

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

PLASMA FUSION CENTER

TECHNICAL RESEARCH PROGRAMS

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This report gives a summary of Plasma Fusion Center research activities. Particular emphasis is placed on describing (a) technical progress during the past year, (b) future plans, and (c) research programs and objectives at the individual research group level.

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Director
Plasma Fusion Center

1. INTRODUCTION AND BACKGROUND

A. Overview

The Plasma Fusion Center (PFC) is recognized as one of the leading university research laboratories in the physics and engineering aspects of magnetic confinement fusion. Its research programs have produced significant results on four fronts:

(a) the basic physics of high-temperature 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, and confinement properties of plasmas at high densities, temperatures and magnetic fields, (c) development of an innovative design for axisymmetric tandem mirrors with inboard thermal barriers, with initial operation of the TARA tandem mirror experiment scheduled for February, 1984, and (d) a broad 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 millimeter wave source development, and system studies of fusion reactor design, operation, and technology requirements).

Emphasis is placed on providing an environment that encourages technical excellence and independent creativity both at the individual researcher level and on the scale of major fusion projects such as Alcator C and TARA. An important strength of the Plasma Fusion Center, and more broadly speaking, of the Massachusetts Institute of Technology, is the ability to evolve new ideas and concepts in critical technical areas, and to train professional researchers. Therefore, there will be a continued emphasis on the involvement of additional faculty, students, and research scientists and engineers in both new and existing PFC research programs. The Plasma Fusion Center, through the

training of students and professional researchers, makes a major contribution both to MIT's educational goals and to the scientific and engineering manpower needs of the national fusion effort.

The Plasma Fusion Center's technical programs are supported principally by the Department of Energy's Office of Fusion Energy at a funding level of approximately \$24 million in FY84. There are approximately 332 personnel associated with PFC research activities. These include: 25 faculty and senior academic staff, 66 graduate students, and 14 undergraduate students, with participating faculty and students from Aeronautics and Astronautics, Electrical Engineering and Computer Science, Materials Science and Engineering, Mechanical Engineering, Nuclear Engineering, and Physics; 115 research scientists and engineers, and 10 visiting scientists; 60 technical support personnel, and 42 administrative and support 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), NW20 (PFC Alternator), and NW21 (PFC Nabisco Laboratory). A new site, NW17, to be available in May 1984, will provide additional office and laboratory space. These facilities are indicated in Figure 1, a map of the MIT campus.

B. Objectives

The general objectives of the Plasma Fusion Center are:

- Maintain a broadly-based research program in the plasma physics and engineering aspects of magnetic confinement fusion. Provide a strong interdisciplinary approach to fusion research.
- Establish the experimental data base and physics understanding required for development of the tokamak and tandem mirror confinement approaches into practical reactor concepts. Conduct

medium-scale plasma confinement experiments with a strong component of student participation.

- Maintain emphasis on technical excellence and the development and testing of innovative concepts. Provide an environment that encourages independent creativity both at the individual researcher level and on the scale of major research projects such as Alcator C and TARA.
- Contribute to an increased university role in fusion engineering and technology development through student training and research programs.

These objectives define several distinctive ways in which the Plasma Fusion Center contributes to fusion research and development.

Program Breadth and Interdisciplinary Approach: As indicated earlier, the Plasma Fusion Center has considerable technical breadth in its research programs. Such a broadly-based research program facilitates establishment of interdisciplinary activities to address complex technical issues that require a wide range of expertise.

Medium-Scale Confinement Experiments: The medium-scale PFC confinement experiments, Alcator C and TARA, are also unique assets. These facilities provide plasma performance conditions on the frontier of confinement research. At the same time, they are sufficiently modest in scale to allow testing of new concepts and detailed study of particular plasma phenomena. A large student involvement in these programs provides an excellent training in tokamak and tandem mirror confinement research.

Small-Scale Plasma Physics Experiments: The Versator tokamak and the Constance mirror devices are experimental facilities which permit rapid testing of new concepts in basic plasma physics such as wave propagation and spectroscopy, among others.

Fusion Engineering and Technology Development: In general, the size of university research programs in fusion engineering and technology development is very modest in comparison with the

national laboratories. Moreover, it is becoming more evident that an increased role for universities in fusion engineering would be of considerable technical benefit to the fusion program. As the physics data base for fusion advances, the relative priority of fusion engineering will increase. With the high cost of large-scale fusion facilities, there is a concomitant need for innovation in fusion engineering and technology development. The Plasma Fusion Center emphasizes new concept development and the training of students and researchers in several areas of fusion engineering and technology development. This, coupled with the broad engineering strengths at MIT, provides the opportunity for a continued strong engineering role in the future.

2. PLASMA FUSION CENTER RESEARCH AREAS

Plasma Fusion Center research activities are carried out in five major program areas. These are:

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

The main objectives and subprograms in each of these technical divisions are outlined briefly here. A more detailed summary of associated research activities, facilities, and staffing is given in Appendix A.

A. Applied Plasma 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
- Fusion Theory and Computations

- Basic Theory of Laboratory and Astrophysical Plasmas
- Diagnostic Development and Laser Systems
- Intense Charged Particle Beams

B. Toroidal Confinement Experiments

Objectives: Develop a basic understanding of the stability, transport and radiation properties of high-temperature toroidal plasmas at near-reactor conditions. Develop and test concepts for optimization of the toroidal confinement approach to magnetic fusion.

At the present time, the subprogram areas include:

- Alcator C Experimental Program
- Alcator DCT 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 analysis for the advanced design projects. Develop advanced superconducting materials and magnet technology.

The subprogram areas include:

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

E. Fusion Systems

Objectives: Identify and investigate critical technical issues related to the design and operation of fusion reactors. Develop advanced components.

The subprogram areas include:

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

As evident from Appendix A, virtually all of the subprograms listed here are at the individual research group and principal investigator level. These research groups are indicated in Figure 2.

3. THE NABISCO LABORATORY

Nabisco, Inc., with headquarters in East Hanover, New Jersey, announced in May, 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 in April, 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, and gypsum deck roof. The west wing of the Nabisco Laboratory was renovated in 1982-83 and is now the site of the TARA tandem mirror experiment (page 20).

As shown in Figure 1, page 3, 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

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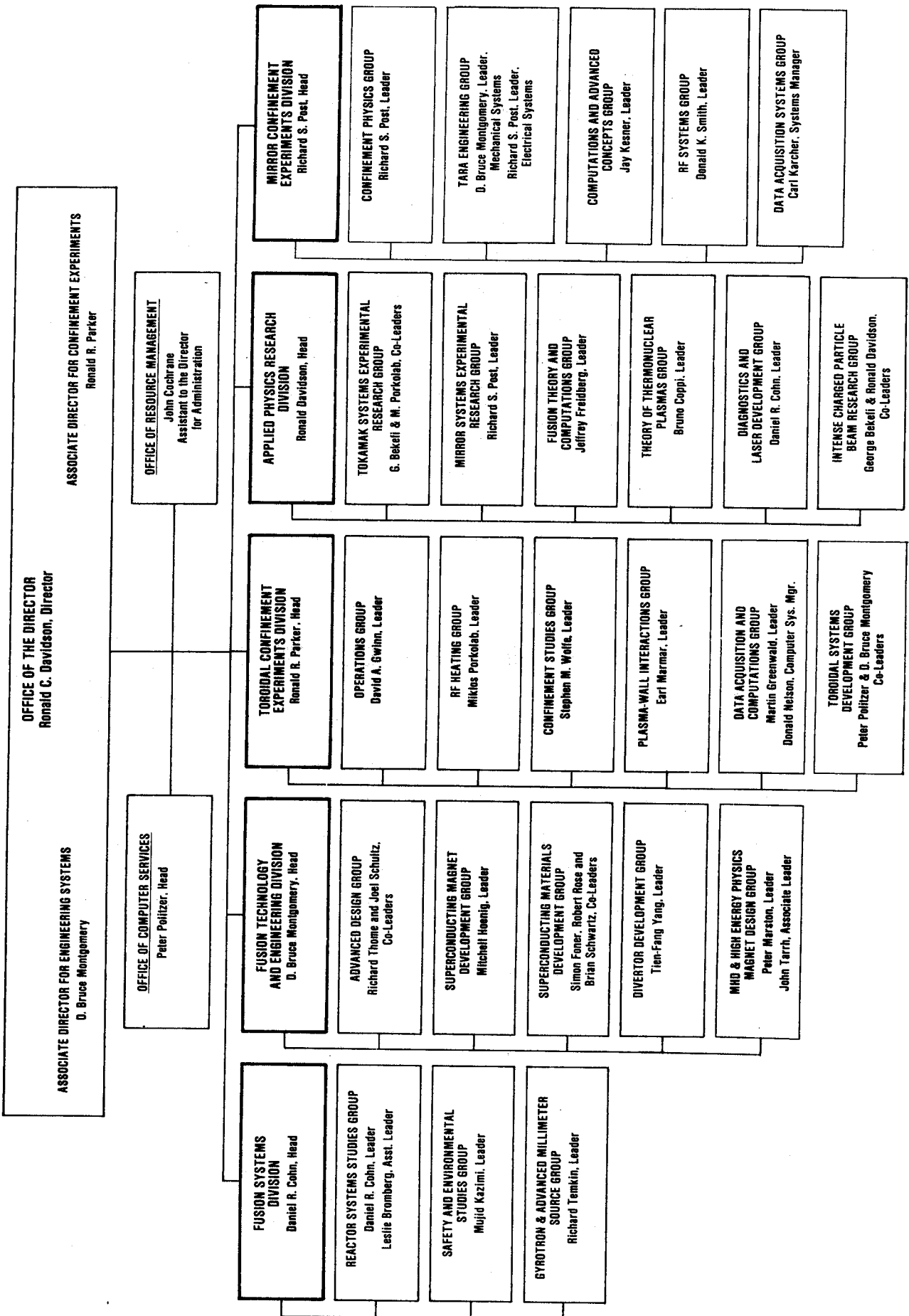


Figure 2

Nuclear Reactor Laboratory (NW12), and the Plasma Fusion research complex (NW16 and NW17). The close proximity to these facilities and to heavy power makes 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, Alcator DCT, Constance, as well as the follow-on device in the Versator experimental program.

4. HIGHLIGHTS OF 1983 RESEARCH ACTIVITIES

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

A. Applied Plasma Physics Research

The primary objective of the Plasma Fusion Center Applied Physics Research Division 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, experimental research on the Constance A and B mirror devices; fusion theory and computations; plasma diagnostics and laser development; and basic experimental and theoretical research on nonneutral plasmas and radiation generation by intense charged particle beams.

Significant progress made during the past year in selected applied plasma physics research areas is summarized below. Applied Physics Research personnel are listed in Appendix A, Section I.

Versator II is a medium-size research tokamak (major radius = 40.5 cm; minor radius = 13 cm; toroidal magnetic field = 15 kG) with primary emphasis on basic investigations of RF plasma heating and current drive. During the past year, a series of

experiments has been carried out testing the interaction of lower-hybrid waves, in various density regimes, with electrons and ions. In the low-density regime ($\bar{n} < 10^{13} \text{ cm}^{-3}$) traveling lower-hybrid waves launched from a phased array of waveguides can impart net momentum to plasma electrons thereby generating a plasma current. Such wave-generated currents may eventually be used to drive the current in a steady-state tokamak fusion reactor.

X-ray spectroscopic measurements on Versator II have shown that wave absorption generates suprathreshold energetic electron components in the energy range 10-100 keV $\gg T_e \sim 0.4$ keV, and that this electron component is generated near the center of the plasma cross section in qualitative agreement with theoretical predictions.

The confinement of particles in tokamaks has loss rates 10-100 times those predicted by collisional transport theory. This anomaly is one of the outstanding unsolved problems in tokamak confinement physics. The Versator II current drive experiments have recently shown that the particle confinement in discharges with RF-driven currents is improved by at least a factor of two relative to discharges with ohmically-driven currents. Further experimentation is required to identify the mechanism for the improved confinement.

In the higher density regime ($\bar{n} \gtrsim 2 \times 10^{13} \text{ cm}^{-3}$), the dispersion of the lower-hybrid wave allows direct interaction and absorption of the wave by the ion component. In Versator II, such wave-ion interaction has been observed experimentally. Ion heating with temperature increase of 40% ($\Delta T_i = 50$ eV) has been obtained by injecting 50 kW of power at $f = 800$ MHz through a four-waveguide array. Further experimentation is required to clarify the heating process.

The theory of lower-hybrid wave propagation in a toroidal plasma predicts that waves launched from the top of the torus will be absorbed more efficiently than those launched from the midplane. Previous experiments have used midplane couplers due

to space limitations. Recently, however, a four-waveguide top-launching coupler has been constructed and installed on Versator II. The technological problems associated with high-power operation of this antenna array have been overcome by coating the vacuum surfaces of the antenna with carbon to minimize secondary electron production. The power transmission of the antenna without carbon coating was limited to 15 kW breakdown in the waveguides. After carbon coating and RF processing to remove hydrogen from the surface, up to 100 kW have been coupled successfully to the plasma with this antenna. High-power experiments are now underway with the top coupler.

During the past year, three graduate students have completed their thesis research on Versator II, and planning for two future experiments has been carried out. Construction has begun on a new power system for Versator II which will allow tokamak operation with current supported by RF current drive only. The new system will initiate the tokamak discharge with an inductively-driven current, then allow for a fully-RF-driven phase where the current will be supported by RF alone.

Construction of a lower-hybrid RF system at higher frequency ($f = 2.45$ GHz) is also underway. The purpose of the new system is to drive current in higher density plasma ($\bar{n} \geq 10^{13} \text{ cm}^{-3}$) than is possible with the present 800 MHz system, thereby testing the frequency dependence of the current-drive mechanism.

The Constance research effort during the past year has concentrated on the design and construction of the new Constance A and B mirror facilities in the Nabisco Laboratory (NW21). Constance B, a quadrupole mirror of moderate size, has been designed to study hot electron production, ion pump-out, and radial electric field control and analysis. Constance A, an upgrade of the Constance II experiment, is concerned with similar physics issues but in axisymmetric systems. Constance B is now in operation in the west wing of the Nabisco Laboratory.

Hot electron plasmas ($T_e \sim 400$ keV, $n \sim 5 \times 10^{11} \text{ cm}^{-3}$) are generated in Constance B using electron cyclotron resonant heating

(ECRH). Up to 1 kW of microwave power at either 8 GHz or 11 GHz is available. Microstability properties and plasma beta are being studied as a function of the cold plasma population. A major long-term experimental goal will be the generation of a negative ambipolar potential.

In support of both experiments, a 3-D orbit code and analytical techniques have been developed to study RF pump-out techniques of ions at the ion bounce and drift frequency. By applying a perpendicular magnetic field driven at the ion bounce frequency, together with the self-consistent electric field, large radial drifts in the ion motion can be produced. This process works in both symmetric and quadrupole fields and will be tested experimentally in Constance B. While theory shows a factor of ten enhancement in the radial diffusion coefficient in the quadrupole case relative to the axisymmetric case, encouraging results from Constance B will certainly warrant further work along these lines in Constance A. Radial electric field control techniques are also being evaluated in Constance A and B. The stability of magnetic mirrors against trapped-particle modes is contingent on the ability to control the plasma radial potential profile.

During the past year, construction of an acousto-optic RF spectrometer has been completed which will allow acquisition of wide-bandwidth (500 MHz), high-resolution (1 MHz) spectra at a high repetition rate (1 spectrum every 10 microseconds). The spectrometer and its associated microwave receiver will provide spectral coverage over the frequency range from 5 MHz up to 4 GHz.

In the area of relativistic electron beams a new type of free electron laser has been proposed and tested experimentally both at MIT and in collaboration with a rotating electron ring facility at the University of Maryland. In these experiments a samarium cobalt magnetic wiggler is placed along the periphery of a rotating ring of electrons moving at relativistic velocities. Intense radiation has been observed in the millimeter wavelength

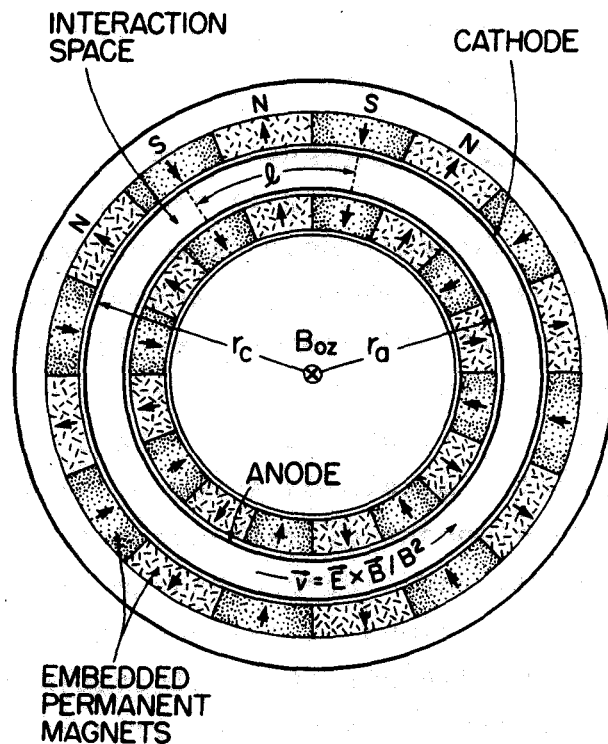


Figure 3a. Schematic diagram of a circular free electron laser ("rippled field magnetron"), showing the positioning of the wiggler magnets relative to circulating electrons.

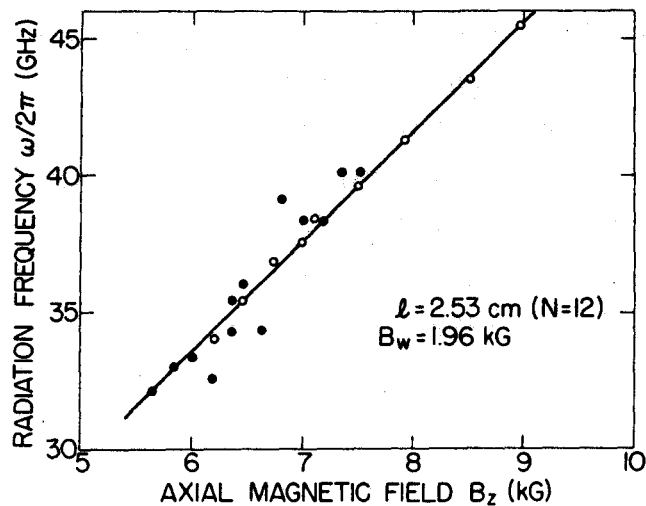


Figure 3b. Measured radiation frequency as a function of the axial magnetic field for a wiggler of 2.53 cm and 1.96 kG strength.

regime. In the MIT experiments the narrow band radiation can be tuned continuously simply by varying the confining axial magnetic field. A schematic of the configuration is shown in Fig. 3.

In the plasma theory and computations area, there has been considerable progress in a variety of important areas. Recent studies include: (a) the continued development of self-consistent plasma models which simultaneously include the effect of neoclassical transport and plasma turbulence, (b) the formulation of a nonlinear kinetic theory of tearing modes, to explain the MHD density limit in Alcator C, (c) the investigation of the stabilizing effects of limiters on external kink mode stability, (d) the continued development of self-consistent theoretical models describing anomalous electron energy transport in tokamaks, (e) 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), (f) the development of a self-consistent kinetic description of the free electron laser instability including the important influence of novel magnetic field configurations and finite radial geometry, (g) 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, (h) development of a 2-D self-consistent model of RF current drive with lower hybrid waves that shows a large (one to two orders-of-magnitude) enhancement of perpendicular temperature of the current carrying electrons, (i) studies of the thermal stability of ignited plasmas, (j) fundamental nonlinear studies of the influence of stochastic magnetic fields on turbulent transport in high-temperature plasmas, and (k) basic studies relating to the equilibrium, stability and transport properties of high-field tokamak configurations using advanced fuels (e.g., D-He³).

In the plasma diagnostic development area, a high-power 385 μm D₂O laser and a Schottky barrier diode heterodyne detector have been used on Alcator C to make the first measurements of

thermal level Thomson scattering in tokamak plasmas. The scattered radiation is broadened in frequency by the Doppler shift due to the ion thermal velocity. The measured broadening was found to be consistent with other determinations of ion temperature. These measurements of thermal level Thomson scattering show the feasibility of the eventual use of Thomson scattering as a means of localized determination of ion temperature in high temperature plasmas of interest in fusion research.

As a result of extensive experimental work, computer simulation, and theoretical studies, free electron laser research has reached a high level of maturity. At MIT, efforts have been concentrated on free electron lasers operating in the high-current (Raman) regime. Particular success has been achieved in the construction and operation of a circular free electron laser in which the electrons orbit in an azimuthally periodic magnetic field. There is also continued emphasis on developing novel concepts for coherent radiation generation.

B. Alcator Confinement Experiments

The Alcator experimental program continues to be one of the most successful and prominent tokamak confinement programs within the international fusion research community. The primary objectives of the Alcator experimental program are to develop the basic physics understanding of the stability, transport and radiation properties of high-temperature plasmas at near-reactor conditions and to develop radio-frequency methods for driving currents and plasma heating at moderate densities. The main Alcator experimental areas include: device operations; confinement studies; plasma-wall interactions; radio frequency heating; and data acquisition and computations. Design efforts on a follow-up device to the Alcator C experiment have been intensified during the past year by the toroidal systems development group. These efforts are now focused on a superconducting high-field tokamak, Alcator DCT, capable of a very long pulse or steady-state operation. Alcator personnel are listed in Appendix A, Section II.

Alcator C: The confinement studies of plasmas under conditions of intense ohmic heating, the first phase of the Alcator C research program, have been extended by the use of pneumatically-injected pellets of frozen hydrogen. This fueling technique results in deposition profiles which are peaked much closer to the magnetic axis than is possible with the conventional gas-puffing procedure. The resulting adiabatic plasma response yields temperature profiles which are not in equilibrium with the pre-injection current density profile. The ensuing relaxation process of both the temperature and density radial profile provides useful information concerning the MHD stability of tokamak plasmas and also the particle diffusion coefficient.

In addition to providing basic information on plasma behavior, pellet injection has permitted tokamak operation at record plasma densities, nearly $2 \times 10^{15} \text{ cm}^{-3}$ near the magnetic axis. There is also evidence that energy confinement under conditions of pellet injection is improved over the conventional gas-puffing case. The combination of very high density and improved energy confinement time τ_E has resulted in advancement of the Lawson parameter $n_0 \tau_E$ to a maximum value of about $0.8 \times 10^{14} \text{ cm}^{-3}\text{-s}$, a value slightly in excess of that required for energy breakeven at higher temperature. Further experiments aimed at advancing the Lawson parameter at plasma currents approaching 1 MA are scheduled for the coming year.

The Alcator C tokamak (major radius = 64 cm, minor radius = 16.5 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 $a = 16.5$ cm and toroidal field $B_T = 120$ kG, the "best" parameters produced in the Alcator C device during this period are: line-averaged density $\bar{n} = 8 \times 10^{14} \text{ cm}^{-3}$, central density $n_0 \sim 20 \times 10^{14} \text{ cm}^{-3}$, electron and ion temperatures of 3 keV and 1.6 keV, respectively, plasma currents of 780 kA, and energy confinement times of approximately 50 ms. These results represent the first achievement of the so-called Lawson criterion, in which the product of the density and confinement

time must exceed $6 \times 10^{13} \text{ cm}^{-3} \text{ s}$. In Alcator C values of $n_0 \tau_E$ $7-9 \times 10^{13} \text{ cm}^{-3} \text{ s}$ have been obtained. Furthermore, central plasma pressures of 8.1 atmospheres and volume-averaged pressures of 1.6 atmospheres have been produced. For reduced limiter size with minor radius $a = 10 \text{ cm}$, major radius $R = 58 \text{ cm}$ and toroidal field $B_T = 120 \text{ kG}$, the best parameters achieved are line-averaged density $\bar{n} = 8 \times 10^{14} \text{ cm}^{-3}$, central density $n_0 = 1.2 \times 10^{15} \text{ cm}^{-3}$, energy confinement time $\tau_E \approx 27 \text{ ms}$, and corresponding value of the Lawson parameter $n_0 \tau_E \approx 0.3 \times 10^{14} \text{ cm}^{-3} \text{ s}$.

Although Alcator C has performed up to design expectations in most areas, an exception had been in the measured value of energy confinement time τ_E when the minor radius $a = 16.5 \text{ cm}$ and the fueling was by gas puffing at the plasma edge. 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 $2 \times 10^{14} \text{ cm}^{-3}$, it was 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.

The results with pellet fueling show that at higher densities the energy confinement is improved when compared to that obtained in the edge fueling cases. In fact, the improvement makes the energy confinement consistent with the extrapolation of Alcator A results and consistent with neoclassical ion energy transport.

RF Heating and Current Drive: Substantial progress has been made in the second phase of the Alcator C experimental program, namely, the use of high power radio frequency (RF) waves to raise the plasma temperature, and to develop the concept of RF current drive. In experiments carried out during the past year, two sixteen-waveguide-array antennae have been used to couple over 1 MW of RF power at 4.6 GHz into Alcator C over a wide range of

es. In the density range of $1 \times 10^{13} < \bar{n}(\text{cm}^{-3}) < 1 \times 10^{14}$, generated toroidal currents of the order of $I \approx 230$ kA have been observed for time durations of up to 0.5 s. This is achieved by launching travelling waves and preferentially heating high energy electrons with energies up to a few hundred keV. RF current generation in Alcator C is achieved at record density levels because of the high frequencies chosen for the microwave sources. For example, in the PLT tokamak at Princeton, where 0.8 GHz frequency sources were chosen, flat-top toroidal currents could be generated only at densities below $1 \times 10^{13} \text{ cm}^{-3}$.

When the density is raised to the regime $1 \times 10^{14} < \bar{n}(\text{cm}^{-3}) < 2 \times 10^{14}$, and the waveguide arrays are phased so as to produce a standing wave at the waveguide mouths, significant plasma heating is observed. Initial measurements indicate that by injecting 850 kW of RF power at the reactor-level density of $\bar{n} \approx 1.5 \times 10^{14} \text{ cm}^{-3}$, the electron temperature was raised from $T_e \approx 2.0$ keV to values $T_e \gtrsim 3.0$ keV, and the ion temperature was raised from $T_i \approx 1.1$ keV to 1.9 keV. These results, which were obtained by using SiC coated carbon limiters, correspond to a heating rate of $n(\Delta T_e + \Delta T_i) \gtrsim 20 \text{ eV} \times 10^{13} \text{ cm}^{-3} / \text{kW}$, a record value. In fact, no other experiment with any type of heating technique has previously produced such a significant heating at the high density typical of these experiments. At the same time there is significant increase in the plasma impurity level. However, these experiments operate at record surface power flux levels which approach (within a factor of two) the expected equivalent thermal flux in a reactor. These results, therefore, indicate the necessity of active impurity control in future reactor-grade plasma devices.

Two additional 16 waveguide arrays are being constructed to inject up to 2 MW of RF power in early 1984. Assuming that the impurity influx can be controlled, further increase is expected in the RF currents generated, and in the electron and ion temperature rise. Meanwhile, a 600 kW ICRF (ion cyclotron resonance

heating) experiment operating at 186 MHz (2nd proton cyclotron harmonic) has been installed in Alcator C. This system combines one of the lower-hybrid power supply (modulator) units, and the FPS-17 radar system donated to the Plasma Fusion Center by the U.S. Air Force.

Advanced Toroidal Development: Design work during the past year has centered on the Alcator DCT tokamak concept, a long-pulse/steady-state superconducting device which will address physics and technology issues critical to the realization of a continuous or quasi-continuous toroidal reactor. The objectives of the program include plasma shape and profile control during long-pulse and steady-state operation with high power loading, and optimization of noninductive (RF) current drive techniques and RF heating with reactor-level plasma parameters. In the technology area, the design provides integration of superconducting magnet systems in an operating tokamak environment and serves as a focus for development and testing of first wall, limiter and divertor materials and configurations.

The proposed Alcator DCT device is a superconducting tokamak with major radius of 2.0 m, minor radius of 0.4 m and an axial toroidal field of 7 T corresponding to 10 tesla at the coil, while the poloidal field system provides a flux swing of 35 volt-seconds, permitting inductively-driven pulse lengths of several minutes. Both poloidal field (PF) and toroidal field (TF) magnets are entirely superconducting and can be operated continuously at full performance. The plasma major and minor radii are 2 m and 0.4 m respectively. The PF system permits plasma currents of at least 1 MA ($q = 3$, circular), allows elongations of 1.5 and produces a single-null divertor configuration with external coils. The baseline auxiliary heating package provides 4 MW of CW power at 4.6 GHz for lower hybrid (LH) heating and current drive, and 5 MW of CW power at 200 MHz for ion cyclotron frequency heating. The LH power can be used either to heat electrons or to drive current, a feature which allows the possibility of true steady-state operation. An isometric view of

the proposed Alcator DCT is presented in Figure 4. Engineering and physics parameters are summarized in Table 1.

Extension of the pulse length to a duration greater than 100 s in a medium-scale experiment such as the proposed Alcator DCT represents a crucial step in the development of the tokamak concept. Successful accomplishment of the objectives will provide essential information for large-scale tokamak test reactors such as the Tokamak Fusion Core Experiment (TFCX), and greatly enhance the potential of the pulsed tokamak as a practical reactor. Even more significant would be the attainment of a true steady-state in a tokamak operating with plasma parameters close to the reactor regime. Several important engineering advantages accrue from steady-state operation, which would lead to a substantially more attractive reactor.

C. Mirror Confinement Experiments

The Mirror Confinement Systems Division is involved in the design, construction and operation of a medium-scale tandem mirror research facility called TARA. The main objective of this research program is to develop an increased understanding of basic tandem mirror physics with emphasis on microstability properties, thermal barrier formation and RF heating. The primary research areas include: confinement physics; TARA engineering; and computations and advanced concepts. Mirror confinement personnel are listed in Appendix A, Section III.

TARA Tandem Mirror: The TARA tandem mirror facility, located in the west wing of the PFC Nabisco Laboratory (NW21), will begin operation in February, 1984. The overall fabrication project, including design, construction, and preparation for operation is a two-year, \$14.9 M effort funded by the Department of Energy. The project has included substantial site preparation in addition to fabrication of the experimental facility and all of the subsystems such as magnet power, vacuum systems, neutral beams, RF heating systems, diagnostics, and data systems and controls. This project remains within the original cost estimate and has

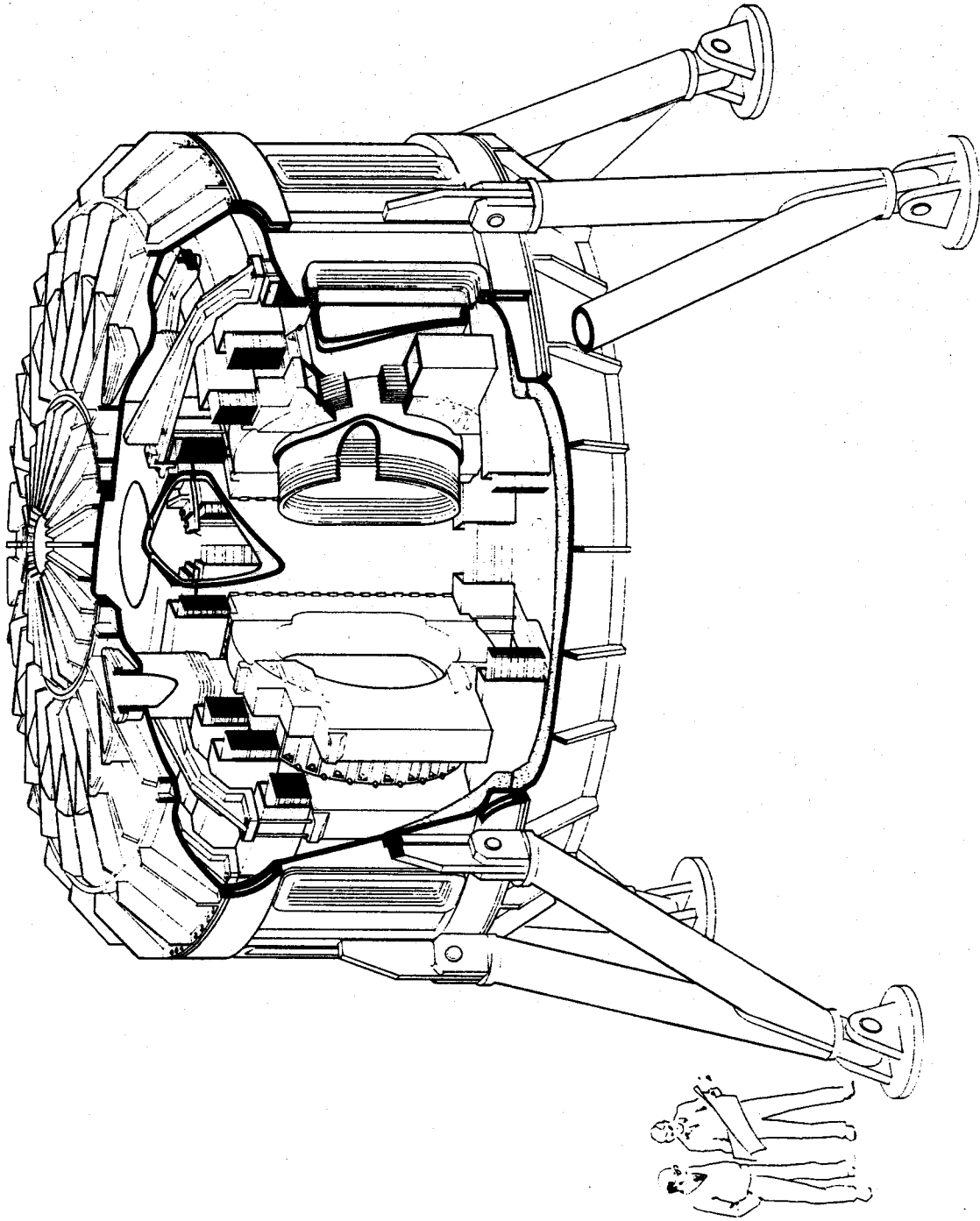


Figure 4 - Conceptual drawing of Alcator DCT

TABLE 1

Alcator DCT Specifications and ParametersA. Plasma Geometry

Major Radius	2.0 m
Minor Radius	0.4 m
Elongation (minimum)	1.4 at 1.0 MA
Triangularity (minimum)	0.2
Current	1.4 MA at $q = 2.0$ and $\kappa = 1.0$

B. Magnetics

Field on Axis	7 T
Ripple on Axis	0.04%
Max Field at Coil	10 T
TF Conductor	Cabled Nb ₃ Sn
TF Stored Energy	550 MJ
PF Conductor	Cabled NbTi
PF Stored Energy	120 MJ
Flux Change	35 Wb (double swing)

C. RF Systems

Lower Hybrid Range	4 MW CW at 4.6 GHz
Ion Cyclotron Range	5 MW CW at 180 - 215 MHz (7 MW at 10 s pulse)

D. Anticipated Range of Plasma Parameters

Average Density	$0.5 - 2.5 \times 10^{20} \text{ m}^{-3}$
Peak Temperature	9 keV
Maximum Average Pressure	2 atmospheres
RF Driven Current	$> 0.5 \text{ MA @ } \bar{n} = 7 \times 10^{19} \text{ m}^{-3}$
Pulse Time	$> 100 \text{ s}$
$\epsilon\beta$	> 0.5
β^p	$> 1\% \text{ @ } 7 \text{ T}$

E. Plasma Edge

Power Density (Average)	$> 0.2 \text{ MW/m}^2$ at plasma surface
Edge Control	Divertor (external coil) Pumped Limiter
Fueling Method	Steady-state Pellet Injection Gas Puff

experienced a schedule slip of only one month, caused by a delay in completion of the site. The site was dedicated in June, 1983.

The configuration of the TARA tandem mirror is unique in that it uses an axisymmetric confining plug with an outboard minimum-B anchor. This has been identified as a very desirable tandem mirror configuration for potential reactor applications. The primary objectives of the TARA experiment are to test trapped-particle mode stability, overall MHD stability limits, central cell radial transport, and enhanced potential formation. The experiment will provide data for the proposed upgrade of the MFTF-B tandem mirror facility under construction at Lawrence Livermore National Laboratory (LLNL). The use of an MHD anchor which is well separated from the central cell ions will allow TARA to investigate the theoretically-predicted tandem mirror trapped-particle instability for certain operating parameters. By varying parameters to determine regions of stable operation, TARA will supply much-needed experimental data on this important class of instabilities.

The following is a brief summary of the TARA design. The TARA central cell is a 18 cm radius, 10 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 $n \approx 4 \times 10^{12} \text{ cm}^{-3}$. 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 are available with a capability of 200 kW per plug for creating the hot mirror-trapped thermal barrier electron species and the supra-

thermal ($T_e \sim 700$ 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 the TMX experiment at LLNL. They will operate steady-state and contain a low-density ($n \sim 5 \times 10^{11} \text{ cm}^{-3}$) hot-electron plasma, formed by ECRH heating in the X-band. Additional ion heating using ICRF will be used to augment beta values in the anchor.

During the past year, construction of the major hardware components for TARA has been completed, including vacuum chambers, magnets, and the magnet power substation. Machine assembly, alignment and wiring was completed in mid-January, 1984. Development of the principal subsystems required to operate the experiment (such as diagnostics, radio frequency heating, programmable controls and data acquisition) has also proceeded on schedule during the past year.

Tandem Mirror Theory: Theoretical work during the past year has been in the areas of the trapped-particle instability mentioned above, plug microstability, enhancement of the plug confining potential beyond the thermal (Boltzmann) regime, and antenna modeling for ion cyclotron heating. This research is described briefly below.

The initial theory of the trapped-particle instability assumed a high mode number and ignored rotation and collisionality. This theory has been extended to include rotation and collisionality for arbitrary azimuthal mode numbers. Results of this work indicate that with proper potential control TARA can be operated in a regime that is stable to trapped-particle modes without compromising the simplicity of the geometry. The key to this stability is the generation of a stabilizing Coreolis force that arises when the radial equilibrium electric field is small and points inward. The theory indicates that a new instability,

a rotationally-driven trapped-particle mode, is present unless the radial potential variation is small (compared to T_e).

To gain a better understanding of microinstability for mirror-confined hot ions, a code has been developed that solves for the axial eigenmodes of the drift cyclotron loss cone (DCLC) and axial loss cone (ALC) instabilities. This code can also perform radial ray tracing to determine radial eigenmodes, and will be valuable in predicting and analyzing experimental results.

In addition, two schemes have been analyzed for plug potential enhancement. The first approach is the axicell thermal barrier. An electron Fokker-Planck code is being developed for detailed predictions of potential enhancement resulting from strong ECRH diffusion. In addition, this code will be consistent with ECRH ray tracing models. A second approach to potential enhancement would make use of electron pumping. This approach tends to be more stable to the trapped-particle mode than the thermal barrier approach. It has been found that strong parallel electron heating can result from RF in the electron bounce frequency range (which is close to the ion cyclotron frequency range). The evaluation of power and efficiency is being pursued through the use of both Monte Carlo and Fokker-Planck techniques.

The TARA experiment will rely on ICRF for start-up and central cell power balance, maintenance of a finite beta ion population in the anchor, as well as radial and axial potential control. This will require a detailed understanding of RF amplitudes and profiles. With this in mind, more sophisticated and versatile antenna-plasma coupling codes continue to be developed. The present antenna coupling code can now model a wide variety of antennae surrounding a cylindrical plasma. Using a stratification technique, the influence of radial plasma density profiles on wave propagation and power deposition can be studied.

Finally, experimental work has been primarily in the area of fusion-related vacuum technology. Experiments with niobium gettering have proven particularly successful, demonstrating a

much higher pumping capacity than conventional titanium gettering. The application of supersonic magnesium jets to control gas flow from neutral beam sources is also being evaluated.

D. Fusion Technology and Engineering

The Fusion Technology and Engineering Division provides critical engineering analysis for advanced design projects, and develops advanced superconducting magnet technology for the national fusion program. Research activities include: engineering support for the TARA tandem mirror experiment and for the proposed Alcator DCT experiment in the PFC toroidal confinement program; advanced magnet design in support of the Fusion Engineering Design Center at Oak Ridge National Laboratory and in conjunction with the TFCX and TFCX-S (Tokamak Fusion Core Experiment and Tokamak Fusion Core Experiment - superconducting version); and the INTOR International Tokamak Reactor study; concept development for improved magnetic divertors for tokamak and mirror upgrades and next-generation test reactors; development of forced-flow superconductors for application to advanced fusion devices; basic research on the development of ductile superconducting materials; advanced magnet design in support of DOE programs in MHD and high energy physics. Research activities in these technology and engineering areas are summarized below. Division personnel are listed in Appendix A, Section IV.

Major upgrades of the large tokamak and mirror experiments in the U.S. are under consideration, and examination of the alternatives is the responsibility of the Fusion Engineering Design Center, an industrially-based design group located at Oak Ridge National Laboratory. The Plasma Fusion Center provides major technical support to that Center, with responsibility for a number of magnetic systems and critical design issues. Analysis of critical magnet design issues for the international INTOR project is also carried out.

The Plasma Fusion Center has been active in developing improved magnetic divertor concepts. 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. Construction of a high-field divertor for the ISX-B tokamak at ORNL has been completed by the PFC. Basic divertor studies are conducted by faculty and graduate students in the Nuclear Engineering Department in conjunction with the PFC.

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 x 3 meter niobium-tin coil for the Large Coil Project at the Oak Ridge National Laboratory. The forced-flow group has also used 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. The coils have been completed and will be installed at LLNL early in 1984.

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.

Advanced magnet design for the national MHD program, and for selected national high energy physics projects is also carried out. While the MHD program is greatly reduced from previous levels, there are several utility/industrially-based activities which show promise of growth. Research by the MIT magnet design group in the high energy physics area was directed at redesigning the Isabelle (Colliding Beam Accelerator) magnet systems to achieve a reliable design, and is now emphasizing work on the

large internationally-funded L3 detector for installation at the LEP facility at CERN. Professor S. Ting of MIT heads that international effort.

In addition to these fusion and related technology areas, the engineering group is involved in the design and construction of the PFC confinement experiments. Advanced design activities during the past year have concentrated on conceptual design studies for a superconducting long-pulse tokamak, Alcator DCT, as a follow-on to the Alcator C experiment.

E. Fusion Systems

The Fusion Systems Division investigates several aspects of fusion reactor design and develops advanced millimeter and sub-millimeter wave technology for plasma heating and diagnostics. Research activities include: safety and environmental studies; reactor systems studies; blanket and first wall structural design studies; gyrotron and advanced millimeter source development; millimeter and submillimeter wave detector development. Personnel in the Fusion Systems Division are listed in Appendix A, Section V.

Safety and Environmental Studies: An evaluation is being made of the impact that different first wall and blanket materials might have on the safety of a fusion plant. The radiological consequences of accident events in 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. Accidental releases of activation products to the atmosphere from vanadium, as a structural material, are less consequential than those from steel or TZM molybdenum alloy.

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 are compared to published risk assessments for electricity generation from other sources. The total power cycle risk from fusion is found to be comparable to (if not less than) the lowest risk imposed by the alternative energy sources.

Reactor System Studies: Design concepts for commercial tokamak reactors with very long pulses have been investigated. An illustrative design has been developed for an ultra long pulse tokamak reactor (ULTR) which could provide 24-hour pulses using current which is inductively driven by the ohmic heating transformer. ULTR is somewhat larger (major radius ~10 m) than current commercial tokamak reactor designs and incorporates a high-performance, high-field ohmic heating transformer. Another important feature is a complete modularization of the tokamak by means of a toroidal field magnet design in which the coils are individually removable. This concept facilitates assembly and maintenance. Parametric studies have been carried out to determine the effect of pulse length on reactor size. It is found that a device with an ULTR type magnetics system and about the same size (7.5 m in major radius) as present commercial reactor designs could provide a pulse length of four hours. The ULTR design approach provides an important alternative if a sufficiently efficient means of steady-state noninductive current drive cannot be found.

A new design concept has also been developed for a long-pulse ignited test experiment (LITE) device, a tokamak which uses high-performance resistive magnet plate technology. The physical size of LITE is similar to the Tokamak Fusion Test Reactor (TFTR) tokamak at Princeton University. However, LITE would provide much higher values of the density and confinement parameter $n\tau_E$ and have substantially greater long-pulse capability. The higher $n\tau_E$ capability is obtained by operation at high magnetic fields and at moderately high values of beta (the ratio of plasma pressure to magnetic field pressure). The main goals of LITE are to

demonstrate long-pulse ignition, and to study the equilibrium and stability features of self-heated plasmas.

A mirror reactor studies program has been initiated in collaboration with the TARA experimental program. Particular emphasis is being placed on a new approach in which radio frequency pumping of electrons is used for potential barrier formation.

Blanket and First Wall Studies: A key issue in assessing the viability of the operation of a tokamak as a pulsed reactor is the effect of thermal fatigue on the first wall. An investigation of this issue has been carried out as part of an evaluation of long-pulse tokamak operation by the reactor system studies group. Effects of thermal fatigue and crack growth have been evaluated using a two-dimensional model. Studies of thermal fatigue of the first wall show that it is not strongly constraining. For representative stainless steel first wall designs with heat depositions of $0.5-1.0 \text{ MW/m}^2$, corresponding to neutron wall loadings of $2-4 \text{ MW/m}^2$, pulses as short as $\sim 100 \text{ s}$ may be acceptable. Vanadium has substantially larger design windows due to its superior thermal and mechanical properties. The use of very long pulse operation provides greater margin for thicker first walls and higher heat deposition.

Gyrotron and Advanced Millimeter Source Development:

Improved power levels and efficiency have been obtained in operation of the gyrotron device (electron cyclotron maser) developed at the Plasma Fusion Center. Output powers of 100 kW at a frequency near 140 GHz have been achieved at an efficiency of 36%. To date, this is the highest efficiency ever achieved at any frequency above 60 GHz by a high-power coherent source, including masers or lasers. Output powers of up to 175 kW at 28% efficiency have also been achieved. Operation is short-pulse (1 μs), but the device appears scalable to long-pulse or even CW operation. The output bandwidth has recently been measured on a single pulse basis and is found to be less than 3 MHz. Studies

have been completed on mode competition and second harmonic emission in the gyrotron. The gyrotron group has also developed a tunable far infrared laser based on stimulated Raman scattering of tunable CO₂ laser radiation in CH₃F gas. Continuous tuning between 32 and 40 cm⁻¹ (250 to 300 μm) has been achieved.

Millimeter and Submillimeter Wave Detector Development:

Schottky barrier diode detectors have been developed at Lincoln Laboratory for a variety of plasma diagnostic applications including submillimeter laser interferometry, cyclotron emission measurements and Thomson scattering measurements of ion temperature. Improvements in detector capability have been investigated. These improvements include development of arrays, use of monolithic detector designs and harmonic mixing techniques.

5. EXPERIMENTAL FACILITIES

In this section, the characteristic operating parameters of major PFC experimental facilities are provided. Further details regarding these facilities are given in Appendix A of this report.

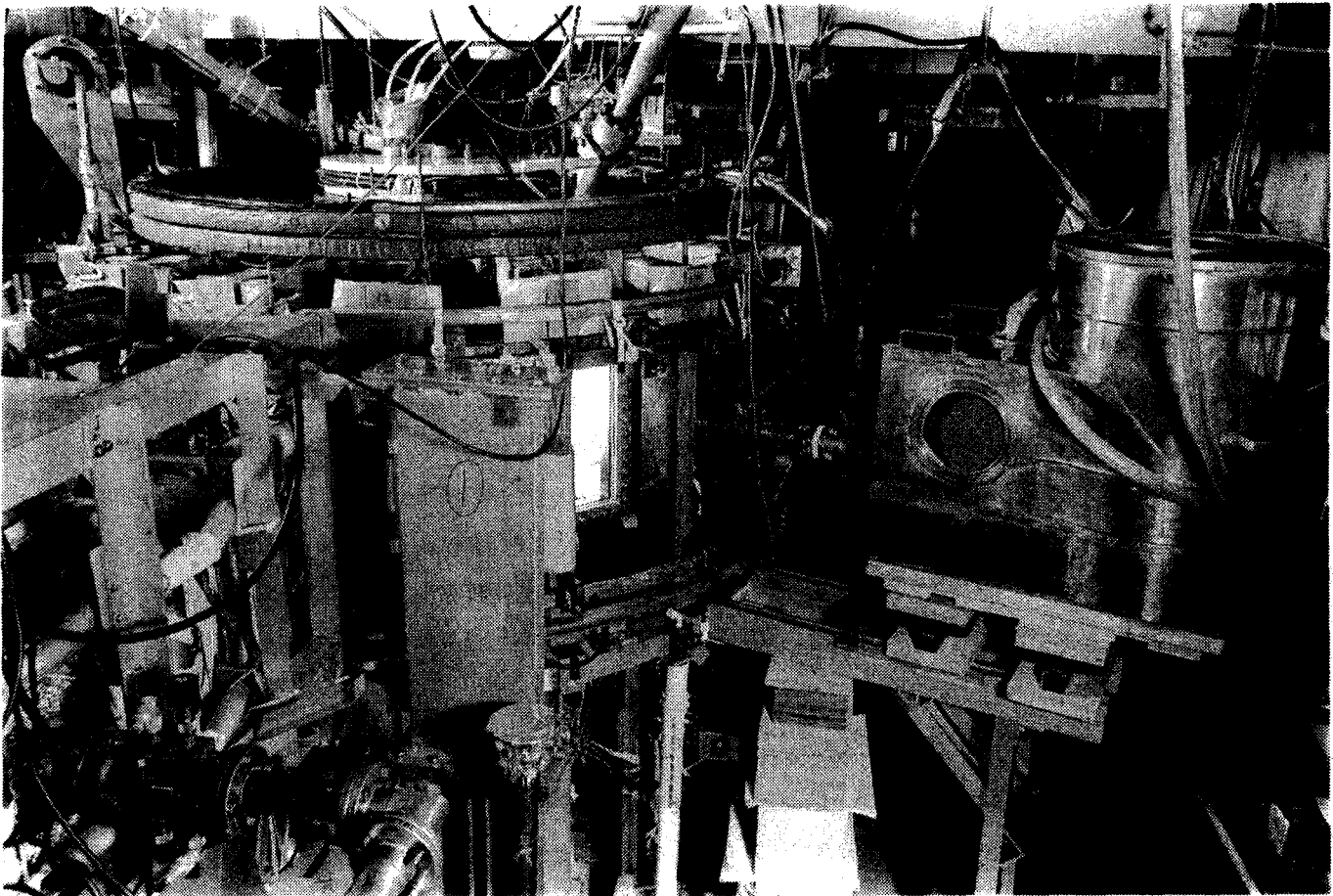
Versator II

Versator II is a medium-sized research tokamak with primary emphasis on basic investigations of plasma heating and confinement properties. Lower hybrid and electron cyclotron heating experiments have been 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 2 on page 39. Shown in Figure 5, page 32, are photographs of the Versator experiment.

Alcator C

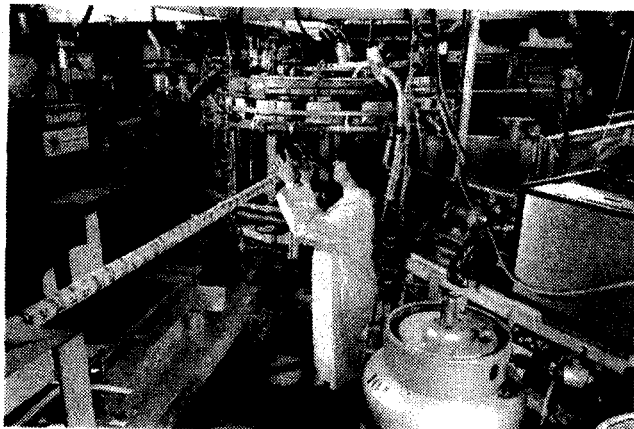
Alcator C is a compact, high-field, high-performance tokamak. It is used to develop the basic physics understanding of the stability, transport and radiation properties of high-temperature

Figure 4. Versator Tokamak

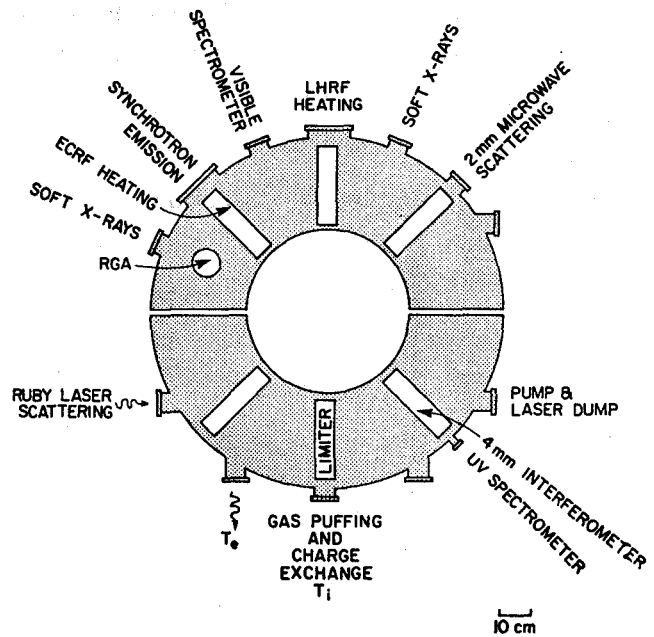


ECRH antenna shown entering plasma from top center of photograph. Soft x-ray detector is visible at right and a portion of the lower-hybrid phase shift system is visible at the left center.

DIAGNOSTIC AND RF HEATING PORTS



Ruby laser (left) and UV Spectrometer (right) diagnostics on Versator.



Plane view schematic showing diagnostic and RF heating ports.

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 $\bar{n} = 8 \times 10^{14} \text{ cm}^{-3}$) with characteristic values of the Lawson parameter in the $n_0 \tau_E \approx 0.8 \times 10^{14} \text{ cm}^{-3}\text{-s}$ range, exceeding the minimum value required for energy breakeven in D-T plasma at higher temperatures.

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 16.5 cm and 10 cm, respectively (page 40). The Alcator C device is shown in Figure 6, page 35.

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; it uses an axisymmetric confining plug with "outboard" minimum-B anchor. Initial operation of TARA in the Nabisco Laboratory is scheduled for February, 1984. The characteristic design parameters for TARA are summarized in Table 4 on page 41. Figure 7, page 36, shows TARA nearing construction completion in January 1984.

Constance A and B

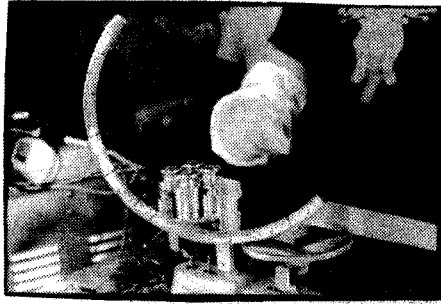
The design parameters for the Constance A axisymmetric mirror and the Constance B quadrupole mirror are listed in Table 5, page 41. Constance B is shown in Figure 8a, page 37. Constance A and B are small, single-cell mirror experiments located in the west wing of the Nabisco Laboratory. They are being used for a number of basic studies that complement the confinement experiments in

TARA. Investigations include the use of ECR heating in an overmoded cavity to generate and study the microstability and equilibrium of high-beta hot electrons, and the development of novel techniques for drift pumping. In addition, an acousto-optical RF-spectrum analyzer which can scan a 500 MHz band in ~ 10 ms with ~ 2 MHz resolution has been developed and will be used to study microinstabilities over a wide frequency band (0.1 to 4-5 GHz).

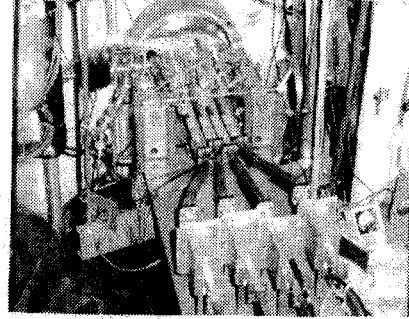
Superconducting Racetrack Pair Test Facility

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 $7.6 \text{ cm} \times 30 \text{ cm} \times 76 \text{ cm}$. 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 6 on page 42. Figure 9, page 38, shows a photograph of the racetrack coil pair.

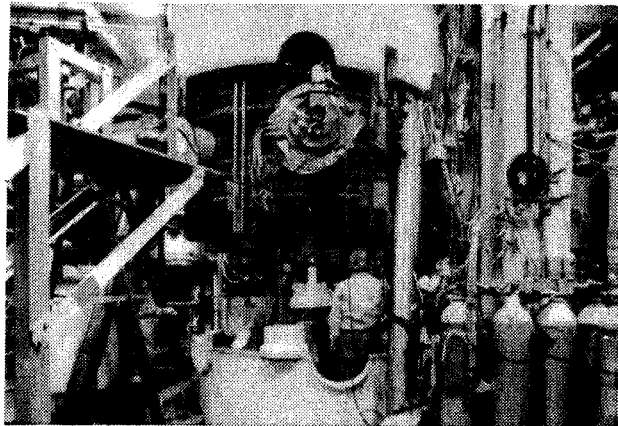
Figure 5. Alcator C Tokamak



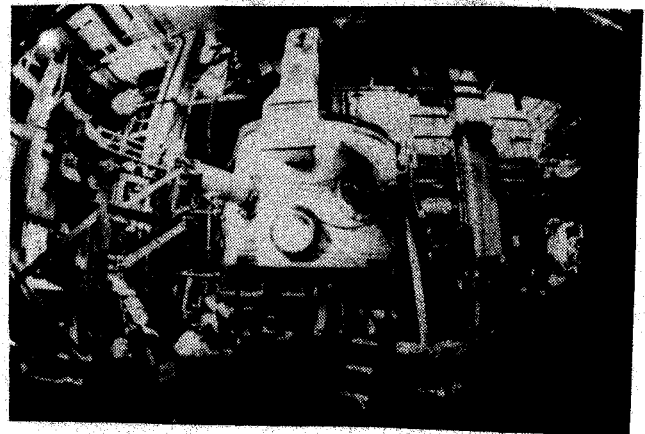
Limiter



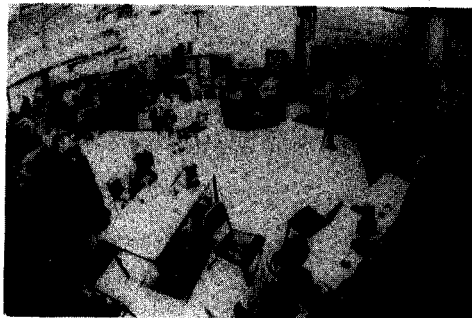
Four Waveguide System



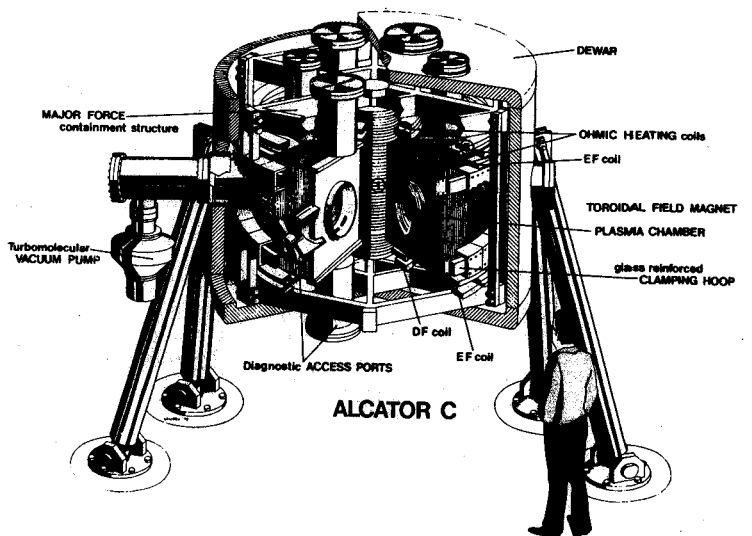
Alcator C with Dewar Open



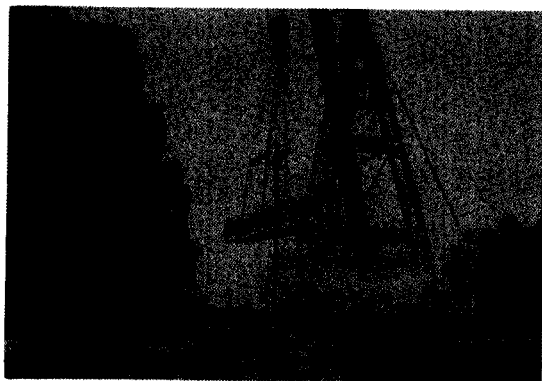
Alcator C



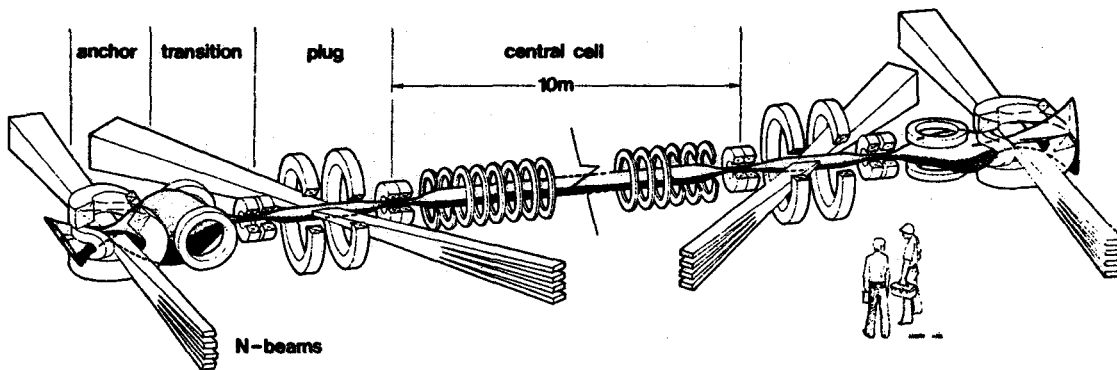
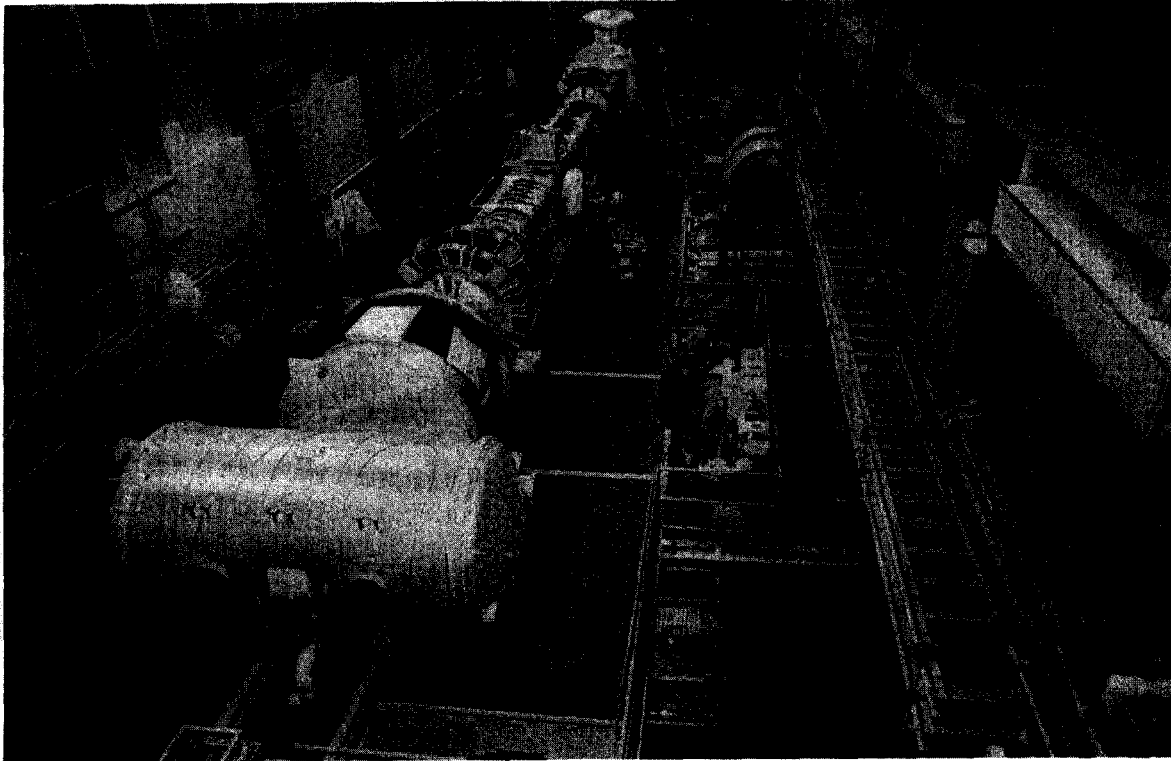
Control Room



Alcator C Schematic



225 MW Generator with Rotor and Stator Visible



TARA-TANDEM MIRROR

Figure 6 - TARA Tandem Mirror

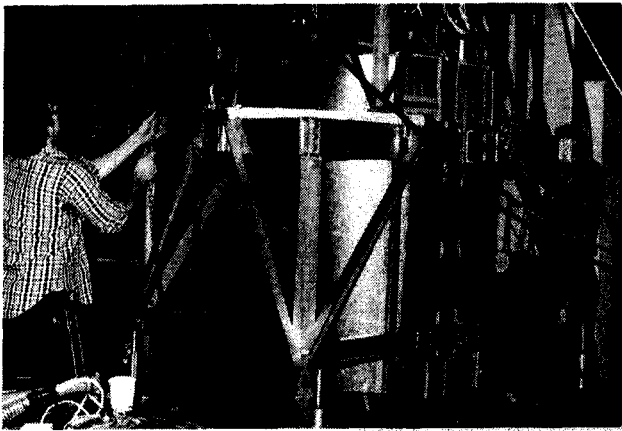


a. Constance B, Single Cell Quadrupole Experiment

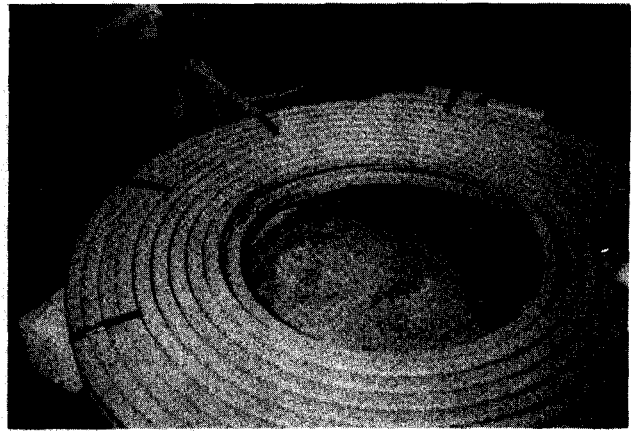


b. Mirror Vacuum System Experiment

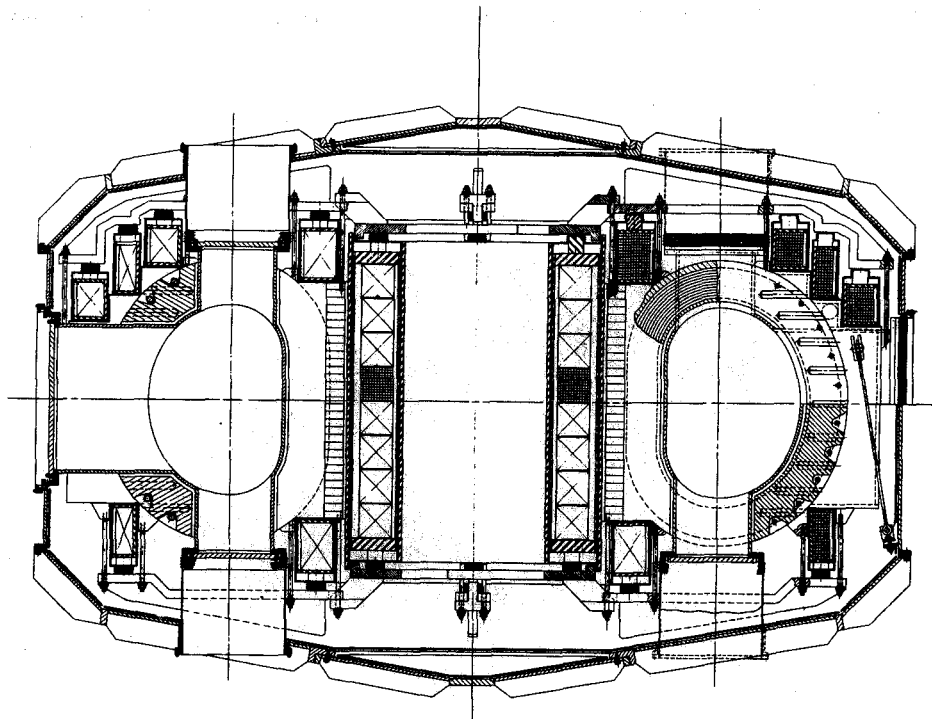
Figure 8



a - Racetrack Magnet
Test Facility



b - 12 Tesla Coil using IGCS
conductor developed for
LLNL High Field Test
Facility.



c - Engineering Design of Alcator DCT

Figure 9. Technology and Engineering

Parameter	Value
a (Minor Radius)	13 cm
R (Major Radius)	40.5 cm
B _T (Toroidal Field)	15 kG
\bar{n} (Average Density)	$\left\{ \begin{array}{l} 0.1-2 \times 10^{13} \text{ cm}^{-3} \\ (4 \times 10^{13} \text{ cm}^{-3})^+ \end{array} \right.$
τ_p (Pulsed Length)	20-40 ms (60 ms) ⁺
I _p (Plasma Current)	40-60 kA (100 kA) ⁺
T _{eo} (Central Electron Temperature)	350-450 eV (600 eV) ⁺
T _{io} (Central Ion Temperature)	120-160 eV (200 eV) ⁺
P _{RF} (Lower Hybrid)	$\left\{ \begin{array}{l} 140 \text{ kW at } 800 \text{ MHz} \\ 100 \text{ kW at } 2.45 \text{ GHz} \end{array} \right.$

Table 2. Versator II Parameters

⁺ (Updated capability anticipated in March, 1984)

Parameter	Achieved (a = 16.5 cm)	Achieved (a = 10 cm)	Ohmic Goal (a = 16.5 cm)	RF Goal (a = 16.5 cm)
B_T Toroidal Field (kG)	120	130	140	100
R Major Radius (cm)	64	58	64	64
\bar{n} Average (cm ⁻³)	8×10^{14}	8×10^{14}	10^{15}	7×10^{14}
I_P Toroidal Current (MA)	0.78	0.38	1	0.7
τ_E Energy Confinement (ms)	50	30	100	60
$n_0 \tau_E$ Lawson Parameter (cm ⁻³ -s)	$0.7-0.9 \times 10^{14}$	0.35×10^{14}	10^{14}	0.5×10^{14}
T_{io} Central Ion Temperature (keV)	1.6	1	2	3.5
P_{RF} Lower Hybrid at 4.6 GHz (MW)	1.2 (at plasma)	-	-	4 (at klystron)

Table 3. Alcator C Parameters

Parameter	Design Value
<u>Central Cell</u>	
a (Plasma Radius)	18 cm
L (Length)	10 m
B (Magnetic Field)	2 kG
n_0 (Central Density)	$4 \times 10^{12} \text{ cm}^{-3}$
T_{eo} (Central Electron Temperature)	400 eV
T_{io} (Central Ion Temperature)	400 eV
<u>Barrier-Plugs</u>	
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	Constance A	Constance B
a (Plasma Radius)	10 cm	10 cm
l (Length)	1 m	1 m
B (Magnetic Field)	5 kG	3 kG
n_0 (Density)	$2 \times 10^{11} \text{ cm}^{-3}$	$\sim 2 \times 10^{11} \text{ cm}^{-3}$
T_{eh} (Hot Electrons)	200 keV	$\sim 200 \text{ keV}$
T_{ec} (Cold Electrons)	100 eV	$\sim 100 \text{ eV}$
T_i (Ion Temperature)	500 eV (ICRF)	$\sim 500 \text{ eV (ICRF)}$
R (Mirror Ratio)	2	2

Table 5. Constance A Axicell and
Constance B Quadrupole 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 6. Racetrack Pair Test Facility Parameters

APPENDIX A

PLASMA FUSION CENTER

DESCRIPTION OF RESEARCH PROGRAMS

I. APPLIED PLASMA PHYSICS

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.

RESEARCH GROUPS:

- Tokamak Systems Experimental Research
George Bekefi and Miklos Porkolab, Co-Leaders
- Mirror Systems Experimental Research
Richard S. Post, Leader
- Fusion Theory and Computations
Jeffrey P. Freidberg, Leader
- Theory of Thermonuclear Plasmas
Bruno Coppi, 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 Plasma Physics Research Division, headed by Ronald C. Davidson, is to develop the basic experimental and theoretical understanding of plasma heating and confinement properties. This is required for meaningful interpretation of data from small- and large-scale confinement experiments. Given the technical uncertainties in the development of fusion energy, it is important to recognize the need for vigorous ongoing research in basic plasma physics. In the plasma theory area, this is accomplished by the continued development of new analytical and numerical tools for handling complex plasma

phenomena, 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 an improved basic understanding of plasma heating and confinement properties.

1. TOKAMAK SYSTEMS EXPERIMENTAL RESEARCH

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 current generation.

B. RESEARCH PROJECTS:

- RF current generation with lower hybrid waves.
- RF heating with lower hybrid waves.
- Comparison of top and side launching of lower hybrid waves.
- Frequency scaling of density limit during lower hybrid current drive experiments.
- Lower hybrid start-up of tokamak plasmas.

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:

M.J. Mayberry, F.S. McDermott, R.R. Rohatgi

Undergraduate Students:

M. Ames, S. Baraniuk, R. Schneider, D. Todd

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 systems (800 MHz, 150 kW, 4 or 6 waveguide antennae; 2.45 GHz, 100 kW, 4 waveguide antenna)

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 25 kHz is also used for discharge cleaning and preionization.

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

- Measurement of perpendicular 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 and hard X-ray spectroscopy for electron tail measurements.

- Bolometers.
- UV and visible spectroscopy for T_i diagnostics.
- ω_{ce} and $2\omega_{ce}$ emission for T_e diagnostics.

Parameter	Value
a (Minor Radius)	13 cm
R (Major Radius)	40.5 cm
B_T (Toroidal Field)	15 kG
\bar{n} (Average Density)	$0.1-2 \times 10^{13} \text{ cm}^{-3}$
τ_p (Pulse Length)	20-40 ms
I_p (Plasma Current)	40-60 kA
T_{eo} (Central Electron Temperature)	350-450 eV
T_{io} (Central Ion Temperature)	120-160 eV
P_{RF} (Lower Hybrid)	{ 140 kW at 800 MHz; { 100 kW at 2.45 GHz

Table 1. Versator II Characteristics

The Versator II research program has 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.
- Frequency scaling of lower hybrid current drive studies.

Initial current-drive studies with lower hybrid waves have been completed successfully. Twenty to thirty kA of RF current have been generated in low density tokamak discharges, with corresponding efficiencies of 1-2 kA/kW. Past experiments with combined lower hybrid current drive and electron cyclotron heating ($f = 35$ GHz) have shown increased efficiencies in current

generation, as well as more stable discharges. Lower hybrid ion heating studies were also carried out in the past and will be continued. Past results indicated successful ion heating with central ion temperature increases of 30-40%, but these results could not be reproduced in a reliable manner. The reason for this is not clear at present, but parametric decay near the surface is believed to play an important role. At present, wave launching from the top of the torus is being tested, for which case theory predicts improved wave penetration and hence better heating. The current drive efficiency, however, is expected to decrease due to an upshift of the $N_{||}$ spectrum.

Successful studies of waveguide breakdown have paralleled the basic lower hybrid experiments. A breakthrough in antenna power handling capability has been achieved recently on Versator. In experiments where an 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 capability still further.

Future plans for lower hybrid current-drive experiments include electron tail studies with soft and hard X-ray spectroscopy and studies of current drive in high-density plasmas. A modification of the Versator II tokamak is being 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 true steady-state, RF-driven tokamak. Finally, a higher frequency ($f_0=2.45$ GHz, 100 kW) lower hybrid current-drive experiment is being installed for operation at higher densities. These experiments should commence in the spring of 1984. The simultaneous application of two different lower hybrid frequencies should also allow lower hybrid start-up of a tokamak plasma to be tested even in the absence of ohmic heating power.

2. MIRROR SYSTEMS EXPERIMENTAL RESEARCH

Richard S. Post, Leader

A. OBJECTIVES:

Study basic microstability properties of mirror-confined plasmas. Study plasma heating by ECRH, ICRH, and electron beams. Produce and investigate stability properties of hot electron plasmas and techniques for drift pumping and radial potential control.

B. RESEARCH PROJECTS:

- Hot electron physics.
- ECRH plasma heating and microinstability.
- Drift pumping.
- Radial potential control.

C. PERSONNEL:

Academic Staff:

R.S. Post

Research Staff:

J.H. Irby, J. Kesner, B. Lane, M. Mael, B. McVey,
D. Smatlak, D. Smith

Technical Support:

K. Rettman, F. Stubbs

Graduate Students:

X. Chen, R. Garner, S. Hokin, D. Liu, D. Goodman

Secretary:

S. Mullin, B. Ogar

D. SPECIAL EQUIPMENT AND FACILITIES:

Experimental Facilities:

- Constance A axisymmetric mirror device (5 kG midplane; $R = 2$; 1 meter long; baseball coil; 10 cm diameter plasma)
- Constance B quadrupole mirror device (3 kG midplane; $R = 2$; 1 meter long, 10 cm diameter plasma)

- Thomson scattering system (5 J ruby laser; 5 channel polychromator)
- 1 MW X-band pulsed ECRH system
- 1 kW CW X-band klystron amplifier
- 100 kW 5 MHz ICRH system
- 150 kW e-beam system
- Computerized data collection
- 5 MW magnet DC power supply

E. TECHNICAL PROGRAM SUMMARY:

The medium-scale tandem mirror facilities, TARA and TMX-Upgrade, are designed to incorporate ECRH and drift pumping as essential elements in the end plugs and in the thermal barrier cells. The Constance experimental program is designed to answer fundamental physics questions about these heating schemes. The Constance II facility has been modified and reconfigured into Constance A and B, which are located in the TARA wing of the Nabisco Laboratory. The Constance A and B experiments use ECH-produced plasmas with $T_e \sim 200$ keV and $n \sim 2 \times 10^{11} \text{ cm}^{-3}$.

Electron cyclotron resonance heating is studied in Constance in an overmoded cavity using a 1 kW, X-band source to generate high-beta, hot electron plasmas. The major aim is to understand the microstability and equilibrium of hot electron distributions. Bulk heating and hot electron tail formation are monitored by soft and hard X-ray detectors, diamagnetism, and VUV measurements. Enhanced end loss is studied by electrostatic end-loss analyzers. High frequency fluctuations are measured by high impedance probes.

Drift Pumping: Pumping of thermal barriers is a major requirement for tandem mirrors. Mirror-trapped ions may be caused to drift out radially by perturbing their bounce motion so as to destroy bounce-averaged omnigenity of a magnetic well with quadrupole symmetry. Theoretical and experimental studies on Constance will develop a practical means of coupling to bouncing

ions efficiently. Drift pumping will be employed as a means of reducing the plasma potential and the fraction of cold plasma in order to study microstability of hot electron plasmas.

Acousto-Optical RF Spectrum Analyzer: In many plasma devices, Constance, 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 μ s, 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 and construction of such an instrument has been completed and will be tested on Constance.

3. FUSION THEORY AND COMPUTATIONS

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 help to plan 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 Physics and Technology
P.A. Politzer and J. Freidberg, Project Co-Leaders

C. PERSONNEL:Faculty:

A. Bers, R. Davidson, T. Dupree, J. Freidberg,
K. Molvig

Research Staff:

R. Berman, M. Gerver, K. Hizanides, G. Johnston,
V. Krapchev, P.A. Politzer, A. Ram, A. Rechester,
D. Tetreault, I. Weiss

Technical Support Staff:

C. Barsotti, M. London, D. Nelson

Visiting Scientists:

G. Berge, P. Rosenau

Graduate Students:

W.H. Choe, E. Esarey, G. Francis, P. Hakareinen,
G. Hilfer, R. Rohatgi, M. Sands, P. Yoon

Secretarial Staff:

H. Budd, G. Chambers, P. Fina, A. Karoghlanian

D. SPECIAL EQUIPMENT AND FACILITIES:Computer Equipment:

- 1 DEC VAX 11/780 with 4×10^6 bytes of memory.
- 3 PDP-11/10 processors with 24,000 words of memory.
- 1 Grinnell 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.
- 3 Tektronix 4000 series terminals.
- 3 VT100 series terminals.
- 1 DEC RMO5 disk drive.
- 1 DEC TU77 tape drive.
- 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, TARA 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 tokamak/stellarator hybrid 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 mirror 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 A and B and the TARA tandem mirror.

Theoretical research in these program areas will continue to emphasize increased 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, a computational support activity has been established recently 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 NMFEC via the VAX 11/780 and NMFEC NAP (network access port) and the local computer network (CHAOS). In addition, the computational support activity provides centralized administration of the PFC time allocation at the NMFEC 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 NMFEC.

In FY82, the VAX 11/780 was installed along with the 4800 baud NAP connection to NMFEC via land line to the PPPPL satellite link. Recently the connection was upgraded to 9600 baud. This data link has now become the primary link to NMFEC with the DARPA connect providing a backup. Users in Building 38 on the main campus, as well as some users in NW16, now use the TV monitor system via the CHAOS net for connection to the VAX. During FY83 a PFC terminal area was set up and furnished with video terminals.

4. THEORY OF THERMONUCLEAR PLASMAS

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:

A. Hamza, J. Martinell

Secretarial Staff:

C. LoRusso, M. Scalleri

C. 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 collaboration with overseas institutions. As a result, several of the numerical codes currently used have been developed in collaboration with the Institut für 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, who participate directly in research projects. An active exchange of ideas is maintained with 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) determination of 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-He³); (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 purposes of illustration, a few selected research accomplishments are summarized briefly.

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 $i_0 \approx 2$ ($q_0 \approx 1/2$) 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.

In addition, research has continued on deriving 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 Duches 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), 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 included 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 enhances the stability of an axisymmetric toroidal configuration when the parameter $G \equiv \beta R q^2 / r_p$, with $1/r_p \equiv -d \ln p / dr$, becomes finite. Thus an expanded "first ideal-MHD-stability region" has been found that roughly corresponds to $G < G_c^{(1)}(s)$ with $s \equiv d \ln q / d nr$, 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 others 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 the FT, PLT, and ISX tokamaks by using numerical simulation and analytical representation of empirical transport coefficients.

- Evaluating elongated equilibria, and their stability properties.
- Collaboration in the design of upgrades to Alcator C.
- Extensive theoretical support of the lower hybrid heating program.

In addition to the research activities summarized above, this group is carrying out 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 (nonideal MHD) modes on finite-beta configurations, and (d) excitation of toroidal magnetic fluctuations by charged particles produced in fusion reactions.

5. ADVANCED DIAGNOSTIC DEVELOPMENT

Daniel R. Cohn, Leader

A. OBJECTIVES

Develop millimeter and submillimeter wave diagnostics.
Develop advanced X-ray imaging technology for making highly resolved measurements in present-day and next-generation plasma confinement devices.

B. RESEARCH PROJECTS:

- Millimeter and Submillimeter Wave Thomson Scattering
P. Woskoboinikow, Project Leader
- Advanced X-ray Imaging
R. Petraso, Project Leader

C. PERSONNEL:

- Millimeter and Submillimeter Wave Thomson Scattering Project

Research Staff:

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

Graduate Students:

J. Machuzak

Secretary:

In transition

- Advanced X-ray Imaging Project

Research Staff:

R. Granetz, R. Petrasso

Visiting Scientist:

F. Sequin (AS & E, Inc.)

Graduate Students:

A. Hamza, J. Parker

Secretary:

A. Kotsopoulos

D. SPECIAL EQUIPMENT AND FACILITIES:

- 1 Digital Equipment MINC Computer.

E. TECHNICAL PROGRAM SUMMARY:Millimeter and Submillimeter Wave Diagnostics Project:

A 100 kW, 1 μ s pulse length, 385 μ m D₂O laser has been developed as the source for ion Thomson scattering measurements. The detection system is a Schottky diode heterodyne receiver. Using this system, thermal level Thomson scattering has been observed for the first time on a tokamak plasma. Future activities will involve efforts to develop submillimeter scattering as a tool with widespread applicability in magnetic confinement studies. The major component of future efforts will be the

development of a gyrotron scattering diagnostic for mirror plasmas. A system which uses a 140 GHz gyrotron will be used for scattering from plasmas in TARA.

Advanced X-ray Imaging Project:

This project has as its primary goal the development and investigation of advanced X-ray imaging techniques applicable to present-day and next-generation plasma confinement devices. The need for this project derives from the importance of relating X-ray emissions to basic conditions within the plasma. For example, such emissions can be directly related to the electron temperature and density, to impurities and their transport, and to plasma MHD stability. In addition, such basic considerations as the Lawson criterion assume that the dominant radiative loss mechanism is hydrogenic bremsstrahlung, which, for a 10 keV plasma, primarily results in emissions in the X-ray region. With the use of three different X-ray imaging arrays, preliminary measurements have been obtained on Alcator C plasmas. Investigations are currently under way to relate these measurements in a direct fashion to basic plasma properties. Based in part on these studies, new X-ray arrays will be designed for next-generation plasma confinement devices.

6. INTENSE CHARGED PARTICLE BEAM RESEARCH

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:

G. Johnston, W. McMullin, R.E. Shefer

Visiting Scientists:

R-J. Li, Y-Z. Yin

Technical Staff:

T. Evans, I. Mastovsky

Graduate Students:

A. Dimos, J. Fajans, F. Hartemann (U. Paris),

D. Hinshelwood, D.A. Kirkpatrick, K. Jacobs,

W. Marable, J. Petillo

Undergraduate Students:

B. Eberman, D. Weidman

Secretarial Staff:

G. Chambers, P. Fina, V. Kaloyanides

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).
- One meter long samarium-cobalt magnetic wiggler.
- 30 kV, 1 A repetitively-pulsed FEL modulator.

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 uses 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 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.
- Design and diagnostics of electron guns capable of producing high current, high quality electron beams.
- Study of the dynamics of intense relativistic electron beam diodes and cathode plasma formation.

The first two areas of experimental research are expected to continue for the next several years. The last-mentioned area will be discontinued in 1984.

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 basic thermal equilibrium properties of intense electron and ion beams with both azimuthally- and axially-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 systems using a kinetic (Vlasov) description to incorporate thermal effects correctly, (d) the development of 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) 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.

II. TOROIDAL CONFINEMENT EXPERIMENTS

A. OBJECTIVES:

The primary objectives of the Plasma Fusion Center toroidal confinement program are to develop a basic understanding of the stability and transport properties of high-temperature toroidal plasmas at reactor-level conditions and to develop and test concepts for optimization of the toroidal confinement approach to magnetic fusion.

B. RESEARCH GROUPS:

To meet these objectives, the Toroidal Confinement Experiments Division, headed by Ronald Parker, is organized into six research groups:

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

The Group Leaders, together with Ronald Parker, are responsible for developing and executing the research programs. Ronald Parker and Bruno Coppi are overall Alcator program principal investigators. A description of the objectives of each research group and the associated personnel roster is given below.

C. RESEARCH GROUPS AND PROJECT AREAS:

1. OPERATIONS

David Gwinn, Leader

A. OBJECTIVES:

Direct day-to-day operations, develop methods of plasma control and provide suitable engineering support in order to produce reliably the high-quality plasmas required to achieve goals set by the 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:

R. Granetz, D. Gwinn, I. Hutchinson, B. Lipschultz,
B. Lloyd, R. Parker

Engineering Staff:

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

Technical Support Personnel:

T. Bakucz, W. Beck, W. Byford, J. Costello,
R. Danforth, B. Doherty, G. Foster, J. Gerolamo,
R. Griffith, J. Heckman, M. Hughes, M. Iverson,
R. Meister, J. Moscaritolo, B. Oliver, W. Parkin,
M. Rowell, H. Shriber, R. Shuffield, L. Storace,
E. Sudenfield, E. Woodworth, K. Woodworth

Graduate Students:

I. Bursuc, F. Camacho, B. LaBombard, P. Pribyl,
T. Shepard, E. Sheu

Administrative and Support Staff:

A. Chernomordik, L. Funari, T. Lloyd, L. Pfeifer,
A. Wyman

2. CONFINEMENT STUDIES

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:

P. Bonoli, B. Coppi, C. Fiore, R. Gandy, M. Greenwald,
S. McCool, D. Pappas, R. Petrasso, R. Watterson,
S. Wolfe

Engineering Staff:

G. Chihoski, R. Childs, N. Pierce, F. Tambini,
E. Thibeault

Technical Support Personnel:

F. Shefton, E. Rollins

Visiting Scientists:

E. Källne, J. Källne, R. Slusher, C. Surko

Graduate Students:

C. Gomez, S. Judd, K. Kato, A. Pachtman, J. Parker,
R. Richardson, D. Yates

Administrative and Support Staff:

L. Funari, M. Lorusso, L. Pfeifer, M. Scalleri,
A. Wyman

3. PLASMA-WALL INTERACTIONS

Earl S. Marmor, 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. Marmor, R. Petrasso, J. Rice,
J. Terry

Engineering Staff:

G. Chihoski, R. Childs, E. Thibeault

Visiting Scientists:

E. Källne, J. Källne, F. Seguin

Graduate Students:

S. Fairfax, M. Foord, H. Manning, T. Moran, J. Moreno

Administrative and Support Staff:

L. Funari, L. Pfeifer, A. Wyman

4. RF HEATING

Miklos Porkolab, Leader

A. OBJECTIVES:

Develop an experimental understanding of the physics of tokamak heating and current drive 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 and current drive.
- Alcator C ion cyclotron heating.
- Heating and current drive in advanced toroidal devices.

C. PERSONNEL:Research Staff:

B. Blackwell, P. Bonoli, S. Knowlton, B. Lloyd,
R. Parker, M. Porkolab, Y. Takase

Engineering Staff:

C. Bredin, R. Childs, K. Fertl, D. Griffin,
C. Kastrenos, P. Mitchell, K. Rice, E. Thibeault

Technical Support Personnel:

P. Telesmanick

Graduate Students:

B. Koester, J. Moody, S. Texter

Administrative and Support Staff:

L. Funari, A. Kotsopoulos, M. Lorusso, L. Pfeifer

5. DATA ACQUISITION AND COMPUTATIONS

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 the PFC, and MIT 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:

J. Bosco, C. Bredin, T. Fredian, I. McCool, D. Nelson,

E. Shaw, R. Thayer

Administrative and Support Staff:

A. Wyman

6. TOROIDAL SYSTEMS DEVELOPMENT

Peter Politzer and D. 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. Propose and evaluate upgrades of the Alcator concept for the purpose of approaching reactor regimes and addressing problems of reactor physics.

B. PROJECTS:

- Alcator DCT Design.

C. PERSONNEL:Research Staff:

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

Engineering Staff:

M. Besen, E. Bobrov, N. Diatchenko, W. Langton,

W. Mann, P. Marston, N. Pierce, R. Pillsbury,

J. Schultz, J. Tarrh, R. Thome

Graduate Students:

P. Rezza

Administrative and Support Staff:

D. Marble

D. SPECIAL EQUIPMENT:

In carrying out its research program over the last decade, the Alcator facility has acquired an impressive array of special equipment. Although the tokamak core is the smallest of any of the major tokamaks, the supporting power supplies are more powerful than those for any other tokamak except TFTR. A list of special equipment and facilities is given below.

Experimental Facility:

- o Alcator C tokamak [$a = 10 - 16.5$ cm,
 $R = 57.7 - 70.7$ cm, B_T ($R = 64$ cm) = 14 T,
 $I_p = 1$ MA].

Major Facility Support Equipment:

- o 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)

Rectifiers/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 - 3.0 kA, 5 kV (Transrex)

- o Plasma Heating Equipment:

16 power supply/modulator outputs (55 kV, 15 A,
500 ms)

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 μ F capacitor bank for ICRF
 50 A, 15 kV, 200 μ F capacitor bank for ICRF
 RF transmission, control, monitoring systems

- Cryogenic Facilities:

2, 8000-gallon LN₂ 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. ALCATOR TECHNICAL PROGRAM SUMMARY:

A brief summary of Alcator research activities is given here. A more detailed summary is presented in the report Alcator C Status and Program Plan (Plasma Fusion Center Report IR-82-3). A comprehensive description of the Alcator DCT device, the proposed next step in the PFC toroidal confinement program, can be found in the report Alcator DCT Proposal (September, 1983).

Both the original device, Alcator A, and its successor Alcator C, have produced a large number of technical advances that are of critical importance to the development of both fusion energy and the tokamak concept. For example, during the decade of the 1970's, Alcator A led the way in advancing the Lawson parameter, $n\tau_E$, by over an order-of-magnitude. More recently, Alcator C has succeeded in advancing the Lawson parameter beyond the threshold value required for thermalized fusion breakeven (at high temperature). This is the first time in the history of controlled fusion research that "breakeven" values of $n\tau_E$ have been achieved. It is widely considered to be one of the most significant milestones yet reached in the international effort to develop fusion energy.

Other important experiments in progress on Alcator C are concerned with the development of RF heating and current drive. The lower hybrid RF experiments, the most powerful in this frequency range in the world, have demonstrated the production and

sustenance of current by RF waves at reactor-level densities. While feasibility experiments had been carried out previously on smaller tokamaks, most notably the PFC's Versator II, the results from Alcator C have been the first in the density range where tokamak reactors would operate. These experiments establish the feasibility of a steady-state tokamak reactor in which the current is maintained by RF waves, rather than by the conventional inductive drive. More details concerning the confinement experiments and the RF heating current drive work are given in the following sections.

Confinement Studies on Alcator C: Tokamak confinement research represents a major focus of the experimental program on Alcator C (major radius 64 cm, minor radius 16.5 cm, toroidal magnetic field up to 14 tesla). This effort has concentrated on the study of ohmically-heated discharges at high density and toroidal field. Recently, injection of frozen hydrogen pellets with a pellet injector based on an ORNL design has been used to increase the maximum line-averaged density to $\bar{n} \gtrsim 10^{15} \text{ cm}^{-3}$. Other maximum parameters obtained in Alcator C include central density $n_0 \gtrsim 1.7 \times 10^{15} \text{ cm}^{-3}$, plasma current $I_p \approx 800 \text{ kA}$ and energy confinement time $\tau_E \approx 50 \text{ ms}$. The highest values of the Lawson parameter obtained so far, $n_0 \tau_E \approx 6-9 \times 10^{13} \text{ cm}^{-3}\text{-s}$, exceed the minimum required for "breakeven". These "high $n\tau_E$ " plasmas exhibit electron and ion temperatures of $\sim 1.5 \text{ keV}$; at lower densities, electron temperatures of 3 keV are obtained.

In addition to producing higher density than has been achievable with gas puffing, the pellet fueling experiments are also providing additional insight into an effect observed on Alcator C several years ago. When densities \bar{n} in excess of $2 \times 10^{14} \text{ cm}^{-3}$ are produced with gas puffing, the confinement time τ_E is found to increase only slowly with increasing \bar{n} , rather than exhibiting the linear dependence discovered on Alcator A. As a consequence, the larger confinement times anticipated for Alcator C are not observed when gas puffing is used as the fueling technique. These high density results are consistent with an

enhanced (anomalous) ion energy transport that is up to a factor of five larger than the neoclassical value. In the case of pellet fueling, on the other hand, the high density confinement is markedly increased, and is roughly consistent with neoclassical ion transport. The improvement may be due to the more peaked density profiles characteristic of pellet fueling or to changes in the edge parameters.

Studies of the dependence of confinement on plasma size, particularly at densities less than $2 \times 10^{14} \text{ cm}^{-3}$, have led to the formulation of the so-called "neo-Alcator" scaling for electron transport. A set of experiments in which the plasma major and minor radii were varied by means of different limiters resulted in a scaling $\tau_E \propto \bar{n} R^{2.3} a^{0.8}$, valid at low densities, $\bar{n} < 2 \times 10^{14} \text{ cm}^{-3}$. Comparison with results from other machines indicates that this dependence, roughly $\tau_E \propto n R^2 a$, is a better fit to the data base than the INTOR scaling $\tau_E \propto n a^2$. Recent results from TFTR are apparently consistent with the neo-Alcator prediction.

In addition to confinement studies, a major area of research is concerned with plasma-wall interactions; specifically, the generation and transport of impurities as well as methods of heat and particle removal. In this regard, it is worth noting that the average wall power density in Alcator C approaches 1 MW/m^2 . Another example of the frontier character of Alcator plasmas concerns the maximum plasma pressures contained by its intense magnetic fields. These pressures (about 1.5 atmospheres) are a factor of seven greater than those which have been contained in any other fusion experiment and only a factor of three below the value required for a fusion reactor. More progress in increasing the plasma pressure is also expected in the future.

Lower Hybrid Current Drive and RF Heating: The Alcator C lower hybrid RF system consists of sixteen 0.25 MW klystrons operating at a frequency of 4.6 GHz for pulse durations up to 0.5 s. Using one 4×4 (16) waveguide array, up to 650 kW of net RF power has been injected into Alcator C (corresponding to 9 kW/cm^2 on the BeO windows and in the stainless steel waveguides). These

are record power levels injected through such a small port with any type of RF heating technique in any fusion device. The RF power injected scaled linearly with the area of a 4 and a 16 waveguide array used in these experiments. Using two 16 waveguide arrays, 1.15 MW of net power has been injected, and the upper limit has not yet been reached since only 1.6 MW of source power was used (out of the available 2.0 MW).

RF current drive experiments have been carried out on Alcator C by opening the primary circuit of the ohmic heating transformer (after initial OH-start-up of the target plasma). In the absence of RF power the plasma decays inductively in an L/R time of 100-150 ms. If the RF power is turned on during this decay phase the current decay can be arrested and the current can be maintained at a constant value of $I \approx 150-200$ kA for 200 ms, and the loop voltage is driven to the zero level during the flat-top current period. These currents can be generated only when adjacent waveguides in a given row are phased progressively with $\Delta\phi \approx 90^\circ \pm 30^\circ$, corresponding to traveling wave generation. RF current drive has been observed at magnetic fields in the range $B_T \approx 6-11$ tesla, with maximum current drive efficiencies at the higher magnetic fields. The current drive efficiency obtained in these experiments is

$$\zeta = \frac{\bar{n} (10^{14} \text{ cm}^{-3}) I (\text{MA}) R (\text{M})}{P (\text{MW})} \approx 0.12 .$$

These efficiencies are observed at densities up to $\bar{n} \approx 8 \times 10^{13} \text{ cm}^{-3}$ and current drive with somewhat lower efficiencies has been observed up to densities $\bar{n} \approx 1 \times 10^{14} \text{ cm}^{-3}$ at RF power levels of 1 MW. It is interesting to note that in the Princeton PLT experiment (where an 800 MHz system is used), for 90 phasing and densities in the range $\bar{n} < 8 \times 10^{12} \text{ cm}^{-3}$, the corresponding efficiency is $\zeta \approx 0.08$, which is comparable (although somewhat below) that obtained in Alcator C. Other experiments in France and Italy at frequencies of 1.3 to 2.45 GHz provide current drive at intermediate densities between those in PLT and Alcator C, all

indicating that current drive at higher densities requires higher frequencies. "Current ramping", namely a current growing with time and the loop voltage driven negative, has also been demonstrated with an efficiency of

$$\frac{\delta \left[\frac{\bar{n} (10^{14} \text{ cm}^{-3}) I (\text{MA})}{P (\text{MW})} \right]}{\delta t (\text{s})} \approx 0.16 .$$

When RF current ramping is performed in the presence of OH power (positive loop voltage) efficiencies as high as ~ 0.8 have been achieved.

The major significance of these experimental results is that they establish that RF-driven current can be produced efficiently at reactor-level densities. While previous demonstrations of current drive in devices such as Versator and PLT have been encouraging, they have all occurred at densities below 10^{13} cm^{-3} , over an order-of-magnitude below that required for a reactor. Clearly, more work needs to be done in order to raise the density further and to investigate the dependence of the efficiency on electron temperature T_e , and on $\omega_{pe}^2/\omega_{ce}^2$, the dielectric constant of the plasma.

During LH heating experiments the most efficient bulk heating was found in the electron heating regime at densities $\bar{n} \approx 8 \times 10^{13} - 2 \times 10^{14} \text{ cm}^{-3}$ (using both carbon and molybdenum limiters). In particular, at $\bar{n} \approx 8 \times 10^{13} \text{ cm}^{-3}$ we obtained $\Delta T_e \approx 400-500 \text{ eV}$, $\Delta T_i \approx 50 \text{ eV}$, in pocographite limited plasmas when $P \approx 0.5 \text{ MW}$ of RF power was injected. However, upon injection of $P_{rf} \approx 1 \text{ MW}$ of RF power, using silicon-carbide coated graphite limiters maximum temperatures of $T_e \approx 3.1 \text{ keV}$, $T_i \approx 1.9 \text{ keV}$ have been achieved ($\Delta T_e \approx 1.1 \text{ keV}$, $\Delta T_i \approx 0.9 \text{ keV}$) at a density of $\bar{n} \approx 1.4 \times 10^{14} \text{ cm}^{-3}$ in deuterium plasmas. The maximum heating efficiencies are of the order of 60% and are comparable with those observed during the best ICRF heating experiments on the French TFR tokamak at densities $\bar{n} \approx 1 \times 10^{14} \text{ cm}^{-3}$. To the present date, only the TFR and

Alcator C tokamaks have been operated at reactor-level densities ($\bar{n} \gtrsim 1 \times 10^{14} \text{ cm}^{-3}$) with auxiliary heating. The high power heating experiments were accompanied by injection of significant amounts of carbon from the limiter. This can be understood by noting that the total maximum (OH + RF) surface power density in these experiments is of the order of $P/S \approx 0.4 \text{ MW/m}^2$, a record (and a reactor relevant) value. These experiments indicate that divertors (or equivalent) will be needed in reactors.

As the Alcator C program plan shows (PFC Report IR-82-3), the RF power will again be doubled to the 4 MW source level early in FY84. All equipment and supporting hardware already exist on site and are installed for this program and the results from the next 24 month period of intensive experimentation should constitute a basis for assessing the viability of lower-hybrid current drive and electron heating at reactor relevant densities. Start-up experiments using lower hybrid current drive will also be carried out, where we preionize, and raise the plasma density, temperature and toroidal current without using ohmic heating current. Such phenomena were demonstrated successfully at low densities on PLT.

Alcator DCT: The conceptual design effort of the past two years has led to the proposal of a moderately high magnetic field, superconducting tokamak, capable of addressing many of the technical issues associated with long-pulse or steady-state operation at reactor-level power densities. The device, called Alcator DCT (Driven Current Tokamak) features sufficient lower hybrid power to provide for a steady-state mode of operation.

The areas of plasma physics, plasma engineering, and fusion technology which will be addressed include: optimization of the time evolution of high performance tokamak discharges for very long pulses; development of methods of shape and profile control to optimize stability and performance under steady-state conditions; development and evaluation of methods of noninductive current-drive and RF heating techniques appropriate for reactor-level plasmas; development of plasma edge, particle and impurity

control methods required for long-pulse to steady-state operation; demonstration of fully integrated, high performance superconducting magnet systems; and, development and evaluation of high heat flux and RF components appropriate for reactor applications.

The Alcator DCT design incorporates a number of features which are essential in implementing these studies. The magnet system is fully superconducting, using Nb_3Sn ICCS conductor for the toroidal field coil system, and NbTi with a similar cabled conductor for the poloidal field system. The toroidal field on axis is 7 tesla, corresponding to 10 tesla at the coil, while the poloidal field system provides a flux swing of 35 volt-seconds, permitting inductively-driven pulse lengths of several minutes. For plasma heating and noninductive current drive, Alcator DCT will use the existing Alcator C equipment, including 5 MW of CW power at 200 MHz for ICRF heating, and 4 MW at 4.6 GHz for lower hybrid heating and current drive. The nominal plasma dimensions in the Alcator DCT device are a major radius of 2 meters, and a minor radius of 0.4 meters, and the toroidal plasma current in excess of 1 MA.

Plasma edge and impurity control investigations are implemented using both magnetic divertor and pumped limiter configurations. The poloidal field system can produce a single-null divertor configuration with elongation of approximately 1.5. Circular and shaped plasmas can also be produced for limiter studies. The heat flux at the limiter or divertor collector will be close to the levels anticipated for reactors, and will provide an excellent opportunity for testing and demonstration of reactor components.

A construction time of four years is anticipated for Alcator DCT. Thus, if detailed design and fabrication begin in 1984, operation is expected in 1988.

III. MIRROR CONFINEMENT EXPERIMENTS

A. OBJECTIVES:

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

B. RESEARCH 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 Mirror Confinement Experiment Division, headed by Richard S. Post, is involved in the design, construction and operation of a medium-scale tandem mirror confinement facility. The TARA tandem mirror configuration is unique in that it uses an axisymmetric confining plug with an "outboard" minimum-B anchor. It has been identified as a highly desirable tandem mirror configuration for potential reactor applications. The principal objectives of the experiment will be to test plug microstability, overall MHD stability and beta limits, central cell radial transport and axial potential enhancement. The experiment will provide data for the MFTF-B facility, now under construction at Lawrence Livermore National Laboratory.

The following is a brief summary of the TARA design. The TARA central cell is a 20 cm radius, 10 m long solenoid with upgrade capabilities to 15 m. Using axial potential enhancement, 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. Potential enhancement by either thermal barrier or electron pumping techniques will be developed. Gyrotrons at 28 GHz are available with a capability of 200 kW per plug for creating the hot mirror-trapped thermal barrier electron species and the suprathemal ($T_e \sim 700$ eV) warm electron species for thermal barrier potential enhancement in the plugs. Alternatively, RF at the electron bounce frequency may be used for potential enhancement by parallel electron heating.

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 the TMX experiment at LLNL. They will operate steady-state and contain a low-density ($n_e \sim 5 \times 10^{11} \text{ cm}^{-3}$) hot-electron plasma, formed by ECRH heating in the X-band. Additional ICRF heating will be used to augment ion beta values in the anchor.

The axisymmetric central cell and plug configuration in TARA are ideally suited for testing full axisymmetric configurations using cusps or EBT rings.

C. TARA RESEARCH GROUPS AND PROJECT AREAS:

1. CONFINEMENT PHYSICS

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, J. Irby, J. Kesner, R.E. Klinkowstein,
M. Mauel, B.D. McVey, E. Sevillano, D.K. Smith,
J. Sullivan, R. Torti

Visiting Scientists:

J. Trulsen

Graduate Students:

T. Farish, P. Goodrich

Support Staff:

S. Mullin, B. Ogar

C. SPECIAL EQUIPMENT AND FACILITIES UNDER CONSTRUCTION:**Experimental Facility:**

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

Major Facility Support Equipment:

- Twelve 600 V, 7 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; three 3 MVA transformers, multiply-tapped to maintain a good power factor even at reduced voltage.

Plasma Heating Equipment:

- 4-28 GHz gyrotrons, 200 kW each, pulsed 50 ms.
- 2 X-band amplifiers, 10 kW each, CW.
- 2 X-band amplifiers, 2 kW each, CW.
- 3 ICRF amplifiers, 1 MW each.
- 6 Neutral beam sources, 20 kV, 50 A, 75 ms.

D. TECHNICAL PROGRAM SUMMARY:

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

2. TARA ENGINEERING

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

A. OBJECTIVES:

Design and construct the TARA experimental facility and heating subsystems.

B. PERSONNEL:

Engineering and Research Staff:

J. Alexander, P. Brindza, D. Bruscella, J.E. Coleman,
M. Dunham, M. Gaudreau, C. Karcher, D.B. Montgomery,
M. Olmstead, D.K. Smith, J. Stillerman, J.M. Tarrh,
P. Thomas, J. Thompson, J.E. Tracey, F. Yee

Technical Support Staff:

R. Alves, A. Arini, D. Babin, J. Brandolini, W. Brooks,
D. Clarke, W. Cochran, R. Davco, W. Hawe, D. Kevan,
M. Lilley, M. Manghi, W. Marston, L. Pires, R. Rameriz,
R. Ranalli, W. Reed, R. Wardenaar, C. Warren, G. Yarworth

Graduate Students:

T. Farish, P. Goodrich

Support Staff:

S. Mullin, B. Ogar, A. Rabasco, D. Williams

C. TECHNICAL PROGRAM SUMMARY:

Site preparation in the Nabisco Building (NW21) to create the experimental area began in April, 1982, and final assembly of the experimental facility began in April, 1983. The completion date for the TARA facility is January, 1984.

Simultaneously with the preparation of the experimental area and construction of the facility, there is a vigorous technology development program. The program has resulted in the development of a 20 kV, 50 A neutral beam prototype, novel neutral beam power supplies, new sublimation pumping techniques and a basic diagnostic set. In the RF heating program, the concept of slot antennae has been developed for ICRF coupling and grill-coupled cavity launchers for the 28 GHz gyrotrons.

3. COMPUTATIONS AND ADVANCED CONCEPTS

J. Kesner, Leader

A. OBJECTIVES:

Analyze and evaluate the various operating modes of the TARA experiment. Investigate areas of tandem mirror physics that impact importantly on the TARA confinement configuration. Explore advanced concepts that might improve the tandem mirror as a potential fusion device.

B. PERSONNEL:

Research Staff:

M.J. Gerver, J. Kesner, B. Lane, M. Mael, B.D. McVey,
T-F. Yang

Graduate Students:

S. Hokin

Support Staff:

S. Mullin, B. Ogar

C. TECHNICAL PROGRAM SUMMARY:

The TARA base program, along with the tandem mirror theory effort provides theoretical support and computational expertise

for the TARA group. Areas of continuing effort include investigations of the needs and limitations of ECRH-formed MHD anchors, the effects of rotation and collisionality on trapped-particle mode stability, ion microstability and MHD equilibrium and stability properties. Detailed analysis will continue on ICRF antenna coupling schemes, which will allow a more complete evaluation of the proposed TARA start-up approach with electron pumping and ICRF. Monte-Carlo RF heating simulation codes are presently being developed for detailed modeling of potential formation and RF heating in tandem mirrors. A multiregion point code to describe the particle and power balance for the TARA experiment is being developed.

IV. FUSION TECHNOLOGY AND ENGINEERING

OBJECTIVES:

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

RESEARCH GROUPS:

- Advanced Design
Richard Thome and Joel Schultz, Co-Leaders
- MHD and High Energy Physics Design
Peter Marston, Leader; John Tarrh, Associate Leader
- Superconducting Magnet Development
Mitchell 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, headed by D. Bruce Montgomery, provides critical engineering analysis for advanced design projects, and develops advanced superconducting magnet technology for the national fusion program.

Major upgrades of the large tokamak and mirror experiments in the U.S. are under consideration, and examination of the alternatives is the responsibility of the Fusion Engineering Design Center, an industrially-based design group located at Oak Ridge National Laboratory. The Plasma Fusion Center provides major technical support to that Center, with responsibility for a number of magnet systems and critical design issues. Major responsibilities in the area of systems engineering and poloidal field design have also been undertaken for the Princeton Plasma Physics Laboratory in the design of TFCX (Tokamak Fusion Core Experiment). Analysis of critical magnet design issues for the international INTOR project is also carried out.

The Plasma Fusion Center has been active in developing improved magnetic divertor concepts. 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.

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, was selected by Westinghouse for the 2 x 3 meter niobium-tin coil for the Large Coil Project at the Oak Ridge National Laboratory. The forced-flow group has also used 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.

Advanced magnet design for the national MHD program, and for selected national high energy physics projects is also carried out. While the MHD program is greatly reduced from its level in 1980, there are several utility/industrially-based activities which show promise of substantial growth. Research by the MIT magnet design group in the high energy physics area was directed at redesigning the finally-successful Isabelle (CBA) magnet systems during 1981-82, and is now emphasizing work on a large international L3 muon detector for the LEP installation at CERN. The international team designing and operating this experiment is headed by Prof. S. Ting of MIT.

In addition to these fusion and related technology areas, the engineering group is involved in the design and construction of the PFC confinement experiments. Advanced design activities during the past year have concentrated on conceptual design studies for a superconducting long-pulse tokamak, Alcator DCT, as a follow-on to the Alcator C experiment.

1. ADVANCED DESIGN

Richard J. Thome and Joel H. Schultz, Co-Leaders

A. OBJECTIVES:

Carry out engineering in critical magnet technology areas for advanced design projects.

B. RESEARCH PROJECTS:

- TFCX

J.H. Schultz, PF Systems Design Project Leader

R.J. Thome, Systems Engineering Project Leader

- INTOR

R.J. Thome, Project Leader

- Magnet Safety and Protection Studies

R.J. Thome, Project Leader

- Engineering Support for Next Step MIT Confinement Experiments

J.H. Schultz, Project Leader

- Evaluation of Organic Insulators Under Neutron Irradiation

H. Becker, Project Leader

C. PERSONNEL:

Research Staff:

H. Becker, Y. Iwasa, W.G. Langton, W.R. Mann,

N.T. Pierce, R.D. Pillsbury, Jr., J.H. Schultz,

D. Sliski, R.J. Thome

Visiting Scientist:

Z. Guo

Designer Drafters:

N. Diatchenko, A. Rabasco

Secretary:

D. Marble

D. SPECIAL EQUIPMENT AND FACILITIES:Computer Equipment:

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

E. TECHNICAL PROGRAM SUMMARY:

TFCX Design Activities: The PFC Fusion Technology and Engineering Division has major responsibilities in the TFCX advanced design project directed by Princeton Plasma Physics Laboratory. Research in FY84 will emphasize:

- Development of superconducting poloidal field concepts and overall responsibility for PF design work carried out at the FEDC, various national laboratories, and by industrial contractors.
- System engineering responsibilities in overall system studies, particularly in the magnetics area.

In addition to the TFCX work, critical problems for the INTOR concept are also carried out, and the magnetics group participates in evaluation of various national activities.

Magnet Safety and Protection Studies: In this task area, large-magnet safety problem areas have been reviewed, the primary technical issues selected, and safety-related experiments defined.

The primary technical issues associated with large superconducting magnet safety include: (1) understanding and control of energy deposition and flow during a fault condition; (2) detection

and discrimination among 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 depends on the ability to predict the propagation of a large-scale quench with the associated voltage and temperature distribution. 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 represent large coil behavior suitably.

Another technical issue identified to be of prime importance to magnet safety is the need to develop means for inspecting impending failure without major disassembly of the magnet. Work in acoustic emission analysis on superconducting magnets has been initiated for use in this area. Acoustic emission sensors were installed on the MFTF-B Yin Yang magnet and are being installed on the two completed Large Coil Test Facility magnets. Development of this technique also benefits from installation of sensors and analysis of output from smaller systems in which controlled failure experiments can be undertaken.

Engineering Support for 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.

During FY83, engineering scoping studies were undertaken in the areas of a major upgrade of Alcator C. Alcator C upgrade studies have focused on the use of the large amount of RF power available at MIT and have resulted in a proposal for the use of RF current drive in an all-superconducting tokamak, called Alcator DCT.

Organic Insulation Limits Under Neutron Irradiation: There is evidence that organic insulation in magnets subject to neutron irradiation can have much greater tolerance than generally believed. If the material is used in thin sheets, subject largely to pure compression, and if use is made of suitable glass reinforcement and epoxies, doses one to two orders-of-magnitude beyond conventional design limits are possible. Tests are being carried out at several national facilities and evaluated by the PFC.

2. MHD AND HIGH ENERGY PHYSICS MAGNET DESIGN

Peter Marston, Leader
John Tarrh, Associate Leader

A. OBJECTIVES:

Design support for the national MHD and high energy physics programs, and execution of magnet technology experimental programs.

B. RESEARCH PROJECTS:

- Design and experimental work in support of the MIT collaboration on the large L3 detector magnet system at CERN.
- Design and analysis in support of national MHD magnet projects, in particular the Southern California Edison MHD topping cycle upgrade.
- Support of various medical programs using magnetic devices.

C. PERSONNEL:

Research Staff:

P.G. Marston, J.M. Tarrh, H. Becker, A.M. Dawson,
R. Hale, D.B. Montgomery

Administrative Assistant:

B. Keesler

D. TECHNICAL PROGRAM SUMMARY:

Major design activities were undertaken in FY81 in support of redesign activities for the Isabelle (Colliding Beam) accelerator magnets at Brookhaven. Experimental work in analyzing the location of premature magnet quenches was carried out using acoustic emission techniques. Major experimental and analytical work was carried out on winding pack mechanical characteristics of improperly-supported end windings. The MIT work was instrumental in pointing out requirements for improved construction and performance.

Design activities in high energy physics are now concentrating on supporting Professor S. Ting's work on a very large magnet detector for installation in CERN. Design review and analysis of interface problems are being undertaken to support the design responsibilities of the CERN magnet group.

The MHD activities are much reduced over activities in 1980, when MIT carried major responsibilities to develop large-magnet technology and to supervise construction of several large magnets. Activities are now largely of a design nature that support current activities such as the proposed upgrade of a California Edison plant with a closed-cycle MHD topping cycle.

The failure of the 6 T LN₂-cooled High Performance Demonstration Experiment magnet at Arnold Research Organization/Calspan in Tullahoma has been analyzed. This catastrophic failure has led to reevaluation of structural analytical procedures for large magnet design. A redesign and cost estimate will be completed for a new HPDE magnet system.

Various medically-oriented programs are also carried out by members of this group including support of an infant-tissue-stretching technique at MGH for repair of birth defects, and magnetic guidance of magnetically-tagged chemotherapy drugs at Lilly Research Laboratories.

3. SUPERCONDUCTING MAGNET DEVELOPMENT

Mitchell O. Hoenig, Leader

A. OBJECTIVES:

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

B. RESEARCH PROJECTS:

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

C. PERSONNEL:

Research Staff:

M.O. Hoenig, M.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 m 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

* ICCS: Internally-cooled, cabled superconductor.

by the magnet group is being used by Westinghouse for the 2×3 meter niobium-tin coil 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 $1 \text{ m} \times 2 \text{ m}$ 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 toward the completion of a 1 m diameter insert coil for the High Field Test Facility at Livermore. This coil will test the steady state and transient stability of a 120 m length of Westinghouse LCP conductor in peak fields up to 12 T. Work in support of this "12 Tesla Coil" includes development and full scale testing of current terminations for the conductor, and critical current optimization of the Nb_3Sn activation cycle.

Work on advanced conductors has focused on the relationship of the conductor sheath to critical properties of the Nb_3Sn . A search is underway for a sheath material with mechanical properties equivalent to JBK-75 superalloy, but with a thermal contraction matching Nb_3Sn in the range 1000-4 K.

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

4. SUPERCONDUCTING MATERIALS DEVELOPMENT

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 Staff:

J. Conlon, I. Puffer

Graduate Students:

J.D. Klein, S-J. 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 temperature 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 kA/m^2 at a 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 strain (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 Professor 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 (Flükiger) have been used to prepare 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).

5. DIVERTOR DEVELOPMENT

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 construct the ISX-B bundle divertor.
- Scoping study of TEXTOR bundle divertor.
- Develop divertor designs for DCT and TFCX.

C. PERSONNEL:

Faculty:

B. Mikić, N. Todreas

Research Staff:

T. Yang

Graduate Students:

A. Wan

Secretary:

A. Kotsopoulos

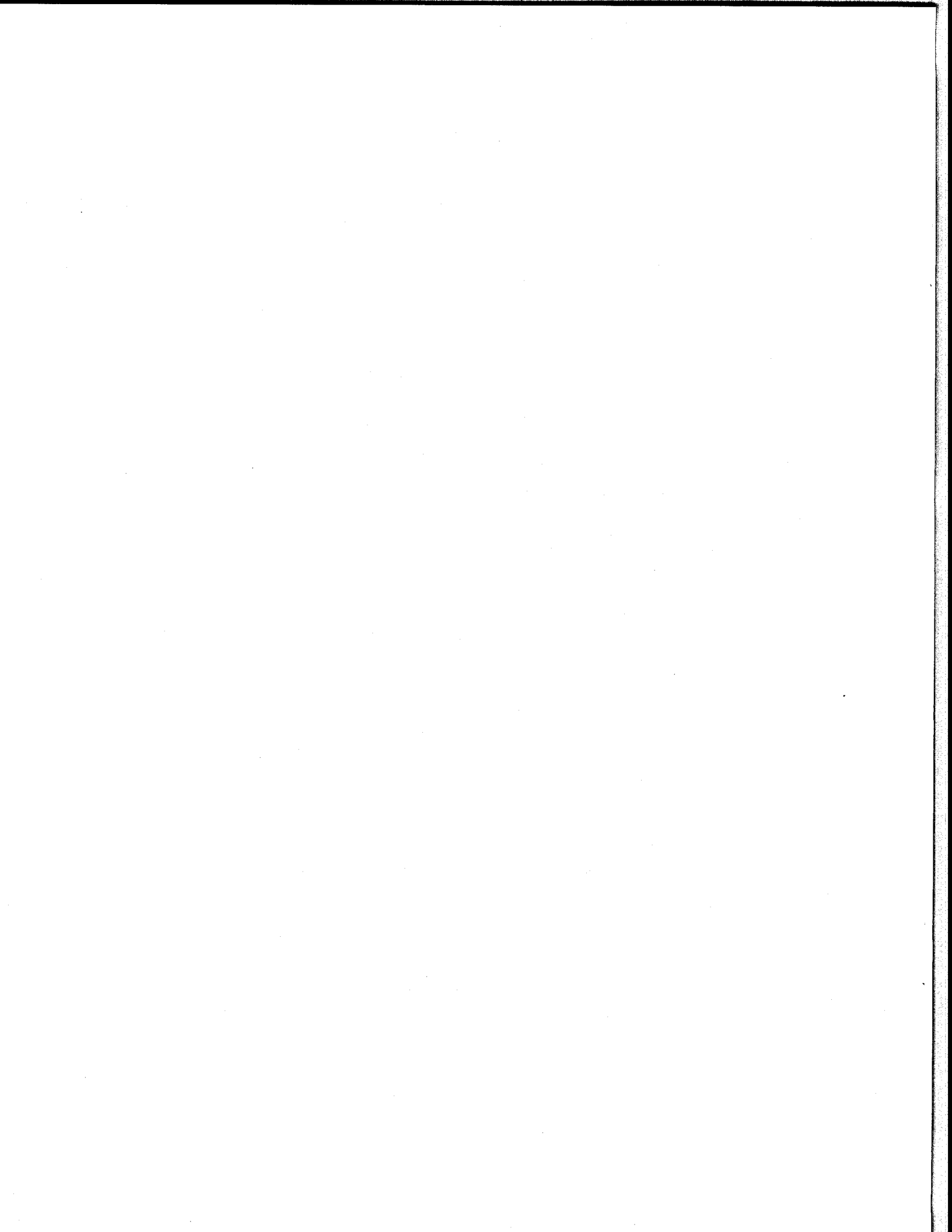
D. TECHNICAL PROGRAM SUMMARY:

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 was 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.

This group has recently been asked to develop divertor concepts and designs for upgrades of two European tokamaks (TEXTOR and DITE). Coupling of this work with possible divertor configurations for Alcator DCT will receive future emphasis. There is no comparable program elsewhere in divertor technology development.

Scoping designs of divertors suitable for reactor application are also being undertaken. Initial results indicate that it will be feasible to use superconducting magnets. Scoping designs suitable for INTOR, based on the reactor-relevant designs, have also been carried out.



V. FUSION SYSTEMS

OBJECTIVES:

Investigate design features and reactor physics of future tokamak test reactors. Increase the basic understanding of operating characteristics and technology requirements of commercial fusion reactors. Develop new design concepts. Develop advanced millimeter and far infrared wave technology for plasma heating and diagnostics.

RESEARCH GROUPS:

- Reactor Systems Studies
Daniel Cohn, Leader
Leslie Bromberg, Assistant Leader
- Safety and Environmental Studies
Mujid Kazimi, Leader
- Gyrotron and Advanced Millimeter Source Development
Richard Temkin, Leader

RESEARCH PROJECTS:

- High Power Submillimeter Laser Thomson Scattering System
Paul Woskoboinikow, Leader
- Submillimeter Wave Technology Development
Peter Tannenwald, Leader

The Fusion Systems Division, headed by Daniel Cohn, carries out a wide range of systems studies activities and advanced millimeter and far infrared wave technology development.

Present system studies programs include investigations of long-pulse commercial tokamak reactors, copper-magnet ignition test reactors, and new mirror reactor concepts. In addition, there are investigations of the effects of pulsed operation on the first wall and blanket, and studies of safety issues connected with possibilities of lithium fires and tritium releases. Two new reactor concepts which have been developed recently include a

commercial tokamak reactor with day-long pulses provided by the ohmic heating (OH) transformer, and a design for a modest size next step tokamak test reactor. The tokamak test reactor concept, referred to as LITE, for long-pulse ignited test experiment, uses high-performance resistive magnets and would provide ignition and equilibrium burn at relatively low cost.

In the area of advanced millimeter technology development, a high-frequency (140 GHz) gyrotron has been constructed and operated at a power level of 100 kW in a 1 μ s pulse. This power level represents a world record at high frequency. The purpose of the program is to provide a basis for the production of devices for millimeter wave plasma heating.

The far infrared wave technology under development for plasma diagnostics includes a high power 385 μ m D₂O laser for Thomson scattering. The first measurement of thermal level Thomson scattering in a tokamak plasma has been obtained using this system on the Alcator C tokamak. In addition, advanced submillimeter wave Schottky barrier diode detectors are being developed by Lincoln Laboratory for diagnostic applications by DOE Laboratories in a variety of plasma confinement studies.

1. REACTOR SYSTEMS STUDIES

Daniel R. Cohn, Leader

Leslie Bromberg, Assistant Leader

A. OBJECTIVES:

Investigate design options for the next step tokamak test reactors. Increase the basic understanding of design and operation of commercial fusion reactors. Develop new concepts.

B. RESEARCH PROJECTS:

- Studies of long pulse commercial tokamak reactors.
L. Bromberg, Project Leader
- Long-Pulse Ignition Test Experiment (LITE).

- Mirror reactor concepts.
- First wall and blanket design for long pulse reactors.
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, C. Lee, J. Nakagawaa, J. Nolley

Undergraduate Student:

J. Zwick

Secretary:

In transition

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 both test reactors and commercial devices.

To summarize recent achievements, new design concepts have been developed for commercial tokamak reactors with very long pulses. An illustrative design has been developed for a device which could provide day-long pulses using the capability of the OH transformer. The illustrative design is only slightly larger than current commercial tokamak reactor designs.

A new design concept has also been developed for a long-pulse ignited test experiment (LITE) device, a tokamak which uses high-performance resistive magnet technology. The physical size of LITE is similar to TFTR. However, LITE would provide much higher values of $n\tau_E$ and have substantially greater long-pulse

capability. The higher $n\tau_E$ capability is obtained by operation at high magnetic fields and moderately high values of beta (the ratio of plasma pressure to magnetic field pressure).

To summarize future plans, improved design concepts for commercial tokamak reactors which use superconducting magnets and provide long pulses will be developed. Designs for commercial reactors which use resistive magnets will also be investigated. Lower-cost versions of the LITE design will be studied. New concepts for mirror reactors will be developed in collaboration with the TARA experimental program. In particular, use of RF pumping for potential barrier formation will be studied. First wall and blanket design issues will be investigated as part of the study of long-pulse commercial tokamaks.

2. SAFETY AND ENVIRONMENTAL STUDIES

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. RESEARCH 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:

D. Hanchar, M. Tillack, E. Yachimiak

Undergraduate Students:

J. Mullany, E. Wilcox

Secretarial Staff:

G. Jacobson

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 such releases from 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 physical 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 conditions (e.g., oxidation rates at high temperatures); (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

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:

- Studies of 100 kW, 140 GHz pulsed gyrotron operation.
- Theoretical and experimental studies of nonuniform resonators.
- Conceptual design of 1 MW high frequency gyrotrons.

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. Davidson, B. Danley, K. Kreischer,
B. Lax, W. Mulligan, R. Temkin, P. Woskoboinikow

Graduate Students:

J. Byerly, S. Evangelides, J. Schutkeker

Undergraduate Student:

R. Chaplya

Secretary:

In transition

D. SPECIAL EQUIPMENT AND FACILITIES:

Experimental Facilities:

- Bitter plate copper solenoid with 10.48 cm bore, modified by two auxiliary electron gun solenoids, for gyrotron operation 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. CO_2 TEA oscillator-amplifier single mode laser with output power of 30 MW.

E. TECHNICAL PROGRAM SUMMARY:

The 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, high-frequency (140 GHz) gyrotrons. The MIT gyrotron operates in a uniform, high magnetic field (5 T) and emits 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.

100 kW operation has been obtained in a pulse length of 1 μ s. This power level represents a world record at high frequency (140 GHz). New effects of multimode operation have been observed.

A theoretical effort in the linear and nonlinear behavior of gyrotrons has been carried out in support of the experiments. Both waveguide and quasioptical gyrotron devices have been investigated. Theoretical results for irregular gyrotron cavities which optimize efficiency and improve mode spacing have been obtained.

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 Plasma Fusion Center using a grating-tuned CO_2 TEA laser, indicate that continuous tuning from 150 to 1200 μ m 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 versus 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. MILLIMETER AND SUBMILLIMETER WAVE THOMSON SCATTERING SYSTEMS

Paul Woskoboinikow, Project Leader

A. OBJECTIVES:

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

B. PERSONNEL:

Research Staff:

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

Graduate Student:

J. Machuzak

Secretary:

In transition

C. SPECIAL EQUIPMENT AND FACILITIES:

Computer Equipment:

1 Digital Equipment MINC minicomputer

Experimental Facilities:

Single-mode, tunable, 50 J CO₂ oscillator-amplifier laser system, pulse length adjustable from 100 ns to 1 μs. Tunability of ±2 GHz over 60 transitions with fourier-transform-limited bandwidth.

D. TECHNICAL PROGRAM SUMMARY:

A 100 kW, 1 μs pulse length, 385 μm D₂O laser has been developed. Laser action in D₂O is obtained by optical pumping with 9.26 μm CO₂ laser radiation. A narrow D₂O laser linewidth is obtained by use of narrow-linewidth CO₂ 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) CO₂ 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. The laser and detector system have been used on Alcator C to make the first measurements of thermal level Thomson scattering in a tokamak plasma.

Future activities will involve efforts to develop far infrared scattering as a diagnostic 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.

The major component of future efforts will be the development of a gyrotron scattering diagnostic to measure waves created by microinstabilities in mirror plasmas. A 140 GHz gyrotron will be used for scattering from plasmas in TARA.

5. SUBMILLIMETER WAVE TECHNOLOGY DEVELOPMENT

Peter Tannenwald, Project Leader

A. OBJECTIVES:

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

B. LINCOLN LABORATORY PERSONNEL:

Research Staff:

B. Clifton, B. Lax, G. Sollner, P. Tannenwald

Technical Support Personnel:

C. Parker, T. Forte

C. SPECIAL EQUIPMENT AND FACILITIES:

Microelectronics epitaxial crystal growth; photolithography and mask making; proton bombardment; ion implantation; diode packaging; submillimeter radiometers; carcinotrons; quasioptical components; InP growth.

D. TECHNICAL PROGRAM SUMMARY:

This project involves the development of 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, improved capability for harmonic generation will be obtained in Schottky diode mixers. Monolithic Schottky barrier diode detectors will be developed. This technology development effort contributes to the diagnostics development program in the Applied Plasma Physics Division.

VI. OFFICE OF RESOURCE MANAGEMENT

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:

The PFC Office of Resource Management is headed by John Cochrane, Assistant to the Director for Administration. The primary areas of administrative support are listed below.

- Headquarters Operations - Provide 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 - Includes 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, L. Bartolet, G. Chambers, B. Colby,
J. Cooper, A. Dawson, C. Foley, A. Karageorge,
M. Langton, T. Lloyd, D. Murphy, N. Robinson

- Fiscal Office:

Kathleen LaPier, Fiscal Officer

Staff:

V. Brooks, P. Catano, C. Enos, M. Gittens,
J. Hagerty, A. LeBlanc, P. Marcus, J. Rigione,
P. White

- Purchasing Office:

Kenneth Wisentaner, Manager

Staff:

M. Bacon, J. Brickle, C. Fitzgerald, P. DiPanfilo,
R. Newcomb, M. Silva

- RLE Administrative Support:

Don Duffy, RLE Fiscal Officer

Staff:

D. Clements, T. Garalis, J. Lauricella, E. LaValle,
J. Mitchell, J. Moore, D. Taylor, V. Taylor

APPENDIX B

PLASMA FUSION CENTER

VISITING AND ADVISORY COMMITTEES

PLASMA FUSION CENTER VISITING 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 at the divisional level on a regular basis. This is an 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:

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

B. PFC Advisory Committee

The PFC Advisory Committee consists of the MIT Vice President for Research, the Director of the Plasma Fusion Center, and the Deans and Heads of MIT academic departments which have 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:

Jonathan Allen
Director, Research Laboratory of Electronics

Ronald Davidson,
Director, Plasma Fusion Center

John Deutch
Dean of Science

Jerome Friedman
Head, Physics Department

Joel Moses
Head, Electrical Engineering and Computer Science Department

Kenneth Smith
Associate Provost and Vice President for Research

Neil Todreas
Head, Nuclear Engineering Department

Gerald Wilson
Dean of Engineering

Peter Wolff
Director, Francis Bitter National Magnet Laboratory

C. PFC Visiting Committee

The PFC Visiting Committee consists of eleven nationally and internationally renowned fusion scientists and engineers, external to the PFC, that meet 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:

Dr. Charles C. Baker
Argonne National Laboratory

Prof. Herbert Berk
University of Texas

Dr. Teranzio Consoli
La Celle Saint-Cloud

Dr. Carl Henning
Lawrence Livermore National
Laboratory

Dr. Richard F. Post
Lawrence Livermore National
Laboratory

Prof. John Dawson
University of California
at Los Angeles

Prof. Norman Rasmussen
Massachusetts Institute of
Technology

Prof. Harold Furth
Princeton University

Dr. Paul J. Reardon
Princeton University

Prof. Roy Gould
California Institute
of Technology

Prof. Weston M. Stacey, Jr.
Georgia Institute of Technology

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 major program issues and help plan future program directions. The present membership of the Plasma Fusion Center Executive Committee is:

Ronald Davidson
Director

Daniel Cohn
Head, Fusion Systems Division

D. Bruce Montgomery
Associate Director for Engineering Systems

Ronald Parker
Associate Director for Confinement Experiments

Richard S. Post
Head, Mirror Confinement Experiments Division