wall structural design studies (John Meyer); gyrotron and advanced millimeter source development (Richard Temkin); millimeter and submillimeter detector development (Harold Fetterman and Peter Tannenwald, Lincoln Laboratory).

During the past year, there has been significant progress in these activities, and we summarize here progress in a few selected areas.

In the safety and environmental studies area, lithium fire risk has been investigated for various tritium breeding blanket designs. A total energy cycle assessment of fusion power production has also been made. Future activities will include studies of risk in non-metal cooled reactors and improved modeling of lithium fires.

The reactor system studies group has developed concepts for the operation and control of ignited (self-heated plasmas and has completed a conceptual design of a compact tokamak ignition test reactor (ITR). The ITR design was carried out in collaboration with the Max Planck Institute for Plasma Physics at Garching, Federal Republic of Germany. Research activities have been initiated on the study of tokamak reactors with stabilizing helical coils, improved stellarator reactor designs, and the design of high performance resistive magnet tokamak reactors for advanced fuel cycle operation and/or as an alternate to the present baseline FED design. New aspects of the use of fusion neutrons for breeding fissile material will also be investigated during the coming year.

In the gyrotron development area, theoretical studies of threshold and cavity design effects in high-frequency ($\sim$ 140 GHz) devices have been carried out. A special gun for high-frequency gyrotron operation has been designed in collaboration with Varian Associates, and an experimental study of high-frequency gyrotron operation is underway.

In the area of plasma diagnostics development, a very sensitive submillimeter wave heterodyne receiver has been used for new measurements of cyclotron emission from Alcator A and Alcator C. This detector system together with a high-power, 385 μm D_2O laser will be employed for ion temperature measurements on Alcator C.

VI. EXPERIMENTAL FACILITIES

In this section, we briefly summarize the characteristic operating parameters of major PFC experimental facilities. Further details regarding these facilities are given later in this report.

Versator II

Versator II is a medium-sized research tokamak with primary emphasis on basic investigations of plasma heating and confinement properties. Lower hybrid heating and electron cyclotron resonance heating (ECRH) experiments are carried out on Versator II. In addition, a feasibility study of current drive using lower hybrid waves is in progress with RF-generated currents in the 1 kA/kW range. The characteristic operating parameters for Versator II are summarized in Table 1 on page 21.

Constance II

Constance II is a medium-sized research mirror used to study the basic microstability properties of mirror-confined plasmas. Research activities on this facility include experimental investigations of plasma heating by ECRH, ICRH and electron beam-plasma interactions. An important objective of this experiment is to produce and investigate stability properties of sloshing ion distributions. The characteristic operating parameters for Constance II are summarized in Table 2 on page 21.

Alcator C

Alcator C is a compact, high-field, high-performance tokamak. It is used to develop the basic physics understanding of the stability, transport and radiation properties of high-temperature plasmas at near-reactor conditions and to develop methods for RF heating of plasmas to fusion temperatures. Alcator C has operated at record values of toroidal field and average density ($B_T = 120$ kG and $\bar{n} = 8 \times 10^{14} \mathrm{cm}^{-3}$) with characteristic values of the Lawson parameter in the $n_0\tau_E \simeq 0.35 \times 10^{14} cm^{-3}$-s range.

A sizeable amount of lower-hybrid power (up to 4 MW) is available for RF heating and current-drive experiments. The characteristic operating parameters for Alcator C are summarized in Table 3 for the two cases where the minor radius a is equal to 16 cm and 10 cm, respectively(page 22.)

TARA Tandem Mirror

The TARA experimental program is involved in the design, construction and operation of a major tandem mirror confinement facility that will complement the tandem mirror research activities at Lawrence Livermore National Laboratory. The main objective of the program is to develop an increased understanding of basic tandem mirror physics with emphasis on microstability properties, thermal barrier formation and RF heating. The TARA configuration is unique and utilizes an axisymmetric confining plug with "outboard" minimum-B anchor. Initial operation of TARA in the Nabisco Laboratory is scheduled for November, 1983. The characteristic design parameters for TARA are summarized in Table 4 on page 22.

Superconducting Racetrack Pair Test Facility

The superconducting racetrack pair is part of a test facility which includes a closed cycle helium refrigerator/liquefier. The coils can produce magnetic fields up to 6 T in a working volume 7.6 cm × 30 cm × 76 cm. Test modules can be mounted in the field and independently excited with currents up to 20 kA. The relatively large-volume, high-current, test region allows modules to be constructed to realistically simulate operational, safety and protection effects in large scale superconducting magnets. The characteristic operating parameters for the racetrack pair are summarized in Table 5 on page 23.

Parameter	Value
a (Minor Radius)	13 cm
R (Major Radius)	40.5 cm
B_T (Toroidal Field)	15 kG
$\bar{n}$ (Average Density)	$1\text{-}4 \times 10^{13} cm^{3}$
τ_p (Pulse Length)	20-40 ms
I_p (Plasma Current)	40 kA
T_{eo} (Central Ohmic Electron Temperature)	350 eV
T_{io} (Central Ohmic Ion Temperature)	120 eV
P_{RF} (Lower Hybrid)	100 kW at 800 MHz
P_{RF} (ECRH)	100 kW at 35 GHz

Table 1. Versator II Parameters

Parameter	Value
B (Midplane Magnetic Field)	5 kG
R (Mirror Ratio)	2
L (Distance Between Mirrors)	1 m
$\bar{n}$ (Average Density)	$10^{12}\text{-}10^{13} cm^{-3}$
T_{io} (Central Ion Temperature)	100 - 150 eV
τ_p (Plasma Lifetime)	0.5 ms
P_{RF} (ICRH)	100 kW at 5 MHz
P_{RF} (ECRH)	0.1 - 1 MW, X-band
P_{EB} (Electron Beam)	150 kW at 15 kV

Table 2. Constance II Parameters

Parameter	Achieved (a=16 cm)	Achieved (a=10 cm)	Ohmic Goal (a=16 cm)	RF Goal (a=16cm)
B_T (Toroidal Field in Kilogauss)	105	120	140	100
R (Major Radius in cm)	64	58	64	64
$\bar{n}$ (Average Density in cm^{-3})	7×10^{14}	8×10^{14}	10^{15}	7×10^{14}
I_p (Toroidal Current in Mega-amperes)	0.75	0.38	1	0.7
τ_E (Energy Confinement in milliseconds)	40	30	100	60
$n_0\tau_E$ (Lawson Parameter in cm^{-3}-s)	0.3×10^{14}	0.35×10^{14}	10^{14}	0.5×10^{14}
T_{io} (Central Ion Temperature in keV)	1.6	1	2	3.5
P_{RF} (Lower Hybrid at 4.6 GHz in megawatts)	0.15	-	-	4

Table 3. Alcator C Parameters

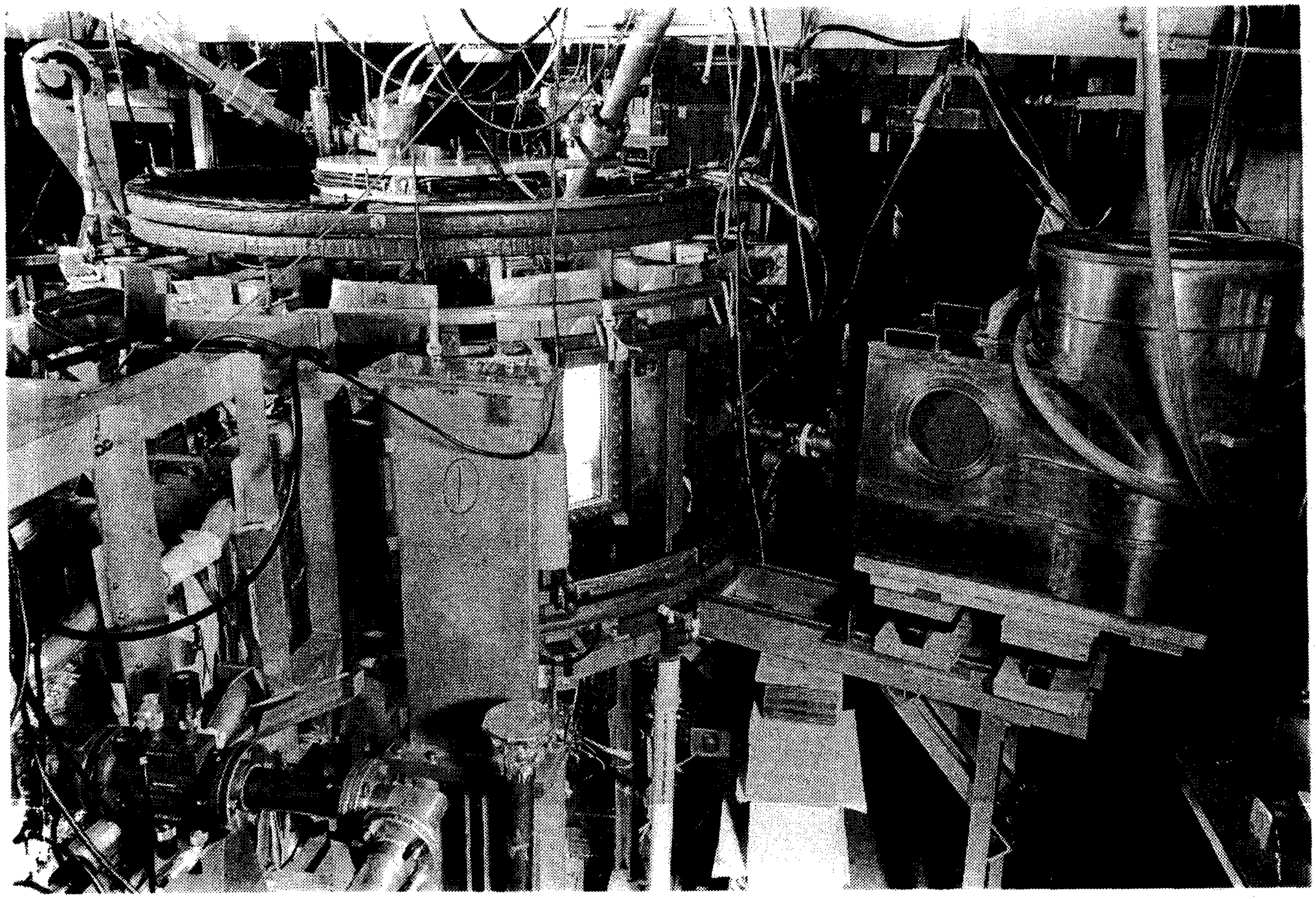
Parameter	Design Value
Central Cell	
a (Plasma Radius)	15 cm
L (Length)	5 m
B (Magnetic Field)	2 kG
n_0 (Central Density)	$4 \times 10^{12} cm^{-3}$
T_{eo} (Central Electron Temperature)	400 eV
T_{io} (Central Ion Temperature)	400 eV
Barrier-Plugs	
R (Mirror Ratio)	5 - 10
B_{MAX} (Maximum Field)	50 kG
E_b (Neutral Beam Energy)	20 keV
I_b (Beam Current)	150 A
P_{RF} (ECRH at 28 GHz)	200 kW/plug

Table 4. TARA Design Parameters

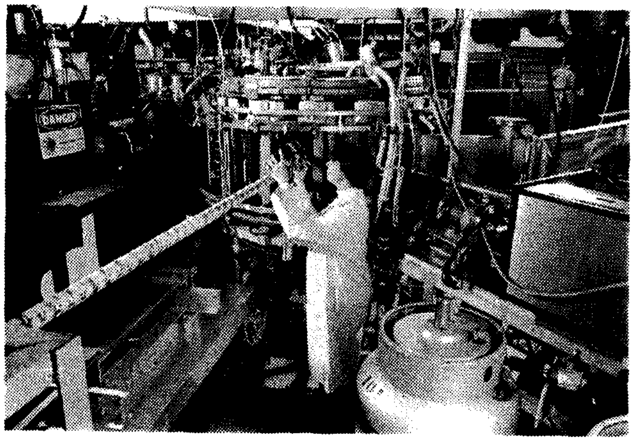
Parameter	Value
B (Magnetic Field)	6.0 T
E_s (Stored Energy)	10.7×10^6 J
V (Test Volume)	7.6 cm × 30 cm × 76 cm
I (Current to Test Module)	20 kA
M (Maximum Test Module Mass)	800 kg

Table 5. Racetrack Pair Test Facility Parameters

VERSATOR TOKAMAK

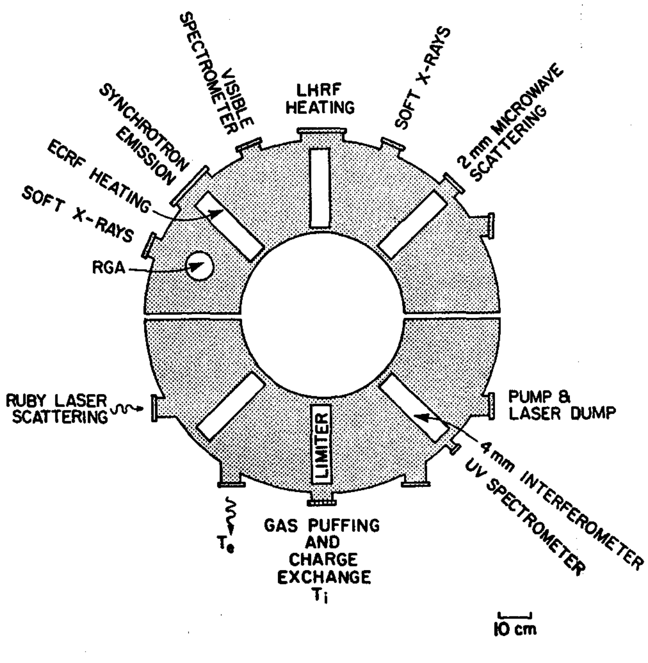


ECRH antenna shown entering plasma from top center of photograph. Soft x-ray detector is visible at right and a portion of the lower-hybrid phase shift system is visible at the left center.



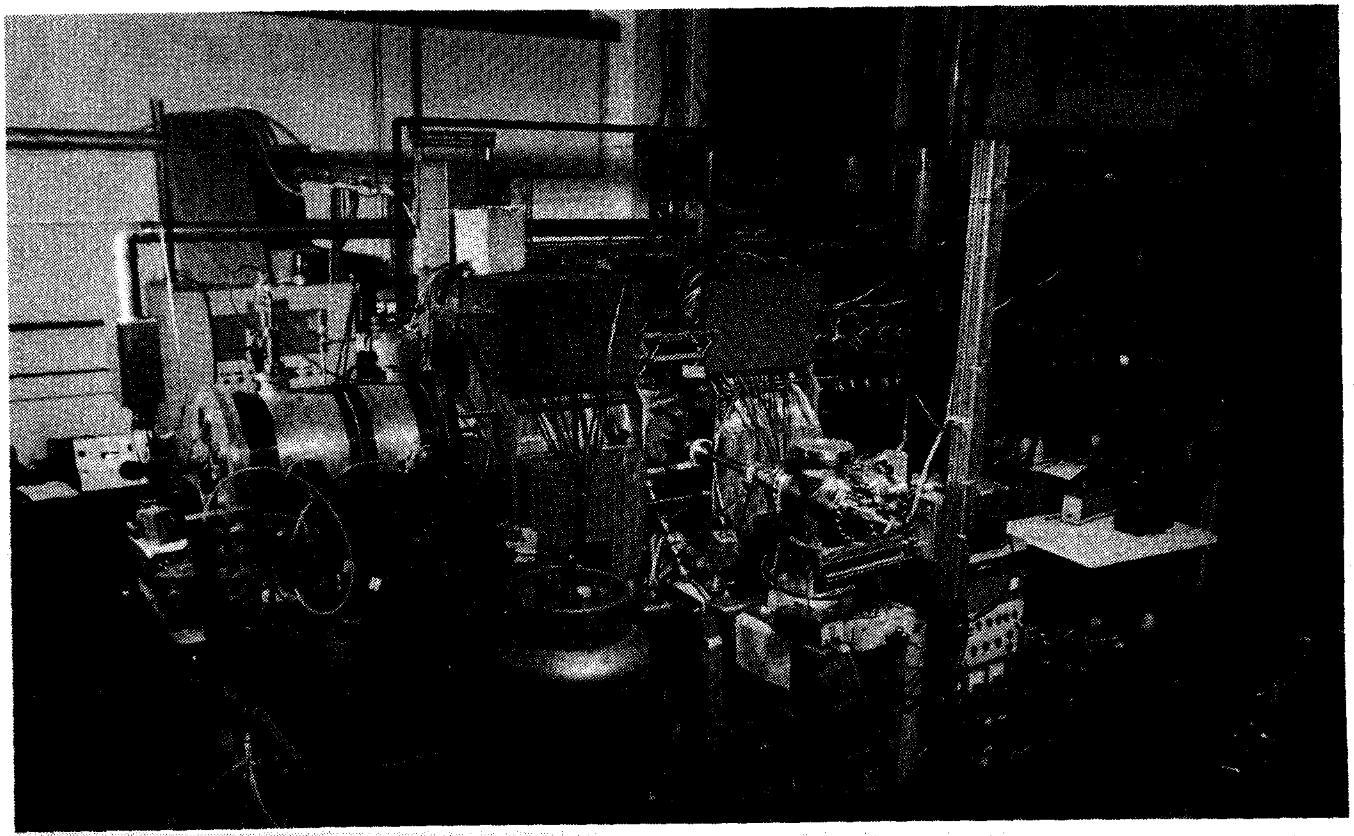
Ruby laser (left) and UV Spectrometer (right) are diagnostics recently added to Versator.

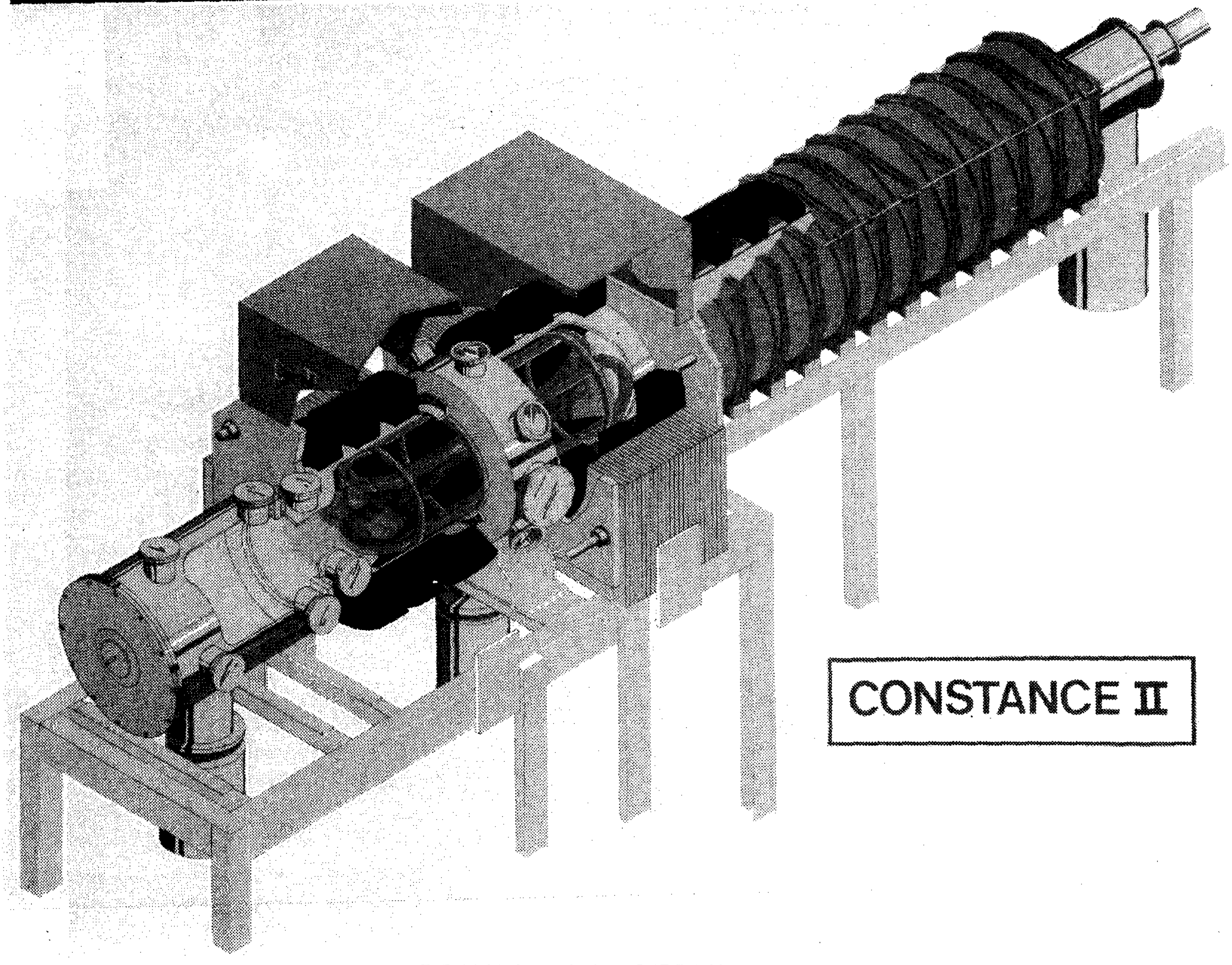
DIAGNOSTIC AND RF HEATING PORTS



Plane view schematic showing diagnostic and RF heating ports.

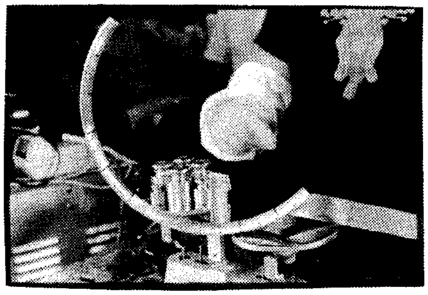
CONSTANCE II MIRROR MACHINE



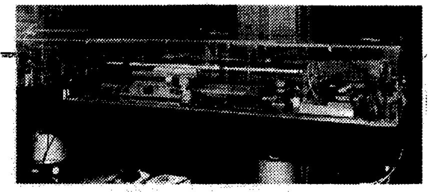


ARTIST'S CONCEPTION: CUTAWAY

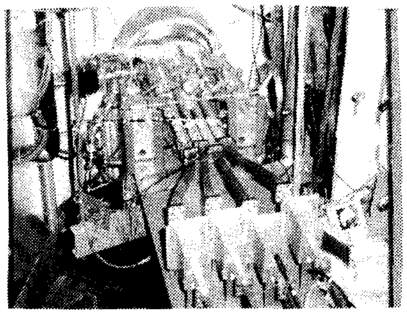
ALCATOR C TOKAMAK



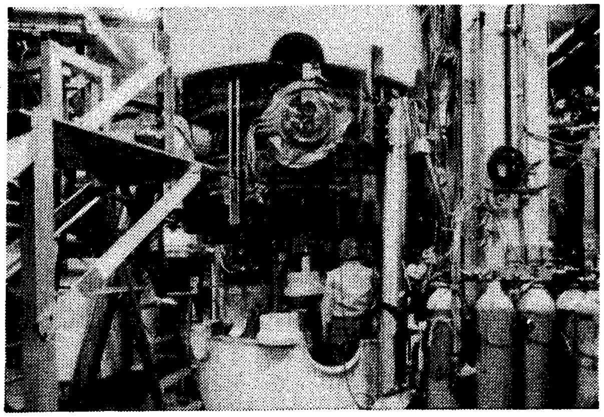
Limiter



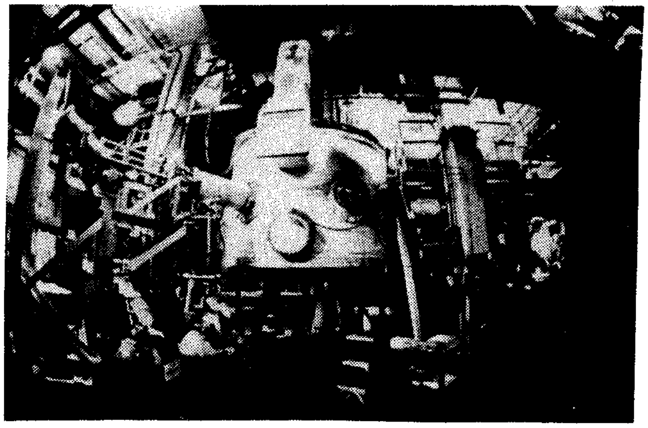
Alcohol Laser



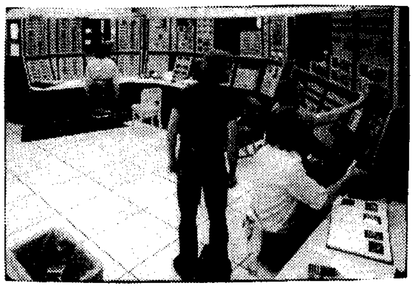
Four Wave Guide



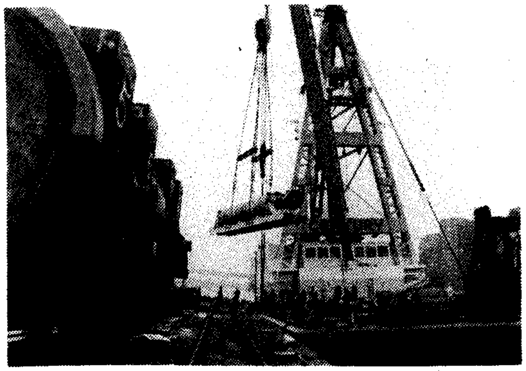
Alcator C with Dewar Open



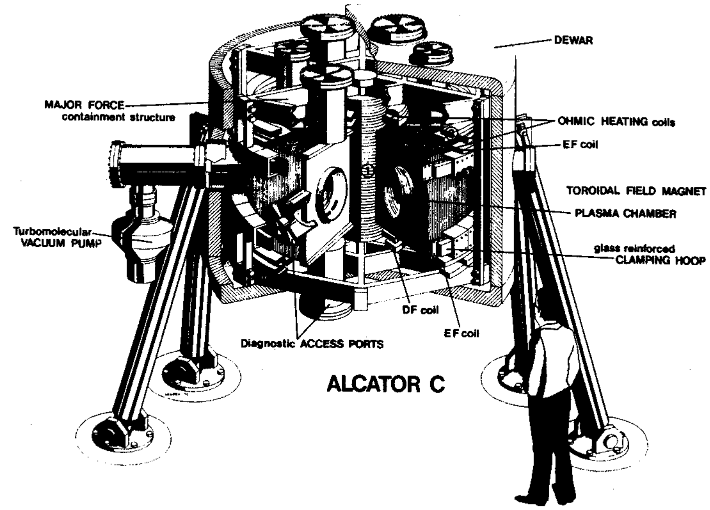
Alcator C



Control Room

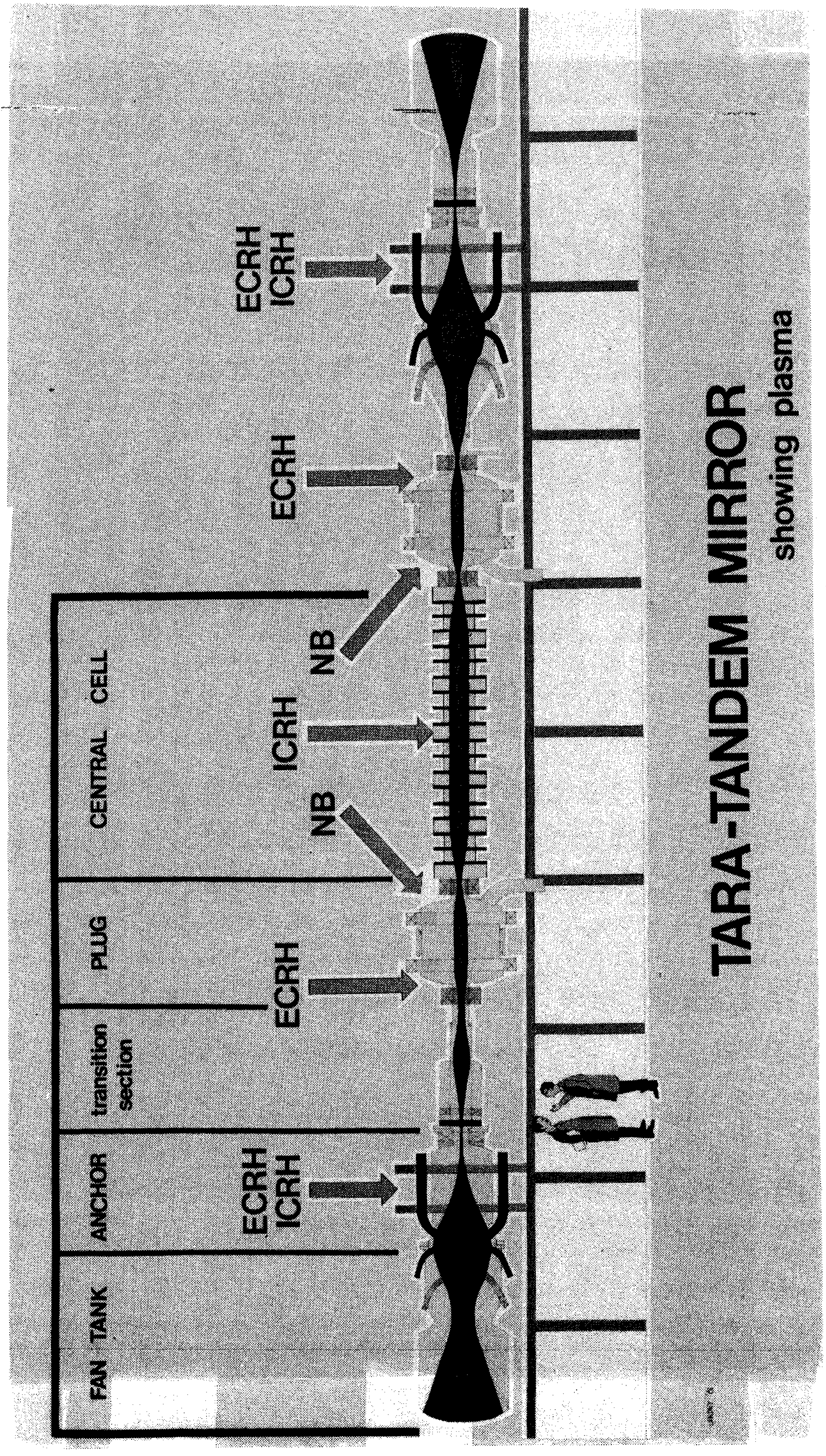


225 MW Generator with Rotor and Stator Visible



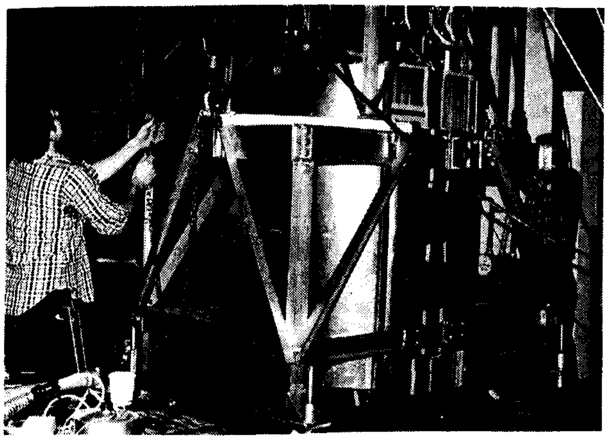
Alcator C Schematic

TARA TANDEM MIRROR



ARTIST'S CONCEPTION OF THE TARA-TANDEM MIRROR MACHINE

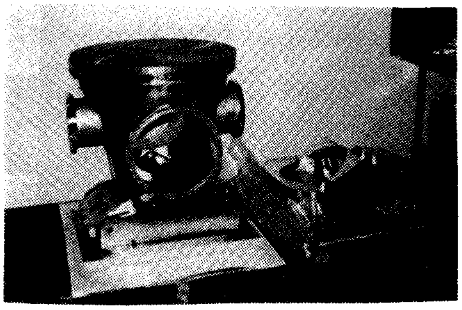
TECHNOLOGY AND ENGINEERING



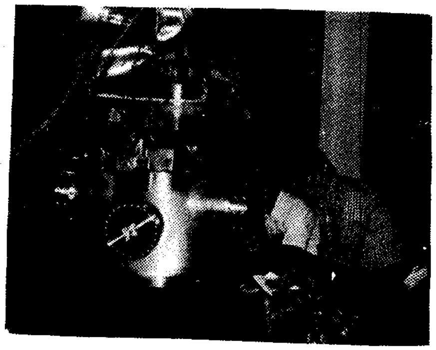
Racetrack Magnet
Test Facility

Facility Layout

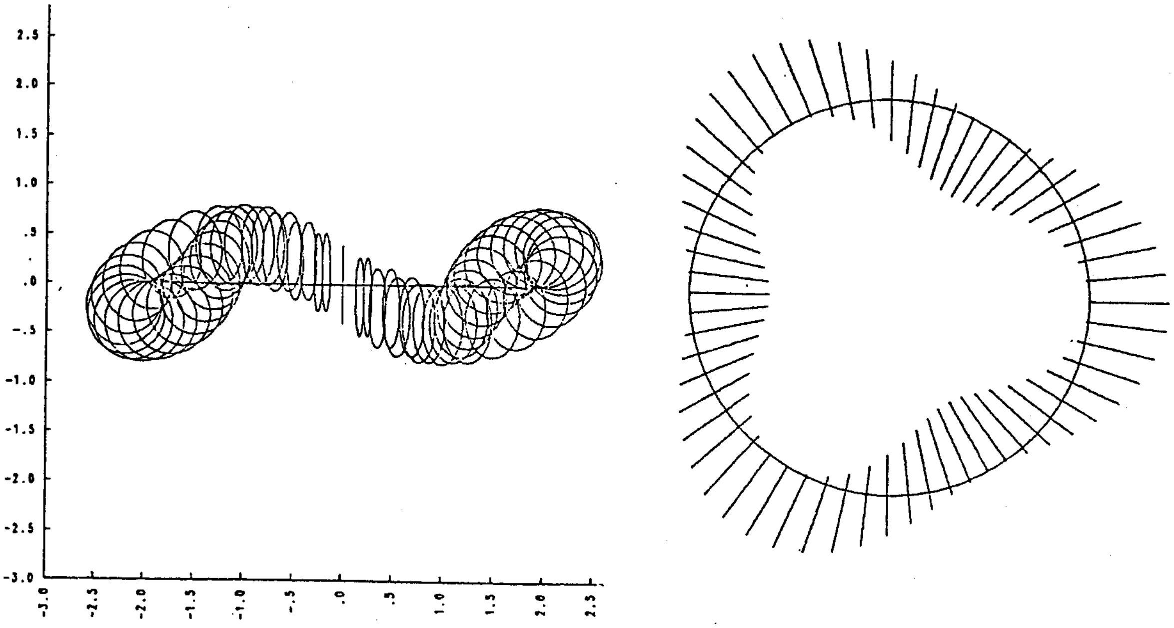
ISX-B Divertor Coils



Casing



Final Assembly



"Dragon" Stellarator: Computer Model
of Toroidal Field Magnet System

MIT PLASMA FUSION CENTER

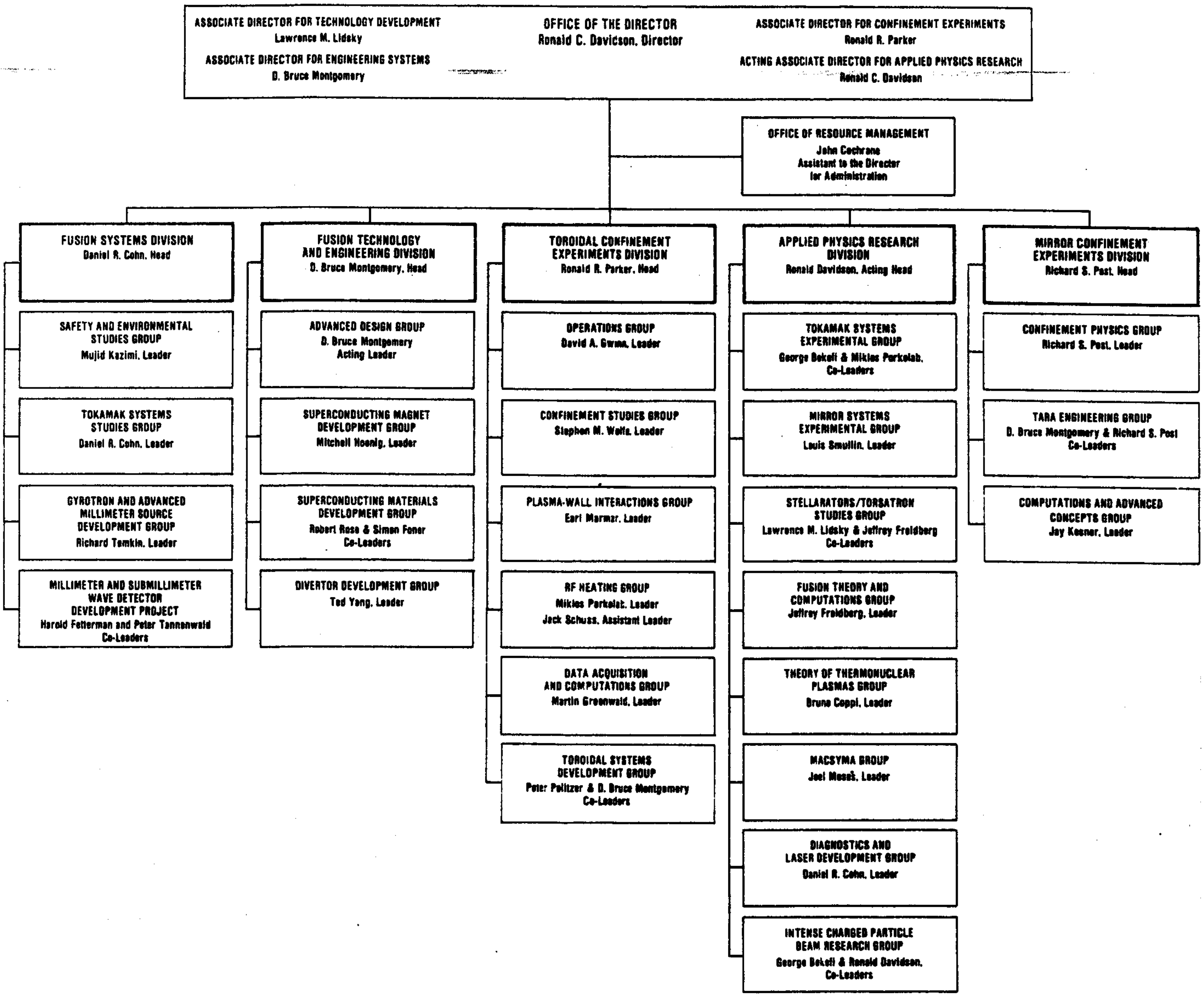


Figure 1: MIT Plasma Fusion Center

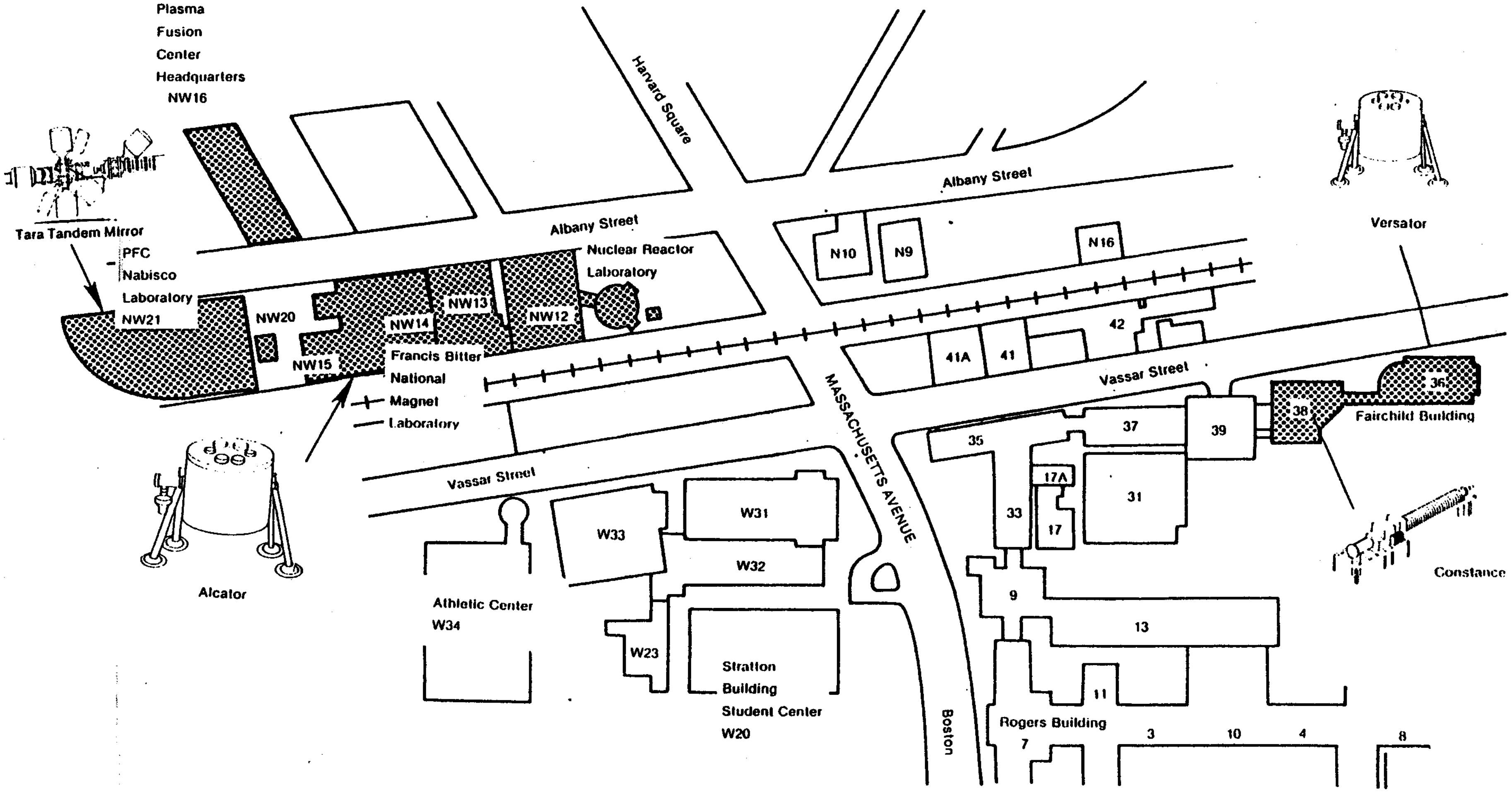


Figure 2: Partial Area Map of MIT Campus Highlighting PFC Facilities

PLASMA FUSION CENTER

I. APPLIED PHYSICS RESEARCH DIVISION

RONALD C. DAVIDSON, ACTING HEAD

A. OBJECTIVES:

Develop the basic experimental and theoretical understanding of plasma heating and confinement properties. Develop advanced fusion concepts consistent with the best available models of plasma physics and the technological requirements of fusion reactors.

B. GROUPS:

- Tokamak Systems Experimental Research
  George Bekefi and Miklos Porkolab, Co-Leaders
- Mirror Systems Experimental Research
  Louis D. Smullin, Leader
- Stellarator/Torsatron Studies
  Lawrence M. Lidsky and Jeffrey P. Freidberg, Co-Leaders
- Fusion Theory and Computations
  Jeffrey P. Freidberg, Leader
- Theory of Thermonuclear Plasmas
  Bruno Coppi, Leader
- MACSYMA
  Joel Moses, Leader
- Diagnostics and Laser Development
  Daniel R. Cohn, Leader
- Intense Charged Particle Beam Research
  George Bekefi and Ronald C. Davidson, Co-Leaders

The primary objective of the Applied Physics Research Division is to develop the basic experimental and theoretical understanding of plasma heating and confinement properties. This is required for effective planning and interpretation of data from large-scale confinement experiments. Given the uncertainties along the path to the development of fusion energy, it is important to appreciate the need for vigorous ongoing research in basic plasma physics. In the plasma theory area, this is accomplished by the continued development of new analytic and numerical tools for handling complex plasma problems, and by the evolution and improvement of existing models together with the development of new models. In the experimental research area, the continued development of new and improved diagnostic techniques is required to provide a basic understanding of plasma heating and confinement properties.

1. TOKAMAK SYSTEMS EXPERIMENTAL RESEARCH GROUP

George Bekefi and Miklos Porkolab, Co-Leaders

A. OBJECTIVES:

Study basic properties of hot tokamak discharges in Versator II with emphasis on RF heating and RF current generation.

B. RESEARCH PROJECTS:

- RF current generation with lower-hybrid waves
- RF heating with lower-hybrid waves
- RF heating at the electron cyclotron frequency

C. PERSONNEL:

Faculty:

G. Bekefi, M. Porkolab

Research Staff:

S. C. Luckhardt, K-I. Chen

Technical Support Personnel:

E.W. Fitzgerald, J.C. Nickerson, T. Evans

Graduate Students:

A.S. Fisher, K.E. Hackett, S.F. Knowlton
M.J. Mayberry, F.S. McDermott, R.R. Rohatgi

Undergraduate Students:

M. Huber, J.B. Schutkeker

Secretary:

V. Kaloyanides

D. SPECIAL EQUIPMENT AND FACILITIES:

Experimental Facilities:

- Versator II Tokamak ($a = 13$ cm; $R = 40.5$ cm; $B_T = 15$ kG)
- Lower-hybrid RF system (800 MHz, 150 kW, 4 or 6 waveguide antennas).
- ECRH System (35 GHz, 150 kW, inside launch X or 0 mode)

E. TECHNICAL PROGRAM SUMMARY:

Versator II is a medium-size research tokamak with primary emphasis on basic investigations of RF heating and current drive in plasmas. The toroidal windings in Versator II are energized by a 700 kJ capacitor bank. By discharging this bank, a magnetic field of 15 kG can be generated on axis. The plasma current is driven by means of an air core transformer positioned at the center of the torus. In addition to this transformer, compensating windings are provided to optimize the flux through the plasma. Moreover, there are vertical field coils and a breakdown oscillator at 28 kHz also used for discharge cleaning.

The characteristic parameters are summarized in Table 1, and the array of the diagnostic measurements is enumerated below:

- Measurement of perpendicular and parallel electron temperature by Thomson scattering
- Measurement of collective density fluctuations by 2 mm microwave scattering
- 2 mm microwave scattering from lower-hybrid waves
- Charge exchange measurement of ion temperature
- Microwave interferometric measurement (4 mm) of electron density
- Langmuir probe measurement of electron density profiles near the plasma edge
- Soft X-ray spectroscopy for electron tail measurements
- Bolometers
- UV and visible spectroscopy for T_i diagnostics

Parameter		Value
a	(Minor Radius)	13 cm
R	(Major Radius)	40.5 cm
B_T	(Toroidal Field)	15 kG
$\hat{n}$	(Average Density)	$1\text{-}4 \times 10^{13} \mathrm{cm}^{-3}$
τ_p	(Pulse Length)	20-40 ms
I_p	(Plasma Current)	40 kA
T_{eo}	(Central Electron Temperature)	350 eV
T_{io}	(Central Ion Temperature)	120 eV

Table 1. Versator II Characteristics

The Versator II research program consists of three major components:

- A feasibility study of current drive using lower-hybrid waves (800 MHz, 150 kW)
- RF heating of tokamak plasmas with lower-hybrid waves
- Electron cyclotron heating (35 GHz, 100 kW)

Initial current-drive studies with lower-hybrid waves have now been completed successfully. Twenty to thirty kA of RF current have been generated in slide-away tokamak discharges, with corresponding efficiencies of 1-2 kA/kW. Experiments in the near future will concentrate on combined lower-hybrid current drive and electron cyclotron heating. Preliminary results of electron cyclotron heating experiments indicate up to a 65% increase in central electron temperature. Future ECRH experiments over the next six months will concentrate on the dependence of the heating on antenna and plasma parameters. Lower-hybrid ion heating studies are also underway and will continue over the next twelve months. Preliminary results indicate successful ion heating with central ion temperature increases of 30-40%.

Successful studies of waveguide breakdown have paralleled the basic lower-hybrid experiments. A breakthrough in antenna power handling capability has been achieved recently at Versator. In experiments where any auxiliary magnetic field was applied to the waveguide antenna, nearly an order of magnitude increase in the antenna power handling capacity was obtained. Future experiments on waveguide breakdown are expected to increase this power handling still further.

Future plans for the lower-hybrid current drive experiment include electron tail studies with soft X-ray spectroscopy and studies of current drive in high density plasmas. In mid-1982 a modification of the Versator II tokamak will be carried out to allow fully-RF-driven tokamak operation without an ohmic heating transformer. This modification of Versator II will allow studies of quasi-steady-state RF-driven tokamak discharges which will be necessary before construction of a steady-state RF-driven continuously-operating tokamak.

2. MIRROR SYSTEMS EXPERIMENTAL RESEARCH GROUP

Louis D. Smullin, Leader

A. OBJECTIVES:

Study basic microinstability properties of mirror-confined plasmas. Study plasma heating by ECRH, ICRH, and electron beams. Produce and investigate stability properties of sloshing ion distributions.

B. RESEARCH PROJECTS:

- ECRH plasma heating
- ICRH plasma heating and production of sloshing ion distribution
- Beam-plasma heating
- Theory of modulated beam-plasma interaction

C. PERSONNEL:

Faculty:

L.D. Smullin

Research Staff:

W.D. Getty, J.H. Irby

Technical Support:

K. Rettman

Graduate Students:

A. Ezzedine, R. Garner, M. Mauel

Undergraduate Students

S. Bradley, D. Furuno, W. Luthiger, M. Milbocker

Secretary:

R. Bella

D. SPECIAL EQUIPMENT AND FACILITIES:

Experimental Facilities:

- Constance II Mirror Device (5 kG midplane; R = 2; 1 meter long; quadrupole Joffe bars; 25.4 cm inner diameter)

- Thomson scattering system (5 J ruby laser; 5 channel polychromator)
- 0.1 to 1 MW X-band pulsed ECRH system; ECRH with X-band magnetron
- 100 kW, 5 MHz ICRH system; ICRH 100 kW pulsed source
- 150 kW E-beam system
- Computerized data collection
- Electron Beam Facility (10-20 kV; 100-500 kW).

E. TECHNICAL PROGRAM SUMMARY:

The large tandem mirror facilities, TARA and TMX-Upgrade, are designed to incorporate ECRH and ICRH auxiliary heating systems as essential elements in the end plugs and in the thermal barrier cells. The Constance experimental program is designed to answer important physics questions about these heating schemes. The plasma in Constance II is generated by a new hot-cathode (LaB_6) plasma gun. Densities in the mirror lie in the range 10^{12}-$10^{13}cm^{-3}$, with an ion temperature T_i in the 100-150 eV range. The neutral gas density is about $3 \times 10^{10}cm^{-3}$, and is almost entirely H_2. The plasma characteristics are highly repeatable from shot to shot.

Electron cyclotron resonance heating is studied with the RF waves launched at several angles to the magnetic field. Bulk heating and hot-electron-tail formation are monitored by soft and hard X-ray detectors, Thomson scattering, diamagnetism, and VUV measurements. Enhanced end loss is studied by an electrostatic end-loss analyzer. High frequency fluctuations are measured by high impedance probes.

Ion cyclotron resonance heating is used to raise the ion temperature above the 100-150 eV level that seems to be characteristic of most plasma guns. Secondary emission energetic neutral detectors will be used to explore the ion velocity distribution along the axis of the plasma. Secondary emission energetic neutral detectors will be used to explore the ion velocity distribution along the axis of the plasma.

Electron-beam-plasma interactions using a 10 kV, 10 A electron beam will be used to heat the plasma electrons. This approach was successfuly demonstrated on Constance I, with the concommitant stabilization of the DCLC instability. Subsequent tests on the 2XII-B at Livermore failed to show any significant interaction. Since there is an extensive literature on electron heating by electron beams, this is a surprising result. The magnetic field geometry in 2XII-B was a minimum-B "baseball" configuration, whereas most beam heating experiments have been carried out in simple mirrors. In Constance II, the quadrupole field is independent of the mirror field and can be varied from zero to the full minimum-B condition. Therefore beam-plasma interactions will be able to be studied over this entire range.

Acousto-Optical RF Spectrum Analyzer: In many plasma devices, Constance II, tokamaks, pinches, etc., the discharges occur with very low repetition rates. In the study of microinstabilities, it is important to be able to detect a wide band RF spectrum in a short time, and with high resolution. This is not possible with the conventional superheterodyne, swept analyzer. The acousto-optical device can scan a 500 MHz band in about 10 μs, with a resolution of 2 MHz. With the aid of auxiliary oscillators and mixers, this band can be located anywhere in the range of 0.1 to about 4-5 GHz. The design of such an instrument has been completed and components are being procured.

3. STELLARATOR/TORSATRON STUDIES GROUP

Lawrence M. Lidsky and Jeffrey P. Freidberg,
Co-Leaders

A. OBJECTIVES:

Develop stellarator/torsatron designs for next generation experiments consistent with the best available models of plasma physics and the technological requirements of the eventual reactor applications.

B. RESEARCH PROJECTS:

- Torsatron reactor conceptual design
- Modularized field coils for stellarator/torsatron systems
- Stellarator/torsatron experimental design study
- Equilibrium, stability and transport models of stellarator physics.

C. PERSONNEL:

Faculty:
L.M. Lidsky, J.P. Freidberg, K. Molvig
Research Staff:
R. Potok, P.A. Politzer, D.R. Cohn
Graduate Students:
J. Aspinall, J. Johnson, T. Uchikawa, P. Roemer, W.H. Choe
Administrative & Support Staff:
L. DiMauro, C. Lydon, L. Thomas

D. TECHNICAL PROGRAM SUMMARY:

Until recently, fusion reactor design studies have attempted to extrapolate particular plasma confinement geometries to reactor scale. On such a scale, these designs have encountered several technological and economic penalties. This result is not surprising. The boundaries of acceptable engineering are more sharply drawn than those of potential plasma confinement schemes and there is no a priori reason to expect them to overlap. It was concluded that the most efficient search scheme required an inversion of the usual process. A list of desirable reactor properties (steady-state, ignited, etc.) was developed, and a search of the literature was made for a confinement scheme compatible with these requirements. The most promising output of this search is the torsatron configuration but the technique of applying "desirability-weighted" technology criteria is also proving useful in assessing other candidate confinement schemes and fuel cycles.

Particle transport properties in torsatron/stellarator geometry are less sensitive to detailed field shape than previously believed. This offers opportunity for design of coil sets which are entirely separable, i.e., linked neither around the system axis nor to any other coil. Several candidate modularization schemes will be studied and the effect of coil perturbations on the flux surface shape and particle trajectories will be assessed.

The maximum stable beta in stellarator/torsatrons is an important limitation in the operation of future experiments and reactor extrapolation. In particular, we must learn to optimize the magnetic field configuration with respect to beta limits as well as transport to guarantee that physics operation is possible in interesting reactor regimes. Several calculations are underway to carry out these tests.

All of these separate issues are to be combined into the most important part of the activity, that of designing a next generation stellarator/torsatron experiment consistent with physics and technology needs and representing a believable extrapolation from our current knowledge.

4. FUSION THEORY AND COMPUTATIONS GROUP

Jeffrey P. Freidberg, Leader

A. OBJECTIVES:

Develop basic theoretical understanding of plasma heating and confinement properties of high-temperature fusion plasmas. Interpret experimental data to formulate self-consistent scaling laws and to plan meaningful experiments.

B. RESEARCH PROJECTS:

- RF Heating and Nonlinear Waves in Toroidal Plasmas
  A. Bers, Project Leader
- Equilibrium Stability and Transport in Fusion Plasmas
  R. Davidson, J. Freidberg and K. Molvig, Project Co-Leaders
- Nonlinear and Turbulent Phenomena in High-Temperature Plasmas
  T. Dupree, Project Leader
- Computational Services and Technology
  J. Freidberg, Project Leader
- Stability and Transport Properties of Linear and Toroidal Fusion Systems
  J. McCune, Project Leader

C. PERSONNEL:

Faculty:

A. Bers, R. Davidson, T. Dupree, J. Freidberg, J. McCune, K. Molvig, T. Boutros-Ghali

Research Staff:

R. Berman, R. Estes, M. Gerver, G. Johnston, V. Krapchev, B. Lane, W. McMullin, A. Rechester, D. Tetreault

Technical Support Staff:

R.L. Lawhorn, D.C. Plummer

Visiting Scientists:

A. Ram, M.L. Xue, G. Berge, P. Roseneau, Y. Pau

Graduate Students:

K. Cogswell, L. Harten, K. Hizanides, G. Svolos, D. Thayer, W.H. Choe

Secretarial Staff:

H. Budd, A. Karoghlanian, C.A. Lydon, C. Robertson, L.Z. Thomas

D. SPECIAL EQUIPMENT AND FACILITIES:

Computer Equipment:

- 1 PDP-11/10 processor with 24,000 words of memory
- 1 Grinell TV system
- 36 Ball Brothers display monitors
- 1 Gould printer/plotter
- 1 Imlac PDS-4 display system
- 1 PDP-11/05 processor with 16,000 words of memory
- 1 Tektronix 4013 terminal
- 1 Tektronix 4012 terminal
- 1 Tektronix 4051 terminal
- Mini-User Service Center
- Versatec Printer

E. TECHNICAL PROGRAM SUMMARY:

The main objective of fusion theory research is to provide the basic physics understanding necessary to interpret present and past experiments and to formulate the appropriate scaling laws needed for meaningful experimental planning and prediction of the performance of future devices. Both analytical and computational studies are performed and the data obtained on experimental devices operating at different temperatures, densities and magnetic fields are evaluated to refine and modify existing theories of plasma behavior as well as to formulate new theories.

Plasma theorists at MIT investigate many aspects of plasma behavior by examining the influence of parameter changes on equilibrium stability and transport properties. This capability makes theory an important interface between experiments based on similar confinement configurations. In addition, mature theories, tested and refined by repeated comparison with experiment, can be used to predict plasma behavior. Such theories form the basis for major program economies since they permit significant progress along different confinement approaches without a full complement of devices in each.

The primary plasma theory areas under intense investigation at MIT include:

- RF heating and nonlinear wave coupling in toroidal plasmas with emphasis on applications to Alcator C and Versator II. Theory of nonlinear waves in plasmas, and induced stochasticity in particle dynamics by coherent waves.
- Confinement properties of fusion plasmas. These studies include: MHD equilibrium and stability properties of tokamak and torsatron/stellarator configurations; microinstabilities and anomalous transport in high-temperature plasmas, and formulation of self-consistent scaling laws needed for meaningful experimental planning.
- Nonlinear and turbulent phenomena. The purpose of these investigations is to develop the basic understanding of a wide variety of nonlinear and turbulent phenomena, including stochastic magnetic fields, clumps and nonlinear saturation of linear instabilities.
- Stability and transport properties of toroidal and linear fusion systems, including investigations of the effects of ambipolar fields on transport and stability properties of toroidal plasmas, high-beta stability properties of the tandem-mirror configuration, and microstability and transport properties of mirror systems with emphasis on applications to Constance II and the TARA tandem mirror.

During FY81 and FY82, theoretical research in these project areas will intensify with a continued emphasis on increasing theoretical support in critical problem areas for the Alcator, TARA, Versator and Constance experimental programs. It should be emphasized that well-formulated theories with sound experimental confirmation may be used in a predictive manner to identify important problems that will be encountered in the physics and engineering of reactor plasmas. This ability provides the magnetic fusion program with continuity and momentum that is otherwise difficult to achieve. Many recent dramatic advances in the fusion program have been facilitated and stimulated by corresponding advances in the theoretical formulation of new ideas and concepts. These advances, in turn, have rested on the rapid growth of basic theoretical and experimental knowledge concerning the plasma state.

Research in these areas is greatly facilitated by the use of high-speed computers and access to the National Magnetic Fusion Energy Computer Center (NMFECC) at Lawrence Livermore National Laboratory. In order to provide the maximum effective access to the NMFECC, we have recently established a computational support activity to provide computation-related services to the entire PFC user community. The responsibilities of this activity include the implementation and maintenance of local facilities for connecting to the NMFECC via existing network ports and the local computer network (CHAOS). In addition, the computational support activity provides centralized administration of the PFC time allocation at the NMFECC and maintains and distributes documentation for users. Because of the importance of computing in both experimental and theoretical programs, it is imperative that PFC researchers have convenient and efficient access to the NMFECC.

During FY81, the TV system was installed and is now operating in Building NW16, the PFC office facility on Albany Street.

There are currently about 16 TV monitors in NW16, and 20 TV monitors in Building 38, on the main campus. Also, a Versatec printer was installed and is operating in NW16. During FY82 we will receive a VAX-780 computer to be located in NW16. Site preparation should be completed by January 1982 and the VAX should be installed shortly thereafter.

5. THEORY OF THERMONUCLEAR PLASMAS GROUP

Bruno Coppi, Leader

A. OBJECTIVES:

The long-range objective of this program is the theoretical study of plasmas at near thermonuclear conditions. The spectrum of research activities ranges from the design of compact ignition experiments to the basic study of plasma transport processes.

B. PERSONNEL:

Faculty:

B. Coppi

Research Staff:

P. Bonoli, R. Englade, J. Ramos, N. Sharky, L. Sugiyama

Graduate Students:

G. Crew

Secretarial Staff:

C. LoRusso

C. SCOPE OF RESEARCH ACTIVITIES AND RELATIONSHIP TO OTHER PROJECTS:

The main theme of this research program is the theoretical understanding of plasmas in regimes of thermonuclear interest and the study of associated transport properties with special emphasis on the effects of collective modes.

Since the fusion program depends on the evolution of a variety of disciplines and can benefit significantly from ideas developed in other fields, collaborative efforts are maintained with members of the scientific community in the Cambridge area whose scientific interest can impact this research program. In particular, fruitful connections have been established with the MIT Applied Mathematics Department, the Center for Theoretical

Physics, the Center for Space Research, the Center for Astrophysics at Harvard, American Science and Engineering, and Raytheon. Two of these institutions have now developed their own direct contracts with DOE.

Another function that has been emphasized is to encourage and maintain a flow of visitors from and in collaboration with overseas institutions. As a result of this, several of the numerical codes currently used have been developed in collaboration with the Institut fur Plasmaphysik in Garching and the Centro di Calcolo CNEN in Bologna.

One of the major tasks of this group is to provide theoretical and numerical support for the Alcator experimental program. In fact, most of the research problems have been suggested by experimental observations in Alcator and, in a broad sense, are directed toward providing an explanation for these observations. The research is also directed at providing guidance for new directions to be taken by the magnetic confinement program.

This research activity involves a number of students, including several experimentalists, through direct participation in research projects, advising, and the teaching of courses on the physics of thermonuclear plasmas. An active exchange of ideas is maintained with the major U.S. laboratories and universities engaged in fusion research.

D. TECHNICAL PROGRAM SUMMARY:

Special areas of research emphasis include: (a) the effective electron thermal conductivity and the anomalous particle transport that determine the plasma parameters obtained in present-day experiments; (b) the transport of impurities and their influence on the heating cycles of experiments designed to achieve ignition conditions; (c) the maximum plasma pressure relative to the magnetic pressure that can be attained in axisymmetric toroidal configurations; (d) the maximum current density that can be achieved without exciting small (internal) and large-scale disruptions of the confined plasma column; (e) the general problem of magnetic reconnection in collisionless plasmas; (f) the investigation of compact experiments to study the possible burning of advanced fuels (D-D and D-He^3); (g) theoretical support of the Alcator confinement program; and (h) the combination of auxiliary RF heating and plasma transport analysis in parallel with the experimental effort on auxiliary heating that is being developed around the Alcator program.

Over the years, this group has made numerous significant research contributions to basic plasma physics and to the physics of thermonuclear plasmas. For purpose of illustration, we briefly summarize here a few selected research accomplishments.

An analysis has been completed of various forms of internal modes, producing magnetic reconnection, that in a toroidal plasma column would correspond to relatively low poloidal wave numbers, in high temperature regimes where the effect of electrical resistivity becomes unimportant and mode-particle resonance takes its place. Interest in this area of research stems from the fact that, if values of the rotational transform as high as $\iota_o \simeq 2$ ($q_o \simeq \frac{1}{2}$) could be attained at the center of the plasma column without exciting macroscopic instabilities (i.e., ideal MHD modes), then there would be a significant increase in the rate of ohmic heating and in the maximum plasma pressure that could be achieved in a given confinement configuration. It is found, in contrast to previous analyses, that the problem requires a four-asymptotic-region treatment unlike the resistive case where only two regions (one where the ideal MHD approximation is valid and the other where resistivity is important) are to be considered. It is found, in contrast to previous analyses, that the problem requires a four-asymptotic-region treatment unlike the resistive case where only two regions (one where the ideal MHD approximation is valid and the other where resistivity is important) are to be considered.

In addition, research has continued on providing a derivation and a consistent microscopic picture for the expression for the electron thermal conductivity first proposed in 1978 in order to reproduce the electron temperature profiles that had been observed in a variety of toroidal experiments. These findings have been confirmed by further analysis carried out after the 1979 Varenna Conference by Duchs and Pfirsch at Garching, Goldston at Princeton, and others. Therefore, considerable emphasis has been placed on studying the consequences of the relevant form of the diffusion coefficient on the heating cycles that can be expected in Alcator C with and without an auxiliary heating system (such as the one at the lower hybrid frequency that is being designed), and in future experiments that are expected to attain regimes of thermonuclear interest.

Because of the expertise acquired in analyzing the transport properties of toroidal plasmas, a joint program with M. Porkolab has been initiated concerning the interpretation of the results of the experiments on lower hybrid heating in the Alcator and Versator tokamaks. In particular, the one-dimensional plasma transport code has been modified to include local heating rates for electrons and ions produced by the absorption of a spectrum of lower hybrid waves launched at the edge of the plasma. The local heating rates include the effects of quasilinear modification of the equilibrium distribution functions due to the waves. In the case of electrons, a one-dimensional Fokker-Planck equation is solved at each radius to determine the shape of the distribution function. This in turn determines the amount of electron Landau damping and local generation of RF current. The most recent version of the code self-consistently includes the effect of the DC electric field in the solution of the Fokker-Planck equation. This code has been used to study RF current generation for Versator II parameters.

A set of physical factors has been identified, mainly the significant dependence of both the poloidal magnetic field and the rate of magnetic shear on the poloidal coordinate, that enhance the stability of an axisymmetric toroidal configuration when the parameters $G \equiv \beta R q^2/r_p$, with $1/r_p \equiv -d\ell np/dr$, becomes finite. Thus an expanded "first ideal-MHD-stability region" has been found that roughly corresponds to $G < G_c^{(1)}(s)$ with $s \equiv d\ell nq/d\, nr$, and a "second stability region" that corresponds to $G > G_c^{(2)}(s) > G_c^{(1)}(s)$. The first oral presentations of these results were given at the Sherwood Theory meeting in 1978 and then at the 1978 Gordon Conference in Santa Barbara. These first reports were received with interest but also with some objections. However, the fact that the relevant stability problem involves an equation with nonlinear coefficients in G, rather than a linear coefficient in G as it was previously thought, was soon confirmed by the analytical work of other authors and later by the numerical study of flux-conserving finite-beta equilibria. These studies were carried out both by this group and by other major U.S. theoretical groups. By now, relatively high values of beta are commonly accepted. Meanwhile, given the interest of other groups in the subject, the MIT activity has been limited to the development of an analytical representation of the main results.

In addition, this group has continued to assist in the development of the Alcator program in a variety of areas, including:

- Evaluating regimes of operation for Alcator C by comparing them with those of other experiments such as FT, PLT, and ISX by numerical simulation and analytical representation of empirical transport coefficients.
- Evaluating elongated equilibria, and their stability properties, to be obtained in the Rector experiment.
- Collaboration in the design of upgrades to Alcator C.
- Extensive theoretical support of the lower hybrid heating program as indicated earlier.

In addition to the research activities summarized above, this group is carrying out theoretical investigations in a variety of other fusion theory areas including: (a) particle and impurity transport in toroidal systems, (b) studies of advanced fuel burning in compact experiments, (c) effects of kinetic (non-ideal MHD) modes on finite-beta configurations, and (d) excitation of toroidal magnetic fluctuations by charged particles produced in fusion reactions.

6. MACSYMA GROUP

Joel Moses, Leader

A. OBJECTIVES:

Research and development of the MACSYMA symbolic manipulation system including provisions for use of the system by the national magnetic fusion community. Support is also provided for access to the NMFECC by MIT fusion scientists and engineers.

B. RESEARCH PROJECTS:

- Algorithm development for symbol manipulation.
- Development of techniques for improving use of numeric routines in symbolic systems.
- Development of the LISP language for computers other than PDP-10.
- Development, maintenance and operation of the PDP-10 computer at MIT.

C. PERSONNEL:

FACULTY:

J. Moses, R. Zippel

Research Staff:

G. Carrette, E. Golden, J. Golden, R. Greenblatt, R. Pavelle

Graduate Students:

C. Hoffman

Secretarial Staff:

R. Hegg, M. Marcucci

D. SPECIAL EQUIPMENT AND FACILITIES:

MACSYMA Consortium Facility

- PDP-10 based MACSYMA user's facility available to national magnetic fusion community

Computer Equipment:

- 1 DEC KL-10 processor
- 3 RP-04 disk drives
- 3 Trident T300 disk drives
- 8 MF-10 memory boxes
- 1 TU-240 tape drive
- 1 DL-10 interface
- 1 PDP-11/40
- 10 VT-52 terminals
- 1 ARM-10L memory box
- ARPAnet interface
- CHAOSnet interface

E. TECHNICAL PROGRAM SUMMARY:

MACSYMA is a symbolic manipulation program implemented on the PDP-10 at MIT and available to the magnetic fusion community. Following a demonstration of the system's capability at the 1976 meeting of the APS Plasma Physics Division and a workshop held at Berkeley, California in the summer of 1977, there has been a rapid growth in the use of this effective tool by theorists throughout the U.S. fusion program.

The MACSYMA effort involves the maintenance and development of the MACSYMA system, its underlying MACLISP system, and the ITS operating system which all operate on the MACSYMA consortium PDP-10. Currently, only minimal maintenance is performed on the MACLISP and ITS components. A new project is underway to develop a LISP system, called NIL, which is exportable and can support MACSYMA on large address machines such as the DEC VAX-11.

In addition to the ongoing algorithm development for the symbolic manipulation of algebraic structures, an effort is underway to implement improved I/O facilities such as a two-dimensional display editor for mathematical expressions.

A central focus of the MACSYMA project is the export of the MACSYMA system to other machine environments such as the VAX and the LISP machine (developed at the MIT Artificial Intelligence Laboratory). Furthermore, the specialization of MACSYMA to specific application areas, such as fusion research, is a major area of emphasis, involving a close interaction between the computer science and plasma physics communities.

7. DIAGNOSTIC DEVELOPMENT GROUP

Daniel R. Cohn, Leader

A. OBJECTIVES:

Demonstrate the feasibility of submillimeter wave Thomson scattering. Measure ion temperature and collective plasma features on Alcator C. Make high-frequency cyclotron emission measurements with heterodyne receiver. Develop new diagnostics with advanced submillimeter wave technology.

B. Projects:

- Submillimeter Laser Thomson Scattering
  P. Woskoboinikow, Project Leader

C. PERSONNEL:

Research Staff:

B. Clifton (Lincoln Laboratory), D. Cohn, H. Fetterman (Lincoln Laboratory), B. Lax. W. Mulligan, F. Tambini, P. Tannenwald (Lincoln Laboratory), R. Temkin, P. Woskoboinikow

Graduate Students:

R. Erickson, R. Lewis

Secretary:

L. DiMauro

D. SPECIAL EQUIPMENT AND FACILITIES:

- 1 Digital Equipment MINC computer

E. TECHNICAL PROGRAM SUMMARY:

A 500 kW, 120 nanosecond pulse length, 385 μm D_2O laser has been developed as the source for ion Thomson scattering measurements. The detection system is a Schottky diode heterodyne receiver. The receiver has been used to make sensitive high harmonic measurements of cyclotron emission in the Alcator A and C tokamaks. The laser and detector, together with appropriate flanges, radiation dumps and a data handling system have been installed on Alcator C. Initial measurements indicate high levels of stray light. Plans for FY82 for the Thomson scattering experiment include the development of absorption cells and other techniques to reduce effects of the stray light. Thermal scattering measurements and determination of ion temperature will also be carried out. Future activities will involve efforts to develop submillimeter scattering as a tool with widespread applicability in magnetic confinement studies. In addition, new diagnostics will be developed with advanced submillimeter solid state sources, mixers and detectors.

8. INTENSE CHARGED PARTICLE BEAM RESEARCH GROUP

George Bekefi and Ronald Davidson, Co-Leaders

A. OBJECTIVES:

Experimental study of the dynamics of relativistic electron-beam diodes. Experimental and theoretical studies of intense microwave generation. Theoretical studies of the equilibrium and stability properties of intense charged particle beams and plasmas with intense self fields.

B. RESEARCH PROJECTS:

- Dynamics of relativistic electron and ion diodes
- Plasma dynamics in magnetically insulated diodes and transmission lines
- Raman backscattering from electron beams
- Equilibrium and stability studies of intense charged particle beams and plasmas with intense self fields
- Experimental and theoretical investigations of intense microwave generation by relativistic electron beams (gyrotrons, free electron lasers)

C. PERSONNEL:

Faculty:

G. Bekefi and R. C. Davidson

Research Staff:

R. Estes, G. Johnston, B. Lane, W. McMullin, and R. E. Shefer

Technical Staff:

I. Mastovsky

Graduate Students:

A. Dimos, J. Fajans, D. Hinshelwood, D.A. Kirkpatrick, K. Jacobs, W. Marable, J. Petillo

Undergraduate Students:

B.D. Nevins, G. Wong, C.K. Mok, M. Barsony, S. Liu

Secretarial Staff:

V. Kaloyanides, C. Robertson

D. SPECIAL EQUIPMENT AND FACILITIES:

Experimental Facilities:

- Physics International Pulserad 110 A high-voltage Electron Beam Facility (1.5 MV, 30 kA)
- Physics International Pulserad 615 MR Electron Beam Facility (0.5 MV, 4 kA)
- Nereus high-voltage Electron Beam Facility (0.5 MV, 100 kA)
- Two capacitor banks for pulsed magnet operation (30 kJ each)

E. TECHNICAL PROGRAM SUMMARY:

There is a vigorous theoretical and experimental program at MIT that investigates a variety of critical physics issues related to intense charged particle beams. Several diverse areas of research have in common the need to understand the basic equilibrium, stability, transport and radiation properties of intense charged particle beams and beam-plasma systems with intense self fields. These include: (a) research on intense relativistic electron beams, with applications that include high-power radiation generation, production of intense ion beams and beam propagation through the atmosphere; (b) research on collective-effect accelerators such as the converging guide accelerator, the modified betatron accelerator and the electron ring accelerator that utilizes the intense self fields on an electron cluster to trap and accelerate ions; (c) studies of the relativistic electron flow in high-voltage diodes; (d) research on the propagation and trapping of intense ion beams and layers with both light-ion and heavy-ion applications; and (e) basic experimental studies of the equilibrium and stability properties of magnetically confined nonneutral plasmas in uniform and mirror magnetic field geometries.

Experimental electron beam research is being carried out in three critical problem areas.

- Generation of intense microwave and submillimeter radiation
- Study of the dynamics of intense relativistic electron beam diodes
- Study of cathode and anode plasmas in magnetically insulated diodes

These three areas of experimental research are expected to continue for the next several years.

There is also a vigorous theoretical program at MIT that investigates critical problems related to the basic equilibrium, stability, transport and radiation properties of intense electron and ion beams and beam-plasma systems with intense self fields. Recent theoretical investigations have included: (a) investigations of the basic thermal equilibrium properties of intense electron and ion beams with both azimuthal and axial directed motion, (b) application of a rigid-beam model to investigate coupled dipole resonance stability properties (both electron-electron and electron-ion interactions) of an intense relativistic electron beam propagating through a background plasma, (c) investigation of the equilibrium and stability properties of intense relativistic electron beam-plasma system using a kinetic (Vlasov) description to correctly incorporate thermal effects, (d) the development of a self-consistent theory of the cyclotron maser and free electron laser instabilities in intense hollow and solid electron beams, (e) investigations of the influence of kinetic effects and beam quality on corresponding stability behavior, (f) investigation of the influence of mode structure and beam geometry on maximizing microwave emission, and (h) the development of a weakly nonlinear (quasilinear) theory of mode saturation. Theoretical research will continue in each of these problem areas with particular emphasis on (a) the equilibrium, stability, radiation and nonlinear properties of intense nonneutral electron beams, and (b) the equilibrium and stability properties of intense electron beams in modified betatron geometry.

The Plasma Fusion Center research program on intense charged particle beams is supported in part by the Office of Naval Research, the National Science Foundation, the Air Force Office of Scientific Research, and the Air Force Aeronautical Systems Division. Particularly strong technical interactions are maintained with research scientists at the Naval Research Laboratory.

PLASMA FUSION CENTER

II. TOROIDAL CONFINEMENT EXPERIMENTS DIVISION

RONALD R. PARKER, HEAD

A. OBJECTIVES:

Develop an understanding of the stability, transport, and radiation properties of high-temperature toroidal fusion plasmas at near-reactor conditions. Develop methods for heating plasmas to fusion temperatures.

B. GROUPS:

- Operations
  D. Gwinn, Leader
- Confinement Studies
  S. Wolfe, Leader
- Plasma-Wall Interactions
  E. Marmar, Leader
- RF Heating
  M. Porkolab, Leader
  J. Schuss, Assistant Leader
- Data Acquisition and Computation
  M. Greenwald, Leader
  D. Nelson, Computer Systems Manager
- Toroidal Systems Development
  P. Politzer and D. B. Montgomery, Co-Leaders

The successful development of fusion energy requires experimentation on large-scale magnetic confinement devices. The Alcator experimental program constitutes one of the most successful and prominent tokamak confinement activities, both nationally and internationally. The primary objective of these activities is to develop a practical understanding of the stability, transport and radiation properties of high-temperature fusion plasmas at near-reactor conditions. The main toroidal confinement experiment is Alcator C. Professors Ronald Parker and Bruno Coppi are overall Alcator program Principal Investigators.

C. ALCATOR GROUPS AND PROJECT AREAS:

1. Operations Group

David Gwinn, Leader

A. OBJECTIVES:

Direct day-to-day operations, develop methods of plasma control and provide suitable engineering support in order to reliably produce high-quality plasmas required to achieve goals set by scientific staff. Plan and execute system and component upgrades and new fabrications to extend the parameters and performance of plasmas produced in Alcator C.

B. PROJECTS:

- Alcator C Operations

C. PERSONNEL:

Research Staff:

D. Gwinn, B. Lipschultz, B. Lloyd, R. Parker

Engineering Staff:

M. Besen, G. Chihoski, R. Childs, J. Daigle, F. Dawkins, K. Fertl, D. Grearson, P. Maruzzi, D. B. Montgomery, C. Park, N. Pierce, J. Rosati, J. Rose, F. Silva, E. Thibeault

Technical Support Personnel:

T. Bakucz, J. Costello, R. Danforth, W. Foster, J. Gerolamo, R. Griffith, J. Heckman, M. Iverson, J. Moscaritolo, B. Oliver, W. Parkin, E. Rollins, M. Rowell, H. Shriber, R. Shuffield, L. Storace, E. Sudenfield, F. Woodworth, K. Woodworth

Graduate Students:

B. LaBombard, J. O'Rourke, P. Pribyl, R. Richardson

Administrative and Support Staff:

S. Geitz, T. Lloyd, L. McKnight, S. Simsek

2. Confinement Studies Group

Stephen Wolfe, Leader

A. OBJECTIVES:

Conceive and carry out measurements which determine confinement properties of ohmically heated and RF heated Alcator plasmas. Develop new diagnostic methods for the purpose of elucidating phenomena affecting transport. Provide interpretation of experimental results in the context of confinement theory.

B. PROJECTS:

- Alcator C Confinement Studies

C. PERSONNEL:

Research Staff:

B. Coppi, C. Fiore, R. Gandy, A. Gondhalekar, M. Greenwald, D. Pappas, S. McCool, P. Woskoboinikow, R. Watterson, S. Wolfe

Engineering Staff:

G. Chihoski, N. Pierce, F. Tambini

Technical Support Personnel:

B. Doherty, F. Shefton

Visiting Scientists:

E. Källne, J. Källne, N. Loter, R. Petrasso, R. Slusher, C. Surko

Graduate Students:

W. Fisher, C. Gomez, R. Granetz, S. Kissel, B. Koester, A. Pachtman, J. Parker, D. Schissel

Administrative and Support Staff:

L. McKnight, S. Simsek

3. Plasma-Wall Interactions Group

Earl S. Marmar, Leader

A. OBJECTIVES:

Study interactions of Alcator C plasmas with the limiter and vacuum chamber wall under conditions of ohmic heating and RF heating. Study the mechanisms of impurity release, impurity transport and control, and retention and recycling of working gas.

B. PROJECTS:

- Spectroscopic determination of type, quantity and transport of light and heavy impurities
- Determination of wall and limiter power flows

C. PERSONNEL:

Research Staff:

B. Lipschultz, E. Marmar, J. Rice, J. Terry

Engineering Staff:

G. Chihoski, R. Childs, E. Thibeault

Technical Support Personnel:

T. Bakucz, J. Heckman, H. Shriber

Visiting Scientists:

E. Källne, J. Källne, R. Petrasso, F. Seguin

Graduate Students:

J. Castracane, S. Fairfax, M. Foord, T. Moran, J. Moreno, M. Pickrell

Administrative and Support Staff:

L. McKnight, S. Simsek

4. RF Heating Group

Miklos Porkolab, Leader
Jack Schuss, Assistant Leader

A. Objectives:

Develop an experimental understanding of the physics of tokamak heating by application of RF power. Assess the technological limits of heating by various techniques and provide theoretical interpretation of experimental results.

B. PROJECTS:

- Alcator C Lower Hybrid Heating
- Alcator C Ion Cyclotron Heating
- Heating of Advanced Toroidal Devices

C. PERSONNEL:

Research Staff:

D. Blackfield, B. Blackwell, P. Bonoli, B. Lloyd, R. Parker, M. Porkolab, J. Schuss, R. Watterson

Engineering Staff:

C. Bredin, K. Fertl, D. Griffin, K. Rice

Technical Support Personnel:

C. Holtjer, C. Kastrenos, R. Meister

Graduate Students:

T. Gentile, J. Machuzak, M. Sansone, Y. Takase, S. Texter

Administrative and Support Staff:

A. Kotsopoulos, L. McKnight, S. Simsek

5. Data Acquisition and Computation Group

Martin Greenwald, Leader
Don Nelson, Computer Systems Manager

A. OBJECTIVES:

Coordinate the acquisition, processing and archiving of data from the Alcator C experiment. Develop appropriate hardware and software for purposes of: (a) maximizing the quantity and quality of reduced data, especially in the time interval between discharges, and (b) facilitating use of PFC, MIT and Fusion Community computers for purposes of modeling and computations.

B. PROJECTS:

- Alcator C Data Acquisition and Processing
- Alcator C Computation

C. PERSONNEL:

Research Staff:
M. Greenwald
Engineering Staff:
C. Bredin, D. Grearson, C. Hume, D. Nelson, E. Shaw, R. Thayer
Technical Support Personnel:
D. LaVoie
Graduate Student:
P. Besen
Administrative and Support Staff:
L. McKnight, S. Simsek

6. Toroidal Systems Development Group

Peter Politzer and Bruce Montgomery, Co-Leaders

A. OBJECTIVES:

Develop advanced toroidal concepts which offer improvement over the conventional tokamak in areas of increased beta, steady-state operation and simplicity of construction. Scope upgrades of the Alcator concept for the purpose of approaching reactor regimes and addressing problems of reactor physics.

B. PROJECTS:

- Advanced Toroidal System Design
- Alcator C Upgrades

C. PERSONNEL:

Research Staff:

D. B. Montgomery, R. Parker, P. Politzer

Engineering Staff:

M. Besen, J. Davin, J. Pierce

Technical Support Personnel:

A. Rabasco

Graduate Students:

K. Kato, G. Laventure, T. Morizio, J. M. Noterdaeme

Administrative and Support Staff:

D. Marble, L. McKnight, S. Simsek

D. SPECIAL EQUIPMENT AND FACILITIES:

Experimental Facility:

- Alcator C tokamak [$a = 10 - 16.5$ cm, $R = 57.7 - 70.7$ cm, B_T ($R = 64$ cm) $= 14$ T]

Major Facility Support Equipment:

- Power Equipment:

  Utility power substation:
    13.8 kV/30 MW
  Generators:
    220 MVA motor/generator (13.8 kV AC)
    2-16 MW, pulsed, 250 V, DC flywheel generators (National Magnet Lab)
  Rectifier/Invertors:
    Alcator C TF - 200 kA, 750 V (4, 50 kA Robicon modules)
    Alcator C OH - 50 kA, 750 V (2, 25 kA Transrex units)
    Alcator C OH - 50 kA, 1200 V (1 Brown-Boveri unit)
    Alcator C HF - 5 kA, 650 V (Transrex)
    Alcator C VF - 5 kV, 3.0 kA (Transrex)

- Plasma Heating Equipment:

  16 power supply/modulator outputs (55 kV, 15 A, 500 msec)
  100 kW, 2.45 GHz RF power for LHH
  17 0.25 MW CW klystrons at 4.6 GHz
  4 MW, 4.6 GHz RF power for LHH
  15 MW, 175-225 MHz power for ICRF
  300 A, 30 kV, 100 μF capacitor bank for ICRF
  50 A, 15 kV, 200 μF capactior bank for ICRF
  RF transmission, control, monitoring systems
- Cryogenic Facilities:

  2, 8000-gallon LN_2 storage facilities
  Liquefied gas handling and transfer facilities
- Computers:

PDP 11-34 (2)	for Data Acquisition
PDP 11-55	for Data Acquisition
VAX 11/780	for Data Acquisition and Processing

E. TECHNICAL PROGRAM SUMMARY:

The Alcator experimental program constitutes one of the most successful and prominent tokamak confinement programs, both nationally and internationally. The primary objective of the Alcator experimental program, headed by Ronald Parker, is to develop the basic physics understanding of the stability, transport and radiation properties of high-temperature plasmas at near-reactor conditions and to develop methods for heating plasmas to fusion temperatures. The main Alcator experimental areas include: device operations (David Gwinn); confinement studies (Steve Wolfe); plasma-wall interactions (Earl Marmar); radio frequency heating (Miklos Porkolab and Jack Schuss); and data acquisition and computations (Martin Greenwald). The experimental design activities during the past year have emphasized advanced toroidal facilities with helical features (such as Alcator A Modification) as well as advanced tokamak designs in the high-field Alcator line (Peter Politzer and D. Bruce Montgomery).

Ronald Parker and Bruno Coppi are overall Alcator program principal investigators.

With the retirement of the Alcator A device at the end of 1981, the focus of the experimental program has now completely shifted to Alcator C, a high-field tokamak similar in concept to Alcator A, but larger and more powerful. The significantly stronger toroidal and poloidal magnetic fields which can be generated in Alcator C are a result of a strengthened magnet design combined with increased power supply capability. The prime power for the experiment is furnished by the 220 MW Plasma Fusion Center Motor Generator. Whereas the peak midplane field strength in Alcator A was 10 T and the plasma volume was $1 \times 10^5 cm^3$, the peak midplane field in Alcator C is 14 T and the maximum plasma volume is $3.4 \times 10^5 cm^3$. Alcator C typically operates for about 30 hours per week in a single-shift mode, more than twice the amount of run time possible with Alcator A during its most intense period of operation.

Alcator A was retired at the end of 1981 after nine years of operation. It was a productive experiment to the end of its operating lifetime, and this is testimony to the skills of the responsible engineering and scientific teams. Two results of major importance to the worldwide controlled fusion effort were achieved. The first was the discovery that plasma confinement improves as the plasma density is increased. The second was the discovery of techniques for producing high temperature plasmas with impurity content (i.e., nonhydrogenic components) in the 10^{-3}-10^{4} range required for reactor operation. The experimentally determined confinement behavior was exploited to achieve the world-record value of $n_0 \tau_E = 3 \times 10^{13} cm^{-3}$-sec, just below that required for fusion breakeven at higher temperatures. This value of $n_0 \tau_E$ is over an order-of-magnitude larger than the best value previously achieved, and is only now surpassed by Alcator C and by a similar high-field tokamak, FT (Frascati Tokamak), located in Frascati, Italy. During the last four years, the work on

Alcator A made important contributions in the area of particle removal and control, and development and testing of techniques for RF heating. These areas of research are critical for the continued development of the tokamak concept for use as a fusion reactor, and research on these problems is being continued on Alcator C as well as on tokamaks at other laboratories.

The principal research activities carried out on the Alcator C are mainly concerned with measurement and interpretation of confinement properties of tokamak plasmas under intense ohmic and RF heating. The toroidal field in Alcator C has a maximum capability of 14 T and this permits an extraordinarily wide range of operating conditions. The "best" parameters produced in plasmas with major radius R = 64 cm and minor radius a = 16.5 cm are: line-averaged density $\bar{n} = 7 \times 10^{14} \mathrm{cm}^{-3}$, central density $n_0 = 8.5 \times 10^{14} \mathrm{cm}^{-3}$, electron and ion temperatures of 3 keV and 1.6 keV, respectively, plasma currents of 750 kA, and energy confinement times of approximately 40 ms.

The flexibility of the Alcator C facility also allows for the study of confinement properties as a function of the geometry (major and minor radii). This in turn permits elucidation of possible dependencies of the thermal and particle transport coefficients on major and minor radius. In recent experiments in the high-density regimes (neutral mean free path less than the minor radius), the confinement time is found to be only a weak function of minor radius a (in contrast to the a^2 - dependence expected if the thermal diffusivity were constant). Preliminary data reveal some dependence of τ_E on major radius R. If characterized by the scaling $\tau_E \propto R^\nu$, the range of ν is found to be $0.5 < \nu < 1.5$. It is worth noting that for reduced limiter size with minor radius a = 10 cm, major radius R = 58 cm, toroidal field B_T = 120 kG, and plasma current I_p = 380 kA, the performance of Alcator C has exceeded that of Alcator A. In this case, the best parameters achieved are line-averaged density $\bar{n} = 8 \times 10^{14} \mathrm{cm}^{-3}$, central density $n_0 = 1.2 \times 10^{15} \mathrm{cm}^{-3}$, energy confinement time $\tau_E \simeq 30$ ms, and corresponding value of the Lawson parameter $n_0 \tau_E \simeq 0.35 \times 10^{14} \mathrm{cm}^{-3}$-s. Variable-size plasma experiments are continuing and are expected to yield fundamental insights into the physics of tokamak confinement.

In the case of "full-bore" plasmas ($a = 16.5$ cm, $R = 64$ cm), the overall performance has been up to design expectations in most areas. However, an exception has been the measured energy confinement time. The best value obtained for τ_E is about a factor of two below that anticipated on the basis of extrapolation of the results from Alcator A. This can be traced to the observed dependence of τ_E as a function of plasma density. At plasma densities $\bar{n}$ in excess of $2 \times 10^{14} \mathrm{cm}^{-3}$, it has been found that τ_E increases only slowly with density rather than continuing to increase linearly with density as found in Alcator A. The main results are consistent with an enhanced (anomalous) ion energy transport that is up to a factor of five times larger than the classical value based on two-body collisions. However, the present experimental uncertainties are such that a departure from an empirically-based scaling law for electron thermal conductivity could also explain the trends in the data. The main significance of these results is that the ion energy confinement time at high densities may be less than expected. This will make the achievement of $n_0\tau_E \approx 10^{14} \mathrm{cm}^{-3}$-s difficult in Alcator C. However, the present best value of $n_0\tau_E \approx 0.35 \times 10^{14} \mathrm{cm}^{-3}$-s obtained in Alcator C does exceed that obtained in Alcator A, and a value of $n_0\tau_E$ in the range $0.5 - 0.7 \times 10^{14} \mathrm{cm}^{-3}$-s is expected to be achieved in Alcator C even with the unfavorable trends discussed above. These experimental studies are receiving continued emphasis with expanded and more accurate diagnostic capability. In addition, fueling the plasma with pellets of hydrogen or deuterium ice will soon be possible, using a multi-shot pellet injector based on a design developed at the Oak Ridge National Laboratory.

RF Heating: Further improvement of plasma parameters in Alcator C will require additional energy input. Phase II of Alcator C has as its objective the increase of plasma temperature from 2 keV to 4 keV. For this purpose, two radio frequency heating methods will be explored and are being developed in parallel. The first will use 4 MW of power at the lower hybrid frequency, which is about 4.6 GHz in Alcator C. The second will employ initially 0.5 - 1 MW of power at the second harmonic of the ion cyclotron frequency. Key physics issues in both programs are: RF wave penetration into the plasma, heating mechanisms, efficiency, and the effect on plasma stability and confinement. Technological issues are concerned with RF power transmission through vacuum interfaces, power densities achievable, and practical RF coupler design. In addition, RF current drive studies will be carried out to see if the toroidal current in Alcator C could be at least partially generated by RF at intermediate densities in the 10^{13} - 10^{14}cm^{-3} range. (In all other experiments, lower hybrid generated toroidal currents are observed only at low densities, $n < 10^{13}$cm^{-3}).

Lower hybrid heating is the primary method selected for heating the plasmas of Alcator C. However, the ICRH program, which has been initiated on Alcator A will also be tested on Alcator C to compare the heating efficiency with that of LHH. Successful completion of this phase will set the stage for a followup experiment to Alcator C. The Alcator C LHH experiments began during June, 1981. Initially, a 4 waveguide array wave launcher is being used to inject RF power up to 200 kW (P/A = 10 kW/cm^2) into the plasma. At present, the system has been tested successfully in vacuum up to this maximum power level. With plasma, a total power of 150 kW (8 kW/cm^2, with a 45 msec pulse length) has been injected into Alcator C (a world record in power density among LHH experiments using multi-waveguide arrays). In addition, very good waveguide-plasma coupling has been observed (with 10% or less reflected power at optimized coupler positions). At present, density scans are being performed to find the electron and ion heating bands which were observed previously in the Alcator A experiments. In addition, initial observations of "RF current drive" have been made at average densities of $\bar{n} \simeq 3 \times 10^{13}$cm^{-3}, well above that used in other LH experiments.

The present plans call for delivery of an 8 and/or 16 waveguide array coupler near the end of January, 1982, and installation into Alcator C in February, 1982. Subsequently, the injected power will be raised to or above the 600 kW level (1.0 MW at the klystrons) and high-power heating and current drive studies will be undertaken. By the end of 1982, two more 16 and/or 8 waveguide arrays will be installed and the injected power should be near 2 MW, or 1.5 - 2 times the ohmic heating input.

During 1982 one or two ICRF antennae will be fabricated and 0.5 MW, 100 msec RF power at 186 MHz will be injected into Alcator C. The heating efficiency will be compared with that associated with LHH. If successful, the power will be upgraded to 1 MW. One of the LH power supplies will be used for this purpose. (These supplies can also be used to give 27 kV, 60 A DC power to energize the FPS-17 transmitter system formerly operated by the USAF at Shemya, Alaska.) Further ICRF couplers and RF power will be added in 1983 if warranted.

Toroidal Systems Development: As indicated earlier, the design activity for the next step in the Alcator program has been initiated and will be intensified as the Alcator C results evolve. This activity is exploring two alternative paths. The first design approach is examining the optimum upgrade of Alcator C that can take full advantage of the RF heating capabilities associated with the lower hybrid and ICRF Shemya equipment. The full 10 to 15 MW of ICRF capability cannot be utilized in Alcator C due to limited access. An upgraded TF coil design with more ports will be examined as a replacement of the present coil. The increased neutron yield for such a device will require location in a shielded installation in the PFC Nabisco Laboratory.

The design activities during the past year have also emphasized advanced toroidal facilities with helical features (such as Alcator A Modification) as well as advanced tokamak designs in the Alcator high-field line. For purpose of illustration, the primary objective in the Alcator A Modification design is the development of an experimental facility for the basic study and control of MHD instabilities and disruptions. The important feature of the design is a helical $\ell = 2$ winding capable of producing substantial vacuum rotational transform. Combining this winding with those of a conventional tokamak leads to a device with considerable flexibility in its modes of operation, ranging from operation as a pure tokamak to operation as a pure stellarator, with an intermediate "hybrid" mode that has both tokamak and stellarator features. The present design (minor radius = 30 cm, major radius = 110 cm) is approximately twice the size of Alcator C but has considerably lower field.

In addition to the Alcator A Modification design, more general stellarator configurations are being examined. The goal of this work is to scope toroidal systems which offer improvement over the tokamak in critical areas such as beta, continuous operation and simplicity of construction.

PLASMA FUSION CENTER

III. MIRROR CONFINEMENT SYSTEMS DIVISION

RICHARD S. POST, HEAD

A. OBJECTIVES:

Develop an increased understanding of basic tandem mirror physics with emphasis on microstability properties, thermal barrier formation and RF heating.

B. GROUPS:

- Confinement Physics
  R. S. Post, Leader
- TARA Engineering
  D. B. Montgomery and R. S. Post, Co-Leaders
- Computations and Advanced Concepts
  J. Kesner, Leader

The TARA experimental program is involved in the design and construction of a major tandem mirror confinement facility. The TARA Tandem Mirror configuration is unique and utilizes an axisymmetric confining plug with an "outboard" minimum-B anchor. It has been identified as the most desirable tandem mirror configuration for potential reactor applications. The primary objectives of the experiment will be to test plug microstability, overall MHD stability and beta limits, central cell radial transport and thermal barrier formation. The experiment will provide data for the proposed upgrade of the MFTF-B facility, under construction at Lawrence Livermore National Laboratory.

The following is a brief summary of the TARA design. The TARA central cell is a 15 cm radius, 5 m long solenoid with upgrade capabilities to 15 m. When a thermal barrier is present, the projected plasma parameters are $T_e \sim T_i \sim 400$ eV and $n_e = 4 \times 10^{12}$ cm^{-3}. Ions are confined by axisymmetric plugs which eliminate the possibility of enhanced radial transport that is driven by the quadrupole moments of the plugs (so-called "resonant" transport).

The central solenoid is bounded by high mirror ratio plugs (R = 5 to 10) with peak fields of up to 5 T. Neutral beams (20 keV extractor energy) with 150 A current are injected at a 40° angle into the plugs to create a sloshing-ion distribution which is expected to exhibit improved microstability properties and provide a partial thermal barrier. Gyrotrons at 28 GHz will be available with a capability of 200 kW per plug for creating the hot mirror-trapped thermal barrier electron species and the suprathermal ($T_e \sim 700$ eV) warm electron species. Thus, a thermal barrier is expected to form at the midplane of the plugs.

A unique feature of the TARA configuration, and one that provides a substantial reduction in cost and technology requirements is the use of RF-driven MHD anchors. The anchor will be formed in externally located baseball coils that were formerly the plugs in TMX. They will operate steady-state and contain a low-density ($n \sim 5 \times 10^{11}$ cm^{-3}) hot-electron plasma, formed by ECRH heating in the X-band. Additional ion heating utilizing ICRF will be used to augment beta values in the anchor.

C. TARA RESEARCH GROUPS AND PROJECT AREAS:

1. CONFINEMENT PHYSICS GROUP

Richard S. Post, Leader

A. OBJECTIVES:

Define the experimental program and develop appropriate plasma diagnostics, RF antennae and improved neutral beam sources for the TARA experiment.

B. PERSONNEL:

Research Staff:

J.E. Coleman, R.E. Klinkowstein, B.D. McVey, D.K. Smith, J.B. Thompson, R. Torti

Support Staff:

C. O'Connor, A. Page

2. TARA ENGINEERING GROUP

D. Bruce Montgomery, Leader, Mechanical Systems
Richard S. Post, Acting Leader, Electrical Systems

A. OBJECTIVES:

Design and construct the TARA experimental facility.

B. PERSONNEL:

Engineering Staff:

P. Brindza, J.E. Coleman, M. Gaudreau, C. Karcher, J. Kesner, R.E. Klinkowstein, M. Olmstead, D.K. Smith, J.M. Tarrh, J.B. Thompson, R. Torti, J.E. Tracey, T. Yang

Graduate Students:

T. Farrish, J. Nolly

Support Staff:

C. O'Connor, A. Page

3. COMPUTATIONS AND ADVANCED CONCEPTS GROUP

J. Kesner, Leader

A. OBJECTIVES:

Analyze and evaluate the various operating modes and outstanding physics questions relating to TARA operation. Explore advanced concepts that could improve the tandem mirror as a potential fusion device.

B. PERSONNEL:

Research Staff:

D. B. Blackfield, M. J. Gerver, B.D. McVey, R.S. Post, D.K. Smith, J.B. Thompson

Support Staff:

C. O'Connor, A. Page

D. SPECIAL EQUIPMENT AND FACILITIES UNDER CONSTRUCTION:

Experimental Facility:

TARA experimental facility (total length = 20 m, power requirement 14 MW).

Major Facility Support Equipment:

- Ten 500 V, 4 kA(nominal), six pulse, SCR phase controlled rectifier units with freewheeling diodes. Magnet current will be ramped up, flat topped and ramped down in 4, 1, and 4 seconds, respectively, once every 2.5 minutes.
- Eight 3 MVA transformers, step down from 20 MVA, 13.8 kV AC to 480 V nominal; the 3 MVA transformers, multiply tapped to maintain good power factor even at reduced voltage.

Plasma Heating Equipment:

- 2-28 GHz Gyrotrons, 200 kW each
- 3 X-band amplifiers, 10 kW each
- 3 ICRF amplifiers, 1 MW each
- 6 Neutral Beam sources, 20 kV, 50 A

E. TECHNICAL PROGRAM SUMMARY:

The objective of the TARA confinement program is to provide a data base for increased understanding of thermal barrier tandem mirror operation, and in particular, the relative advantages of the TARA axisymmetric central cell and hot electron anchor. This information will then help determine the future emphasis and direction of proposed experiments such as MFTF-B at Lawrence Livermore National Laboratory.

Site preparation in the Nabisco Building (NW21) to create the experimental area will begin in April, 1982, and final assembly of the experimental facility will begin one year later. The completion date for the TARA facility is November, 1983.

Simultaneously with the preparation of the experimental area and construction of the facility, a vigorous technology development program will begin. Critical areas of effort include testing of prototype neutral beam sources, exploration of neutral beamline pumping techniques, design of ECRH systems, and design of ICRF antennae.

The TARA base program, along with the tandem mirror theory effort provides theoretical support and computational expertise for the TARA group. One area of continuing effort is the understanding of the needs and limitations of ECRH-formed MHD anchors. Investigations of neutral beam driven hot-ion anchors will continue with particular emphasis on a stabilization scheme known as a "bellyband." Detailed analysis will continue on ICRF antenna coupling schemes, which will allow a more complete evaluation of the proposed TARA startup scheme. Monte-Carlo RF heating simulation codes are presently being developed for detailed modeling of potential formation in tandem mirrors.

PLASMA FUSION CENTER

IV. FUSION TECHNOLOGY AND ENGINEERING DIVISION

D. BRUCE MONTGOMERY, HEAD

A. OBJECTIVES:

Provide critical engineering support for the advanced design projects. Develop advanced superconducting magnet and divertor technology for the national fusion program.

B. GROUPS:

- Advanced Design
  D. Bruce Montgomery, Acting Leader
- Superconducting Magnet Development
  Mitchell O. Hoenig, Leader
- Superconducting Materials Development
  Simon Foner, Robert Rose and Brian Schwartz, Co-Leaders
- Divertor Development
  Tien-Fang Yang, Leader

The Fusion Technology and Engineering Division provides advanced design to support the Magnetics Branch activities of the Fusion Engineering Design Center (FEDC) and other nationally based fusion engineering design activities such as magnetics for INTOR and magnetics critical studies. Engineering support is also provided for next-step planning activities in the MIT confinement program.

Major experimental programs are also carried out in the development of conductors for superconducting fusion magnet projects. A helium refrigerator and 2-meter Dewar are the principal facilities. A supercritical helium-cooled conductor conceived and developed by the magnet group is being used by Westinghouse for the 2 × 3 meter niobium-tin coils for the Large Coil Project at the Oak Ridge National Laboratory (ORNL), and by the MIT group for the 12 T advanced magnet project at Lawrence Livermore National Laboratory (LLNL). An experimental and analytical program is also being carried out in the area of magnet safety.

Basic programs in advanced superconducting materials are also carried out. The objective is to develop materials and techniques for producing superconductors capable of generating 15 tesla magnetic fields which are sufficiently ductile to be suitable for advanced fusion devices. This work concentrates on finely divided materials, and has made significant progress in improving mechanical properties.

Advanced design is being carried out in the area of magnetic divertors to support the FED and advanced reactor designs. A bundle divertor for ISX-B has been constructed at MIT and is now awaiting installation. An advanced bundle divertor for Textor (Julich) is under study.

1. ADVANCED DESIGN GROUP

D. Bruce Montgomery, Acting Leader

A. OBJECTIVES:

Carry out engineering functions in support of advanced design projects.

B. RESEARCH PROJECTS:

- FED Magnetics Engineering
  J. H. Schultz, Project Leader
- Magnet Safety and Protection Studies
  R. J. Thome, Project Leader
- Engineering Support of Next-Steps Planning in the MIT Confinement Program
  D. Bruce Montgomery, Project Leader
- Engineering Support for High Performance Reactor Studies
  John E.C. Williams, Project Leader

C. PERSONNEL:

Research Staff:

H. Becker, J.M. Davin, Y. Iwasa, N.T. Pierce, R.D. Pillsbury, J.H. Schultz, R.J. Thome, J.E.C. Williams

Draftsman:

A. Rabasco

Secretary:

D. Marble

D. SPECIAL EQUIPMENT AND FACILITIES:

Computer Equipment:

- 5 teleray computer terminals, accessing MIT facilities and the NMFECC
- 28-channel magnetic tape recorder and 13 channels of preamplifiers for Acoustic Emission Studies

E. TECHNICAL PROGRAM SUMMARY:

FED Magnetics Design:

The PFC Fusion Technology and Engineering Division has had responsibility for the Magnetics Branch of the FED Center activities during the past two years. This work has been carried out in close cooperation with the FED Center Headquarters at ORNL, which has overall responsibility. Starting in FY82 General Electric will assume responsibility for the branch activities, and the PFC will take responsibility for critical issues.

The FEDC has recently issued extensive documentation of the 1981 FED design. The magnetics branch, supervised by an MIT on-site manager, Dr. Roger W. Derby, has been responsible for magnetic and cryogenic design. This ORNL-based activity has been supplemented by work at MIT, principally in overall systems modeling and cryogenic refrigerator design.

Work in FY82 for the FEDC will concentrate on selected critical areas in magnetics. These have been identified as:

- Development of toroidal and poloidal field concepts which will yield the highest reliability of operation and result in the simplest overall machine concept.
- Develop an overall structural and cryogenic concept which will maximize the opportunities for maintenance and replacement of magnetic components.
- Develop analytical tools to allow closer examination of the electromagnetic interactions between the magnetic systems, the plasma and the structural and cryogenic components.
- Develop optimum start-up and shut-down concepts which minimize technological and systems problems.

In addition to investigation of these critical problems for the baseline FED and INTOR concepts, the magnetics group will also participate in evaluation of various national activities. Alternative approaches to the establishment of the engineering feasibility for fusion will be examined.

Magnet Safety and Protection Studies:

During FY81, large-magnet safety problem areas were reviewed, the primary technical issues selected, safety-related experiments were defined, and data from existing test modules were supplied to Argonne National Laboratory (ANL) for integration with computer analyses.

The primary technical issues associated with large superconducting magnet safety include: (1) understanding and control of energy deposition and flow during fault condition; (2) detection and discrimination between types of faults; and (3) means of inspection to detect impending failure without disassembly of major components.

The understanding and control of energy deposition in a large magnet hinges on the ability to predict the propagation of a large-scale quench with the associated voltage and temperature distribution. Computer models are under development, but results have not been adequately correlated with experimental data. Predictions tend to be barely adequate for simple configurations (e.g., conduction-cooled windings without helium passages) and inadequate for more complex designs involving circuitous helium cooling paths or internally cooled conductors.

This leads to a need for an experimental program to define conditions conducive to arc initiation or extinction in realistic large coil geometries and to the need for detailed data on quench effects in models large enough to suitably represent large coil behavior.

Another technical issue identified to be of prime importance to magnet safety is the need for means to inspect for impending failure without major disassembly of the magnet. Work in acoustic emission analysis for use in this area on superconducting magnets has been initiated. Data accumulation has begun on the superconducting racetrack pair in the MHD magnet test facility at FBNML, on selected ISA dipoles at Brookhaven and on the CFFF MHD magnet. Acoustic emission sensors have been installed on the MFTF-B Yin Yang magnet and are planned for installation on the Large Coil Test Facility magnets and CDIF MHD magnet. Development of this technique also requires installation of sensors and analysis of output from smaller systems in which controlled failure experiments can be undertaken.

As part of the FY81 activity in magnet safety, voltage taps were installed in two of the test modules in the MHD racetrack facility magnet. Turn-to-turn voltage distributions during quench were obtained and provided to ANL for analysis with the quench code under development at that laboratory.

In considering the technical issues described earlier, concepts for future experiments have been developed in the context of using and extending existing facilities to develop background information on safety-related problems common to large magnet systems for fusion, MHD and high-energy physics.

Engineering Support of Next-Step Confinement Experiments:

Several studies have been undertaken to examine various next-step options in the MIT toroidal confinement program. These have ranged from upgrades of Alcator C to pure stellarators to hybrid tokamak/stellarator configurations. One of the major studies has involved a hybrid tokamak with helical windings capable of partial transform, called Alcator A-Modification.

The favored Alcator A-Mod design is a machine of major radius 1.1 m and minor radius 0.28 m with a toroidal field of

4 tesla. A vacuum helical transform of 0.2 can be provided at this field. This helical transform is thought to be sufficient to allow disruptions to be controlled and to therefore allow operations below the q = 2 resonance.

During FY82, engineering scoping studies will be undertaken in the area of new stellarator configurations and upgrades of Alcator C in order to form a more complete picture of future MIT toroidal confinement options. Alcator C upgrade studies will focus on the use of the large amount of RF power available at MIT and examine machine upgrades with access more appropriate to these large powers. The possible use of RF current drive will also be investigated.

Stellarator design studies will focus on "snake" configurations using a twisted plasma chamber. Studies will be made of the feasibility of building a Versator II-scale low-field machine with steady-state windings to explore new ideas in this area. Low-field superconducting coils will also be considered.

Engineering Support of High Performance Reactor Studies:

Engineering support is provided to the Fusion Systems Division in carrying out high performance reactor design studies. A class of high-field copper coil tokamaks are under investigation which yield high power densities and large neutron fluxes. Engineering concepts developed during the joint US-IPP Garching study of a high field Ignition Test Reactor (ITR) are being used in the present studies.

2. SUPERCONDUCTING MAGNET DEVELOPMENT GROUP

Mitchell O. Hoenig, Leader

A. OBJECTIVES:

Develop forced-flow cooled niobium-tin conductors for national fusion program applications.

B. PROJECTS:

- Develop 12-tesla coil for testing at the Lawrence Livermore High Field Facility
- Develop advanced conductor concepts for toroidal and poloidal magnetic systems.

C. PERSONNEL:

Research Staff:

M.O. Hoenig, M. Steeves

Technical Support Personnel:

C. Cyders

D. SPECIAL EQUIPMENT AND FACILITIES:

Special Facilities:

- 2-meter LHe cryostat
- 1 × 2 meter Dee Coil Facility with 7.4 T, 15 cm diameter field coil
- 1 m × 0.2 Racetrack Structural Test Facility (6 T)
- CTI 1400 Liquefier/circulator
- 12 T, 15 cm bore Bitter coil
- 8 T, 25 cm bore Bitter coil
- 7 kA, 20 V DC Power and Supply

E. TECHNICAL PROGRAM SUMMARY:

Major experimental programs are carried out in the development of conductors for superconducting fusion magnet projects. A helium refrigerator and 2-meter Dewar are the principal facilities. The supercritical helium-cooled ICCS* conductor developed by the magnet group is being used by Westinghouse for the 2 × 3 meter niobium-tin coils for the Large Coil project, and is being used by the MIT group for the 12 T advanced magnet project at Livermore. The ICCS concept was conceived and developed at MIT in 1974 following attempts to use hollow superconductor technology developed by Morpurgo at CERN in 1970. The concept of cooling the internally-cooled superconductor with supercritical helium also finds its roots at MIT in the form of heat transfer experiments performed in 1965 by Kolm, Leupold, and Hay.

During the early years of this program, fundamental studies were carried out on the stability of ICCS conductors and included discovery and subsequent detailed exploration of the fact that stability is essentially independent of bulk flow. Local heating generates a pressure wave, which causes sufficient local turbulence even in quiescent fluid to assure stability.

A large 1 m × 2 m test "Dee" coil was constructed of NbTi and subjected to a local 8 T field produced by high-field solenoids. Since 1978, efforts have been directed at the design, development, fabrication and testing of a 40 cm bore test insert for the 12 Tesla High Field Test Facility at Livermore. Small samples of the conductor are tested in the FBNML 15 cm 12 tesla facility.

The group has also participated in an MHD-sponsored experiment in which a heavy-wall ICCS is formed into an oval coil in

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* ICCS: Internally-cooled, cabled superconductor

order to simulate conductor stress of a much larger coil. The long sides of the oval are unsupported, and when the coil is operated in a background field, the sides bow out, subjecting the conductor to a large stress.

3. SUPERCONDUCTING MATERIALS DEVELOPMENT GROUP

Simon Foner, Robert Rose and Brian Schwartz,
Co-Leaders

A. OBJECTIVES:

Develop ductile 15-tesla superconducting materials for national fusion program applications.

B. RESEARCH PROJECTS:

- Development of in situ materials
- Development of powder metallurgy materials
- Development of ultrafine filamentary composites
- Development of fine filament modeling programs

C. PERSONNEL:

Faculty:

T.P. Orlando, R.M. Rose

Research Staff:

S.F. Cogan, S. Foner, J. Otubo, S. Pourrahimi, B.B. Schwartz, H. Zhang

Technical Support Staff:

J. Conlon, I. Puffer

Graduate Students:

J.D. Klein, Soon-Ju Kwon, J. Landis

Undergraduate Students:

C. Braun, P. VanLare

UROP Students: P. Goldwhite, L. Granick, J. Parse

Support Staff:

L. Lawrence, Staff Assistant

M. Filoso, Sr. Editorial Assistant

D. SPECIAL EQUIPMENT AND FACILITIES:

Special Facilities:

- Instron Test Facility at LHe and 18.5 T for small wire tests
- 18 T, 5 cm bore Bitter coil
- 23 T, 3 cm bore Bitter coil

E. TECHNICAL PROGRAM SUMMARY:

A basic program in advanced superconducting materials has been initiated. The objective is to develop materials and techniques for producing superconductors capable of generating 15-tesla magnetic fields suitable for advanced fusion devices. This work concentrates on finely-divided materials. The purpose of this project is to develop relatively strong, ductile high-field superconductors. In essence, these properties consist of the ability to carry 10^5 A/cm^2 at 15 T magnetic field; to sustain at least 2% static strain without significant degradation of these properties; and to sustain at least 0.5% cyclic strains (superimposed) without degradation, or at least to stabilize properties at an acceptable level under such loading.

The program involves several activity components:

- Development and characterization of "in situ" multifilamentary superconducting materials
- Development of cold powder metallurgy process for multifilamentary superconducting materials
- Composite micromechanics and fatigue models
- Development of microfilamentary composites
- Ultrafine filamentary materials
- AC losses at high magnetic fields
- New materials using in situ and powder metallurgy processes
- Technology transfer and scale up technologies

Most of the facilities required for this research already exist at MIT. Mechanical properties at high magnetic fields and low temperatures are measured at the Francis Bitter National Magnet Laboratory in apparatus constructed for the above purpose. Composites are fabricated in the facilities of the Department of Materials Science and Engineering at MIT, beginning with machining, electron beam welding and extrusion, through wire drawing, plating and heat treatment to the final product. Analytical facilities (electron microscopy, computation, etc.) are all available at MIT. The "in situ" and cold powder metallurgy and Nb-Sn-In samples are prepared at the Magnet Laboratory making use of swaging, rod rolling, wire drawing, heat treatment, metallographic and hardness testing, plating and associated facilities at the National Magnet Laboratory as well as the analytical facilities of the Materials Research Laboratory and facilities of the Department. The initial scale-up runs for the fast casting technique have been carried out at Prof. Flemings' laboratory at MIT. In addition to MIT's excellent facilities, the metallurgical capabilities of IREQ in Canada (Roberge) and the facility of the University of Geneva (Flukiger) have been used to prepare additional as well as specialized materials. Scale-up activities are carried out at MIT and collaboratively (at the Bekaert Steel Wire Corporation, Teledyne Wah Chang, Airco, and IREQ, Hydro-Quebec and Intermagnetics General Corporation) or on a subcontract basis (intermagnetics General Corporation and Magnetic Corporation of America).

4. DIVERTOR DEVELOPMENT GROUP

T.-F. Yang, Leader

A. OBJECTIVES:

Develop divertor designs and divertor technology suitable for fusion program applications. Design and construct specific divertor systems.

B. RESEARCH PROJECTS:

- Develop magnetic divertor concepts
- Design and construction of the ISX-B bundle divertor
- Scoping study of TEXTOR bundle divertor
- Develop divertor designs for FED

C. PERSONNEL:

Faculty:
B. Mikić, N. Todreas
Research Staff:
D. Blackfield, E. Rapperport, T. Yang
Graduate Students:
P. Gierszewski, A. Wan
Secretary:
A. Kotsopoulos

D. TECHNICAL PROGRAM SUMMARY:

Several advanced bundle divertor configurations which consist of arrangements of L-shaped coils have been developed. The parametric study and particle confinement tests for these configurations are under way.

The bundle divertor for the ISX-B tokamak at ORNL has recently been fabricated at MIT. The 5 MW, 6-tesla copper coils required careful thermal and stress analysis. The sophisticated mounting structure required careful finite element analysis, and numerically controlled machining. The completed and magnetically tested divertor was delivered in September, 1981 and is awaiting installation on ISX-B.

There has been recent interest in construction of an advanced bundle divertor for the German TEXTOR tokamak utilizing the MIT designs. The current density requirements of these improved designs are sufficiently low that a superconducting magnet could be considered for this application. Preliminary scoping studies have been initiated.

Scoping designs suitable for reactor application are also being undertaken. Initial results indicate that it will be feasible to utilize superconducting magnets. Scoping designs suitable for FED and INTOR and based on the reactor relevant designs have also been carried out.

There are advantages to limiting the neutron shielding in the bundle divertor to the minimum level. The more stringent limitation appears to be the organic insulators typically used with normal or superconducting magnet designs. Therefore a small program has been undertaken to find a suitable form of inorganic insulation. Properly anodized aluminum tapes continue to show promise.

PLASMA FUSION CENTER

V. FUSION SYSTEMS DIVISION

DANIEL R. COHN, HEAD

A. OBJECTIVES:

Participate in overall design and reactor physics investigations of the next generation of major toroidal fusion devices. Increase understanding of the potential characteristics and technology requirements of power-producing fusion reactors. Develop new reactor design concepts. Develop advanced component technology.

B. GROUPS:

- Fusion Systems Studies
  Daniel Cohn, Leader
- Safety and Environmental Studies
  Mujid Kazimi, Leader
- Gyrotron and Advanced Millimeter Source Development
  Richard Temkin, Leader

C. PROJECTS:

- High Power Submillimeter Laser Thomson Scattering System
  Paul Woskoboinikow, Leader
- Submillimeter Wave Technology Development
  Harold Fetterman and Peter Tannenwald, Co-leaders

The purpose of the system studies programs in the Fusion Systems Division is (a) to contribute to the conceptual design basis for the construction of the next generation of major toroidal devices, (b) to deepen understanding of the potential features of power-producing fusion reactors and to develop new design concepts, and (c) to provide guidance in the development

of fusion energy technology. Present system studies programs include: scoping studies of tokamak reactors with high performance resistive magnets, hybrid tokamak-stellarator reactor design studies, and improved torsatron reactor designs. In addition, there are investigations of reactor operation with advanced fuels, advanced first wall and blanket designs, and safety issues connected with possibilities of lithium fires and tritium releases. Design studies of tokamak reactors with high performance resistive magnets have pointed out significant new possibilities for exploiting the potential of the tokamak as a compact device with relatively low plant cost, high power density and high values of $n\tau_E$.

There are two advanced component development programs in the Fusion Systems Division. High frequency ($\sim$140 GHz) gyrotron designs have been developed, and 100 kW level, 10 μs, pulsed devices are being built and tested. The purpose of the program is to provide a basis for the production of devices for millimeter wave plasma heating. Submillimeter source development includes the construction of a high power 385 μm D_2O laser for Thomson scattering and the development of compact solid state sources for low power diagnostic applications. Advanced millimeter and submillimeter wave Schottky barrier diode detectors are being produced by Lincoln Laboratory for use by DOE Laboratories in a variety of plasma confinement studies. This program also involves further development of these detectors.

1. FUSION SYSTEMS STUDIES GROUP

Daniel R. Cohn, Leader

A. OBJECTIVES:

Develop new system and subsystem concepts for the design and operation of toroidal fusion reactors.

B. RESEARCH PROJECTS:

- Scoping studies of high performance tokamak reactors for DD-DT advanced fuel operation
  L. Bromberg, Project Leader
- Study of compact FED design with high performance resistive magnets
  J. Williams, Project Leader
- Hybrid tokamak -- stellarator reactor scoping study
- Scoping study of improved torsatron reactors
- Development of advanced first wall and blanket designs
  J. Meyer, Project Leader

C. PERSONNEL:

Research Staff:
H. Becker, E. Bobrov, L. Bromberg, D. Cohn, N. Diatchenko, L. Lidsky, J. Meyer, R. Potok, J.E.C. Williams
Graduate Students:
J. Doyle, R. LeClaire
Secretary:
L. DiMauro

D. SPECIAL EQUIPMENT AND FACILITIES

Computer Equipment:
2 TI 745 portable terminals

E. TECHNICAL PROGRAM SUMMARY:

This activity involves the development of new concepts and engineering designs for toroidal fusion reactors. Both test reactors and commercial reactors are being studied.

To summarize recent achievements, new design concepts have been developed for tokamak reactors with high performance resistive magnets. These devices could serve as compact ignition test reactors and physics/engineering test reactors. High performance versions could operate with advanced fuel mixtures. High magnetic fields are used to produce high values of $n\tau_E$ and fusion power density. The inboard blanket/shield thickness is minimized to facilitate compact designs and exploit the potential of the tokamak as a low-unit-cost device. Tradeoffs that result from operation in the DD-DT advanced fuel mode, with a required tritium breeding ratio between 0 and 1, have been investigated. A range of designs developed for advanced fusion test reactor (AFTR) devices indicate that this approach can provide very significant advantages in compactness, simplicity, high $n\tau_E$ and high power density.

To summarize future plans, improved design concepts for compact tokamak test reactors with resistive magnets will be developed. New approaches to minimize inboard blanket/shield thickness will be investigated. More detailed studies of maintenance operations will be carried out. Prospects for commercial applications will be more fully evaluated, and designs of first walls which can sustain high wall loading will be studied. A scoping study of physics and engineering constraints on hybrid tokamak-stellarator designs will be completed, and a study of improved torsatron reactor design concepts will be initiated.

2. SAFETY AND ENVIRONMENTAL STUDIES GROUP

Mujid Kazimi, Leader

A. OBJECTIVES:

Develop the methodology and quantitative tools for safety and environmental analysis of fusion reactor power plants. Apply safety-related criteria to fusion reactor design.

B. PROJECTS:

- Develop methodology for radiological hazard assessment
- Lithium fire modeling and mitigation
- Tritium modeling assessment
- Assessment of structural response to plasma disruption

C. PERSONNEL:

Research Staff:
M. Kazimi, L.M. Lidsky, N.C. Rasmussen
Graduate Students:
V. Gilberti, D. Hanchar, S. Piet, M. Tillack
Undergraduate Students:
J. Mullany, E. Wilcox

D. TECHNICAL PROGRAM SUMMARY:

The overall objectives of this program are the development of a methodology suitable for safety and environmental analysis of proposed fusion reactor power plants and the development of criteria to guide fusion reactor designs in order to ensure admissible environmental risks.

A major task in progress has been to evaluate the impact that different first wall/blanket materials have on the safety of a fusion plant. To accomplish this evaluation, seven basic designs have been chosen to span the various options for the materials choices. They include four blanket coolants: water, helium, lithium and flibe. Several compatible structural materials and tritium breeding materials have been included in this study. The radiological consequences of accidental events in the seven plant conceptual designs are being evaluated. The events include loss of piping integrity and loss of coolant flow capability under operational and decay-heat conditions. It has been found that the levels of activation-product inventory vary within an order of magnitude, while the tritium inventories in the blanket breeder could vary by three orders of magnitude. Oxidation of the structural materials (corrosion) plays a significant role in mobilizing (during normal operation) the activity of the structural materials for water and lithium. Sputtering dominates as a source of activation mobilization in helium-cooled reactors. Accidental releases of activation products to the atmosphere from vanadium, as a structural material, are less consequential than steel or TZM. Detailed results of this study will be published during the coming year.

The lithium combustion model (LITFIRE) has been applied to the conditions of the scoping experiments performed at the Hanford Engineering Development Laboratories (HEDL). The comparison between the predicted and observed results led to few adjustments in the description of heat and mass transfer functions. In general, the initial model overpredicted the rate of atmospheric heating in the building confining the lithium fire.

The LITFIRE model has also been extended to describe the phsycial and chemical processes occurring during an accidental contact of water and a lithium compound (the tritium breeding material). This has been applied to investigate the consequences of hypothetical reactions in the NUWMAK reactor design. Various breeding materials were considered. The results indicate that pure lithium leads to a higher temperature generation within the blanket than the other materials. The compounds Li_2Pb_7 and LiO_2 lead to the lowest heating rates. This model will be further refined to account for the pressurization of the interior of the blanket accompanying the exothermic reactions.

The environmental and economic acceptability of presently conceived D-T fueled fusion power plants will depend in large part on the ability to contain and handle tritium within the reactor building and to control tritium releases to the environment without incurring exorbitant costs. In order to analyze the time evolution (from reactor start-up) of the inventories, a transient tritium permeation model was developed based on a simplified conceptual fusion reactor design. The major design constraints employed in the model for the fusion plant were the use of a solid breeder blanket, a low-pressure purge gas in the blanket and high-pressure (helium) primary coolant. Both diffusive hold-up and solubility considerations were found to be important contributors to the solid breeder tritium inventory, while fluid resistance to permeation offered by the primary coolant in the heat transfer loop, although included in the model, was found to be negligible compared to the resistance offered by the primary containment metal. Using the STARFIRE-Interim Reference Design system parameters as input, the model predicted a total tritium inventory of approximately 4.5 kg after 18 days for the LiO_2 breeder. The addition of oxygen (up to a partial pressure of 10^{-13} torr) to the primary coolant loop was required in order to keep the tritium losses through the heat exchanger (and, hence, to the environment) to within the design goal of 0.1 Ci/day.

An assessment has been made of the total risk to human life implied by all the activities associated with electricity generation from fusion. This includes the expected mining, manufacturing and construction activities related to the power plant as well as the operation and maintenance of the plant. The results were compared to published risk assessments for electricity generation from other sources. The total power cycle risk from fusion was found to be comparable to (if not less than) the lowest risk imposed by the alternative energy sources.

Future plans, within the next five years, include the following activities: (a) carry out experiments to determine the characteristics of the important phenomena that affect the behavior of materials used in fusion plants under abnormal condition (e.g., oxidation rates at high temperature); (b) completion of safety evaluation of reactor concepts other than the lithium-cooled tokamak; (c) study analytically and experimentally structural response to plasma disruptions in actual plasma-driven devices.

3. GYROTRON AND ADVANCED MILLIMETER SOURCE DEVELOPMENT GROUP

Richard J. Temkin, Leader

A. OBJECTIVES:

- Experimental research on high power (100 kW), high frequency (140 GHz) gyrotrons for use in electron cyclotron heating of plasmas.
- Basic theory of the electron cyclotron maser interaction in waveguide and optical configurations.
- Experimental and theoretical studies of irregular gyrotron resonators.
- Theoretical and experimental research on laser-pumped, far infrared molecular lasers. Studies of laser tuning and efficiency enhancement.

B. RESEARCH PROJECTS:

Gyrotron Research:

- Development of a 100 kW 140 GHz pulsed gyrotron
- Theoretical studies of high-frequency gyrotron design
- Theoretical and experimental studies of nonuniform resonators

Laser-pumped Far Infrared Molecular Gas Lasers:

- Development of a pulsed, far infrared laser continuously tunable from 150-1200 μm
- Theory of efficiency enhancement techniques for far infrared lasers

C. PERSONNEL:

Research Staff:

D. Cohn, R.C. Davidson, H. Fetterman, K. Kreischer, B. Lax, W. Mulligan, R. Temkin, P. Woskoboinikow

Consultant:

C. Chase

Graduate Students:

B. Danly, S. MacCabe

Undergraduate Student:

R. Chaplya

Secretary:

L. DiMauro

D. SPECIAL EQUIPMENT AND FACILITIES:

Experimental Facilities:

- Bitter copper solenoid with 10.48 cm bore, modified by two auxiliary electron gun solenoids, for gyrotron operation at up to 10 T using the National Magnet Laboratory magnet power supply.
- Continuously tunable (9-11 μm), transversely excited 10-atmosphere CO_2 laser, operating in 100 ns pulses at 5 MW output power in 100 ns pulses. CO_2 TEA oscillator-amplifier single-mode laser with output power of 30 MW.

E. TECHNICAL PROGRAM SUMMARY:

This technical program consists of two main projects. The first project, sponsored by the Department of Energy, includes experimental and theoretical research on high-frequency gyrotrons. The second project, sponsored by the National Science Foundation, consists of experimental and theoretical research on laser-pumped, far infrared molecular gas lasers. These projects are interrelated in several ways: they share a common goal of generating coherent millimeter wave radiation; they share personnel; and they often share equipment, such as detectors and interferometers. In addition, there is a strong interaction between the activities of this group and those of the Diagnostics and Laser Development Group.

The gyrotron development program is devoted to the experimental and theoretical investigation of advanced concepts for high-power (100 kW), high-frequency (140 GHz) gyrotrons. A gyrotron is a microwave tube operating in a uniform high magnetic field (5 T) and emitting electron cyclotron radiation. The purpose of this program is to demonstrate new techniques for achieving efficient, single-mode emission and improved output coupling in the high-frequency region. A second purpose of the program is to establish a sound theoretical basis for predicting the efficiency and mode characteristics of high-power, high-frequency gyrotrons. A third purpose of this program is to develop new diagnostics to evaluate gyrotron performance. The results of this program will be useful to the industrial gyrotron programs for the development of high-frequency gyrotron systems.

In the planned experiments, the voltage will be 65 kV, the current 5 A, the pulse length 1 μs and the output power 100 kW. Among the unique features of the program is the investigation of gyrotron operation in a whispering gallery mode (TE_{511}, TE_{611}, TE_{711}). Whispering gallery modes are used in high-power gyrotrons developed in the USSR. A second unique feature is the investigation of gyrotron operation in an azimuthally symmetric mode (TE_{021}, TE_{031}, TE_{041}) with an electron beam placed at the second radial maximum of the RF field (vs. the first radial maximum in the industrial tubes). Placement of the electron beam at a higher radial maximum may be necessary in very high-power, higher-frequency gyrotrons in order to reduce space charge effects and electron velocity spread. Initial gyrotron operation is expected in early 1982.

A theoretical effort in the linear and nonlinear behavior of gyrotrons has been carried out in support of the experiments. Both waveguide and quasi-optical gyrotron devices have been investigated. Theoretical results for irregular gyrotron cavities which optimize efficiency and improve mode spacing have been obtained. Experimental tests of the theory are being conducted using X-band and K-band models.

The laser research program is devoted to demonstrating and studying, for the first time, wide-range tuning of a far infrared (FIR), laser-pumped molecular gas laser system. The pump laser is a continuously tunable, 10-atmosphere, 100 ns pulsed CO_2 laser. The FIR laser is a waveguide laser using a gas such as CH_3F. FIR laser emission occurs via a stimulated, near-resonant Raman process with output at about the kW power level. Tuning of the pump-laser frequency results in equal tuning of the FIR laser frequency in order to maintain the Raman, two-photon resonance condition. Previous experiments at the PFC using a grating-tuned CO_2 TEA laser indicate that continuous tuning from 150 to 1200 μm should be feasible with modest pump-laser power (1 or 2 MW). The experiments will test the physics of the tuning process, the nature of tuning steps, the threshold for high-intensity, off-resonance laser pumping, the onset of various multiphoton processes and the rates of molecular excitation and relaxation. Tuning will be investigated in a variety of gases and at both near and far infrared wavelengths. A quantum mechanical theory will be developed, using the density matrix approach, to predict the saturated FIR laser output vs. pump-laser power and frequency in various gases. This research will lead to further understanding of laser pumping of molecular gases, as well as to the demonstration of a widely tunable, far infrared laser.

4. HIGH POWER SUBMILLIMETER LASER THOMSON SCATTERING SYSTEM

Paul Woskoboinikow, Project Leader

A. OBJECTIVES:

Develop a submillimeter wave Thomson scattering system using high-power laser technology.

B. PERSONNEL:

Research Staff:

D. Cohn, B. Lax, W. Mulligan, F. Tambini, R. Temkin, P. Woskoboinikow

Graduate Student:

R. Erickson

Secretary:

L. DiMauro

C. SPECIAL EQUIPMENT AND FACILITIES:

Computer Equipment:

1 Digital equipment MINC minicomputer

Experimental Facilities:

Single-Mode, Tunable, 50J CO_2 Oscillator-Amplifier Laser System, Pulse Length Adjustable from 100 ns to 1 μs. Tunability of ±2 GHz on over 60 transitions with fourier transform limited bandwidth.

D. TECHNICAL PROGRAM SUMMARY:

A 500 kW, 120 ns pulse length, 385 μm D_2O laser has been developed. Laser action in D_2O is obtained by optical pumping with 9.26 μm CO_2 laser radiation. A narrow D_2O laser linewidth is obtained by use of narrow-linewidth CO_2 laser radiation. The power level of the submillimeter laser has been increased by a factor of one hundred over the course of the project. The development of an etalon-tuned (2 GHz tuning range) CO_2 laser also represents a significant advance in laser technology.

A Schottky diode heterodyne detector has been developed by Lincoln Laboratory to provide the necessary sensitivity to measure the Thomson scattered radiation. Future activities will involve efforts to develop far infrared scattering as a tool with widespread applicability for magnetic confinement studies. These activities will involve consideration of advanced high-power sources. This technology development effort contributes to the Diagnostic Development Program in the Applied Plasma Physics Division.

5. SUBMILLIMETER WAVE TECHNOLOGY

Harold Fetterman and Peter Tannenwald, Project Co-leaders

A. OBJECTIVES:

Develop new submillimeter wave sources and detector technology for plasma diagnostics.

B. LINCOLN LABORATORY PERSONNEL:

Research Staff:
B. Clifton, H. Fetterman, B. Lax, P. Tannenwald
Technical Support Personnel:
C. Parker, T. Forte
Graduate Student:
R. Lewis

C. SPECIAL EQUIPMENT AND FACILITIES:

Micro-electronics epitaxial crystal growth; photolithography and mask making, proton bombardment; ion implantation; diode packaging; submillimeter radiometers; carcinotrons; quasi-optical components; InP growth.

D. TECHNICAL PROGRAM SUMMARY:

This project involves the development of solid state sources, mixers, and advanced detectors for plasma diagnostics. In addition, state-of-the-art Schottky barrier diode detectors are provided to diagnostic groups at other fusion research laboratories.

To summarize future plans, InP devices will be developed for operation in the 150- 500 GHz range. Improved capability for harmonic generation will be obtained in Schottky diode mixers. An array detector system will be developed. This technology development effort contributes to the Diagnostics Development Program in the Applied Plasma Physics Division.

PLASMA FUSION CENTER

OFFICE OF RESOURCE MANAGEMENT

JOHN L. COCHRANE
ASSISTANT TO THE DIRECTOR FOR ADMINISTRATION

A. OBJECTIVES:

Provide key administrative support services to meet the technical goals and objectives of the Plasma Fusion Center.

B. SUPPORT SERVICES AND OPERATIONS AREAS:

- Headquarters Operations - Provides administrative support in the areas of personnel, payrolls, proposal preparation, travel, space and all other administrative functions not specifically assigned to other areas.
- Fiscal Office - Monitors detailed program spending and compliance with the contract provisions. Provides financial reports to meet both contract and PFC requirements.
- Purchasing Office - Provides on-site general purchasing and subcontracts services to all PFC activities.
- General Support Services - Services include word processing, PFC library, report dissemination, driver and messenger support.

C. PERSONNEL:

Headquarters Operations and General Support Services:

John Cochrane, Assistant to the Director for Administration

Staff:

A. Anderson, B. Colby, J. Cooper, A. Dawson, D. Florentino
M. Glidden, M. Langton, T. Lloyd, J. Peach, C. Robertson
L. Thomas

Fiscal Office:

Paul Smith, Fiscal Officer

Staff:

P. Catano, M. Gittens, R. Goodridge, J. Hagerty, S. Kenneally, A. LeBlanc, J. MacDougall, K. McMahon

Purchasing Office:

Kenneth Wisentaner, Manager

Staff:

M. Bacon, C. Fitzgerald, P. Garrity, R. Newcomb, J. Rodrigues, M. Silva, R. Stevens

RLE Administrative Support:

Don Duffy, RLE Fiscal Officer

Staff:

R. McKinnon, J. Mitchell, J. Peck, J. Scalleri, D. Taylor, V. Taylor

APPENDIX A

PLASMA FUSION CENTER
STEERING AND ADVISORY COMMITTEES

PLASMA FUSION CENTER STEERING AND ADVISORY COMMITTEES

The roles of the various PFC advisory and steering committees are summarized on page 4 of this report. The present membership of these committees is given below.

A. PFC Technical Steering Committee

George Bekefi
Abraham Bers
Daniel Cohn
Bruno Coppi
Ronald Davidson
Thomas Dupree
Jeffrey Freidberg
Mujid Kazimi
Benjamin Lax
Lawrence Lidsky
Earl Marmar
Jim McCune
D. Bruce Montgomery
Joel Moses
Ronald Parker
Peter Politzer
Miklos Porkolab
Richard Post
David Rose
Louis Smullin
John Williams

B. PFC Executive Committee

Ronald Davidson, Director
Daniel Cohn, Head, Fusion Systems Division
Lawrence Lidsky, Associate Director for Technology Development
D. Bruce Montgomery, Associate Director for Engineering Systems
Ronald Parker, Associate Director for Confinement Experiments
Richard Post, Head, Mirror Confinement Systems Division

C. PFC Visiting Committee

Dr. Charles C. Baker
Argonne National Laboratory

Dr. Terenzio Consoli
La Celle Saint-Cloud

Prof. John Dawson
University of California at
Los Angeles

Prof. Harold Furth
Princeton University

Prof. Roy Gould
California Institute of Technology

Dr. Carl Henning
Lawrence Livermore National
Laboratory

Prof. Richard F. Post Lawrence Livermore Laboratory	Dr. Paul J. Reardon Princeton University
Prof. Norman Rasmussen Massachusetts Institute of Technology	Prof. Weston M. Stacey, Jr. Georgia Institute of Technology

D. PFC Advisory Committee

Jonathan Allen
Director, Research Laboratory of Electronics

Ronald Davidson
Director, Plasma Fusion Center

John Deutch
Dean of Science

Herman Feshbach
Head, Physics Department

Joel Moses
Head, Electrical Engineering and Computer Science Department

Kenneth Smith
Vice President for Research

Neil Todreas
Head, Nuclear Engineering Department

Gerald Wilson
Dean of Engineering

Peter Wolff
Director, National Magnet Laboratory

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  C.N.E.N.-Centro Frascati, Italy
Brzosko, J.S.
  Inst. of Physics, Warsaw University
Cap, F.
  Inst. fur Theor. Physik, Innsbruck
Conn, R.W.
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Consoli, T.
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  Rijksuniversiteit, Gent, Belgium
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  Max-Planck Inst. für Plasmaphysik

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