MASSACHUSETTS INSTITUTE OF TECHNOLOGY

PLASMA FUSION CENTER

TECHNICAL RESEARCH PROGRAMS

August, 1980

PFC/RR80-18

The MIT Plasma Fusion Center research activities cover a broad range of engineering and scientific disciplines related to the development of fusion energy. This report gives an updated overview of Plasma Fusion Center technical research programs and staffing and objectives at the individual Research Group level.

Ronald C. Davidson
Director
Plasma Fusion Center

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I. INTRODUCTION

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

By way of background, the Plasma Fusion Center technical programs are supported by the Department of Energy's Office of Fusion Energy at a funding level of approximately $14 million in FY 80. Moreover, there are approximately 220 personnel associated with Plasma Fusion Center reserach activities. This includes: 25 faculty members and 70 graduate students, with participating faculty and students from Aeronautics and Astronautics, Electrical Engineering and Computer Science, Materials Science and Engineering, Mathematics, Nuclear Engineering, and Physics; 80 research scientists and engineers contributing to numerous physics and engineering aspects of fusion energy development; and 50 support personnel, including technical support staff, secretaries, and administrative staff. At the present time, the Plasma Fusion Center's major experimental and engineering facilities are located at several sites on the MIT campus, including NW13 (Nuclear Engineering), NW14 (National Magnet Laboratory), NW16 (Plasma Fusion Center), Building 36 (Research Laboratory of Electronics), Building 38 (Electrical Engineering and Computer Science), and NW21 (PFC Nabisco Facility).

II. PLASMA FUSION CENTER TECHNICAL PROGRAMS

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

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

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

Applied Physics Research

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

The subprogram areas include:

- Experimental Research - Tokamak Systems
- Experimental Research - Mirror Systems
- Advanced Fusion Concepts
- Fusion Theory and Computations

- Theory of Thermonuclear Plasmas
- MACSYMA
- Diagnostic Development and Laser Systems
- Intense Charged Particle Beams

Confinement Experiments

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

At the present time, the subprogram areas include:

- Alcator A
- Alcator C

Fusion Technology and Engineering

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

The subprogram areas include:

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

Fusion Systems

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

The subprogram areas include:

- Safety and Environmental Studies
- Tokamak System Studies

- Blankets and Structures
- Gyrotron and Advanced Millimeter Source Development
- Millimeter and Submillimeter Wave Detector Development

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

Finally, the Plasma Fusion Center and the Massachusetts Institute of Technology have made a strong institutional and intellectual commitment to the establishment of a center of excellence for mirror systems fusion research at MIT. In this regard, Drs. Richard Post and Jay Kesner have recently accepted appointments at MIT to initiate a tandem mirror experimental program that will significantly complement the mirror research activities at Lawrence Livermore Laboratory as well as the ongoing PFC research activities in mirror theory and the Constance I and II experimental program. The Plasma Fusion Center has submitted a proposal to the Department of Energy for Phase I renovations of the west wing of the Nabisco Building to establish a mirror systems experimental facility that will house the tandem mirror experiment, related support facilities, and follow-on devices in the Constance program. The technical proposal for the tandem mirror experiment is presently in preparation and will be submitted to the Department of Energy in the fall of 1980.

III. PLASMA FUSION CENTER TECHNICAL STEERING AND ADVISORY COMMITTEES

The PFC Technical Steering Committee, which is composed of the Principal Investigators of all major fusion research activities in the Plasma Fusion Center, meets on a regular basis.

This is an extremely 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 includes:

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

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

Robert Alberty
Ronald Davidson
Herman Feshbach
Thomas Jones
Jack Kerrebrock
Benjamin Lax
Norman Rasmussen
Robert Seamans
Gerald Wilson
Peter Wolff

Finally, the PFC Associate Directors and Division Heads, Drs. Daniel R. Cohn, Lawrence M. Lidsky, D. Bruce Montgomery and Ronald R. Parker form an Executive Committee to the Director, and meet with the Director on a frequent basis to address all major program issues and help plan future program directions.

IV. THE NABISCO FACILITY

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

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

V. HIGHLIGHTS OF 1979-80 RESEARCH ACTIVITIES

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

Applied Physics Research

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

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

Versator II is a medium-sized research tokamak (major radius = 40.5 cm; minor radius = 13 cm; toroidal magnetic field = 15 kG) with primary emphasis on basic investigations of plasma heating and confinement properties. Versator II operates routinely with plasma density in the range 10^{13}cm^{-3} - $4 \times 10^{13}\text{cm}^{-3}$, electron temperatures of 400-600 eV, and ion temperatures of approximately 100 eV. Easy access and excellent plasma diagnostics make this device ideal for testing various supplemental plasma heating schemes. At this time, lower hybrid heating experiments are underway in which 150 kW of RF power at 800 MHz is available for injection into the tokamak. In addition, research is in progress to investigate electron cyclotron resonance heating of the plasma. For this purpose, a gyrotron oscillator capable of supplying 100 kW of RF power at a frequency of 35 GHz is being installed on Versator II in collaboration with the Naval Research Laboratory.

Plans are also underway for designing Versator III, an upgraded version of the present device. Larger-scale RF heating experiments are planned for Versator III and possibly a series of heating studies using intense relativistic electron or ion beams. Two high-voltage accelerators are available and capable of supplying 20-100 kA of electrons at energies in the 0.5-1.5 MeV range.

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

Constance I and II are medium-sized mirror research facilities with primary emphasis on the basic experimental development of RF and beam-plasma techniques for stabilization of mirror loss-cone instabilities. During the past year, the Constance II mirror facility (midplane magnetic field = 5 kG), has been improved and modified, and a multi-channel data acquisition system connected to the internal MIT CHAOS computer network has been put into operation. In addition, an improved plasma gun using a newly developed, fast gas valve, has been tested, and a 100 kW pulsed RF source has been built for ion cyclotron resonance heating experiments in Constance II. During the past year, basic supporting research has ranged from investigations of instabilities in negative ion sources to the calculation of electron trajectories in space-charge-limited magnetron injection guns.

In the plasma theory and computations area, there has been considerable technical progress during the past year in a variety of important areas. Recent studies include: (a) the continued development of a self-consistent theoretical model describing anomalous electron energy transport in tokamaks, (b) 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), (c) the development of a self-consistent kinetic description of the free electron laser instability for arbitrarily large values of the transverse wiggler magnetic field, (d) continued theoretical investigations of RF heating, including basic studies of the interaction of lower hybrid waves with plasmas, current generation and plasma heating, (e) basic studies of the MHD stability properties of toroidal fusion systems with external helical windings and (f) fundamental nonlinear studies of the influence of stochastic magnetic fields on turbulent transport in high-temperature plasmas.

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

In the area of advanced diagnostic development, a heterodyne receiver using advanced Schottky barrier diode technology has been used to make far-infrared measurements of cyclotron emission from the Alcator A tokamak plasma. Significant increases in sensitivity relative to other techniques have been achieved. A pulsed 700 kW, 385 μm D_2O laser system has been developed for Thomson scattering measurements of ion temperature in conjunction with the heterodyne receiver. The entire Thomson scattering system will be tested on the Alcator C tokamak beginning in late 1980. The development of a far-infrared laser Thomson scattering system will represent a major contribution to the development of plasma diagnostics.

Alcator Confinement Experiments

The Alcator experimental program constitutes one of the most successful and prominent tokamak confinement programs, both nationally and internationally. The primary objective of the Plasma Fusion Center Confinement Experiments Division, headed by Ronald Parker, is to develop the basic physics understanding of the stability, transport and radiation properties of high-temperature plasmas at near-reactor conditions and to develop methods for heating plasmas to fusion temperatures. The main Alcator experimental activity areas include: equilibrium, stability and operations (David Overskei); confinement studies (Awinash Gondhalekar); plasma-wall interactions (Earl Marmar); and radio frequency heating (Miklos Porkolab and Jack

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

We summarize here the significant progress made during the past year in several of the Alcator experimental program areas.

Alcator A: The Alcator A is a relatively small (minor radius = 10 cm, major radius = 54 cm) tokamak which is able to operate at extremely high toroidal field strengths (up to 100kG). The Alcator A program has continued to provide basic physics information pertinent to high-temperature plasma behavior. Specific programs now in place are aimed at the understanding and control of plasma-wall interactions. Important results have been obtained during the past year on the problems of impurity transport and removal of particles by interaction with the limiter. Studies of silicon impurity transport indicate that there is no accumulation of impurities in the center of the plasma and that the confinement time increases with toroidal current and the mass of the background plasma ions. Experiments have also been performed to determine the efficiency of particle removal from the limiter shadow by a passive mechanical limiter. Measurements indicate that one to two percent of the particles leaving the plasma may be easily removed by pumping ports in the immediate area of the limiter.

An additional major program on Alcator A is a modestly powered (100 kW) RF heating experiment near the ion cyclotron frequency, which for Alcator A is about 100 MHz. The experiment is providing information on the physics of wave penetration, heating mechanisms and efficiency, as well as information on the technological problems of vacuum window and RF coupler design. This experiment may be considered prototypical of the much higher power experiments planned for Alcator C, and the results are being integrated into the design of that program.

During the past year, a design study activity has been initiated to examine modifications to the Alcator A tokamak. An important aspect of Alcator-A Mod. would be the basic study of MHD activity at high densities and high temperatures, with particular emphasis on understanding and controlling major disruptions. In order to pursue this effort, the Alcator A Bitter magnet would be replaced by a Bitter magnet intermediate in size between Alcator A and C, incorporating external helical windings. The helical windings will be capable of adding a rotational transform of 0.2 to the transform generated by the toroidal current. The size, magnetic field and plasma current will be chosen in order to enable direct comparison with Alcator C and prior Alcator A performance. This modification should allow exploration of stable, low q ($\sim$1.5) operating regimes. It should also allow much better control than is presently available during startup of tokamak discharges. It is expected that this modification will take two years, beginning with detailed magnet design early in FY 81, leading to operation at the end of FY 82.

Alcator C: Alcator C is an upgrade of the A device, in which the plasma minor radius has been increased to 16 cm, the major radius to 64 cm, and the maximum toroidal field strength to 140 kG. This machine is powered by a new power supply, in which the prime power is supplied by a 220 MW alternator. The alternator is 25 years old, having supplied power for this length of time in the Consolidated Edison system. Due to poor economy of the steam turbine drive, the system was retired and the alternator donated to MIT.

As a result of the Alcator C design, parameters even closer to those required for fusion are expected to be achieved. During the first phase in which the only power to the plasma is supplied by the ohmic heating system, values of the density-confinement time ($n\tau_E$) product approaching 10^{14}sec-cm^{-3} and temperatures approaching 2 keV are expected to be achieved. This value of $n\tau_E$ is well above the minimum required for energy breakeven, although actual breakeven requires higher temperatures. Plasma equilibrium, stability, fueling and purity are the main physics issues investigated during this phase.

During the past year, Alcator C has operated at toroidal fields in the range 60 kG - 100 kG and plasma currents up to 525 kA. These represent about 75% of the design capability. The maximum $n\tau_E$ values are now comparable to the best values achieved on Alcator A, and an increase to $n\tau_E \simeq 0.5 \times 10^{14}$cm^{-3}-sec is expected during the summer of 1980. Electron temperatures of 1.5 keV have been achieved and advanced limiter designs for Alcator C have been developed that withstand average power loads of 1 kW/cm^2.

RF Heating: Further improvement of plasma parameters in Alcator C will require additional energy input. Phase II of the Alcator C program has as its objective the increase of plasma temperature from 2 keV to 4 keV or more. For this purpose, two radio frequency heating methods are being developed in parallel, and will be investigated intensively on Alcator C during the remainder of 1980 and in 1981.

The first heating method will use 4 MW of power at the lower hybrid frequency, which is about 4.6 GHz in Alcator C. The second heating method will employ up to 4 MW of power at the first or second harmonic of the ion cyclotron frequency. Lower hybrid heating is the primary approach selected for plasma heating on Alcator C. However, the ion cyclotron heating program, which has been initiated on Alcator A, will be explored in parallel with lower hybrid heating and will be emphasized on Alcator C in the event that this method proves more successful. Key physics issues in both RF heating programs include RF wave penetration into the plasma, heating mechanisms and efficiency, and the effect on plasma stability and confinement. Technological issues are concerned with RF power transmission through vacuum interfaces, power densities achievable and practical RF coupler design.

During 1980 and 1981, RF heating and ohmic heating experiments on Alcator C are expected to reach a level of achievement that will give a clear direction for Alcator D or a major upgrade of Alcator C. Design activities for the next step in the Alcator program have been initiated and will be intensified as the Alcator C results evolve. These activities are exploring two alternative paths. The first design approach is examining the optimum upgrade of Alcator C that can take full advantage of the RF heating capabilities associated with the lower hybrid and ion cyclotron heating equipment. The full 10 to 15 MW of ion cyclotron capability cannot be utilized in Alcator C due to limited access. An upgraded toroidal field coil design with more ports will be examined as a replacement of the present coil. The increased neutron yield for such a device will require location in a shielded installation in the PFC Nabisco facility. The second, more aggressive approach is examining compact high-field designs that lead to an early D-T ignition experiment. This device may be RF heated and utilize limited compression.

Fusion Technology and Engineering

The Fusion Technology and Engineering Division, headed by Bruce Montgomery, provides engineering support for the advanced design projects, and develops advanced superconducting magnet technology for the national fusion program. Research activities include: advanced design for the proposed Alcator A modification and for the proposed Garching high-field Ignition Test

Reactor; responsibility and design support for the magnetics systems of the Engineering Test Facility (John Williams and Roger Derby); responsibility for a National Divertor Development program to develop improved magnetic divertor concepts (Ted Yang); the development of forced-flow superconductors for application to advanced fusion devices (Mitchell Hoenig); basic research on the development of ductile superconducting materials (Simon Foner, Robert Rose and Brian Schwartz).

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

The next major step in the United States fusion program will be a fusion engineering device presently known as the Engineering Test Facility (ETF). The Plasma Fusion Center has been selected by the Department of Energy to take responsibility for the Magnetics Branch of the ETF Design Center activities. This work is carried out in close cooperation with the ETF Design Center Headquarters at Oak Ridge National Laboratory, which has overall responsibility for systems integration and management of ETF design activities. Dr. Roger Derby, MIT Magnetics Branch Manager at Oak Ridge National Laboratory, is responsible for coordinating the design work done by General Electric, the industrial magnetics contractor, and the support magnetic design work done at MIT and elsewhere in the country. The superconducting magnet systems will be an order-of-magnitude larger than any current projects and hence represent the most demanding magnet design project ever undertaken.

The Plasma Fusion Center has been asked by the Department of Energy to formulate a national program in Divertor Technology. A long-burning fusion reactor must deal with the buildup and removal of helium "ash" and impurities, and magnetic or mechanical divertors are considered an extremely demanding but necessary component. During the past year, Dr. Ted Yang, a recognized expert in this area, joined the Plasma Fusion Center to head the divertor development program. Professors Lawrence Lidsky, Borivoje Mikić and Neil Todreas of the Nuclear Engineering Department are involved in various technical aspects of the program, carrying out pilot experiments, preliminary design and planning of the national program.

Critical experimental tests are also being carried out in the development of forced-flow conductors for superconducting fusion magnets. The supercritical helium-cooled conductor conceived and developed by the magnet group has been selected by Westinghouse for the 2 × 3 meter niobium-tin coils for the Large Coil Project at the Oak Ridge National Laboratory, and for the 12 tesla High Field Test Facility at the Lawrence Livermore Laboratory. Heat transfer in supercritical helium is being investigated and a significant discovery has been made concerning the strong effects of sonic reflections within the conductor.

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. This research emphasizes finely-divided materials and sufficient progress has now been made to consider two of the techniques ready for commercial scale-up to magnet materials with mechanical properties representing a significant improvement over conventional preparations.

Fusion Systems

The Fusion Systems Division, headed by Daniel Cohn, carries out a variety of design and reactor physics investigations related to the next generation of fusion devices. Emphasis is placed on the increased understanding of the potential characteristics and technology requirements of power-producing fusion reactors and the development of advanced component technology. Research activities include: fusion safety and environmental studies (Mujid Kazimi); advanced tokamak systems studies (Daniel Cohn); development of new design concepts for fusion blankets and first wall (John Meyer and Borivoje Mikić); gyrotron and advanced millimeter source development (Richard Temkin); millimeter and submillimeter wave detector development (Harold Fetterman and Peter Tannenwald, Lincoln Laboratory).

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

In the tokamak system studies area, there have been important new computational studies of ignited plasmas. Characteristic spatial features and instability modes have been calculated and new concepts for thermal equilibrium and stability control have been developed. The Plasma Fusion Center is serving as a coordinator for U.S. participation in the ZEPHYR ignition test reactor (ITR) project at the Max Planck Institut für Plasmaphysik in Garching, Federal Republic of Germany. Related technical activities include the development of improved designs for high-performance copper magnets for the ITR. The tokamak systems study group is also participating in the plasma systems design for the Engineering Test Facility.

In the safety and environmental studies area, a total energy cycle assessment of fusion power production is being developed for the first time. Work is also underway to assess risk from lithium fires in fusion reactors and to compare the safety features of various blanket designs.

A new program aimed at the development of high frequency ($\sim$140 GHz) gyrotrons for plasma heating has been initiated. The program involves both experimental and theoretical components. A linear gyrotron theory which facilitates device design has been completed and a special electron gun is being developed in collaboration with industry.

The basic technology for far-infrared plasma diagnostics is also being developed. Advanced Schottky barrier diode detectors for use in the 300 GHz-3 THz range will be produced for designated fusion laboratories by Lincoln Laboratory, and these detectors will be used in a variety of applications including measurements of plasma density by laser interferometry, cyclotron emission studies and submillimeter laser scattering experiments.

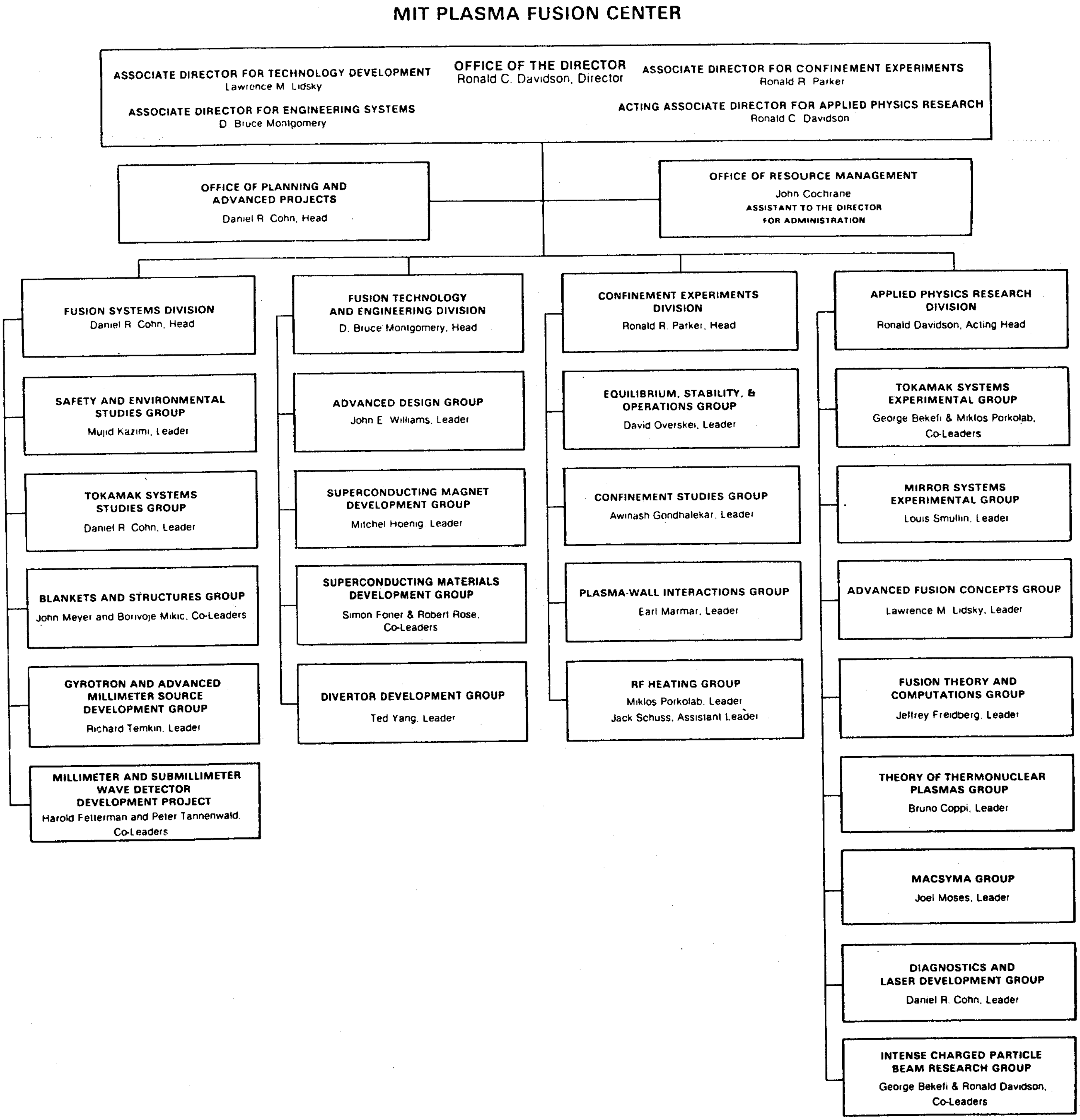

Figure 1. Plasma Fusion Center Research Groups

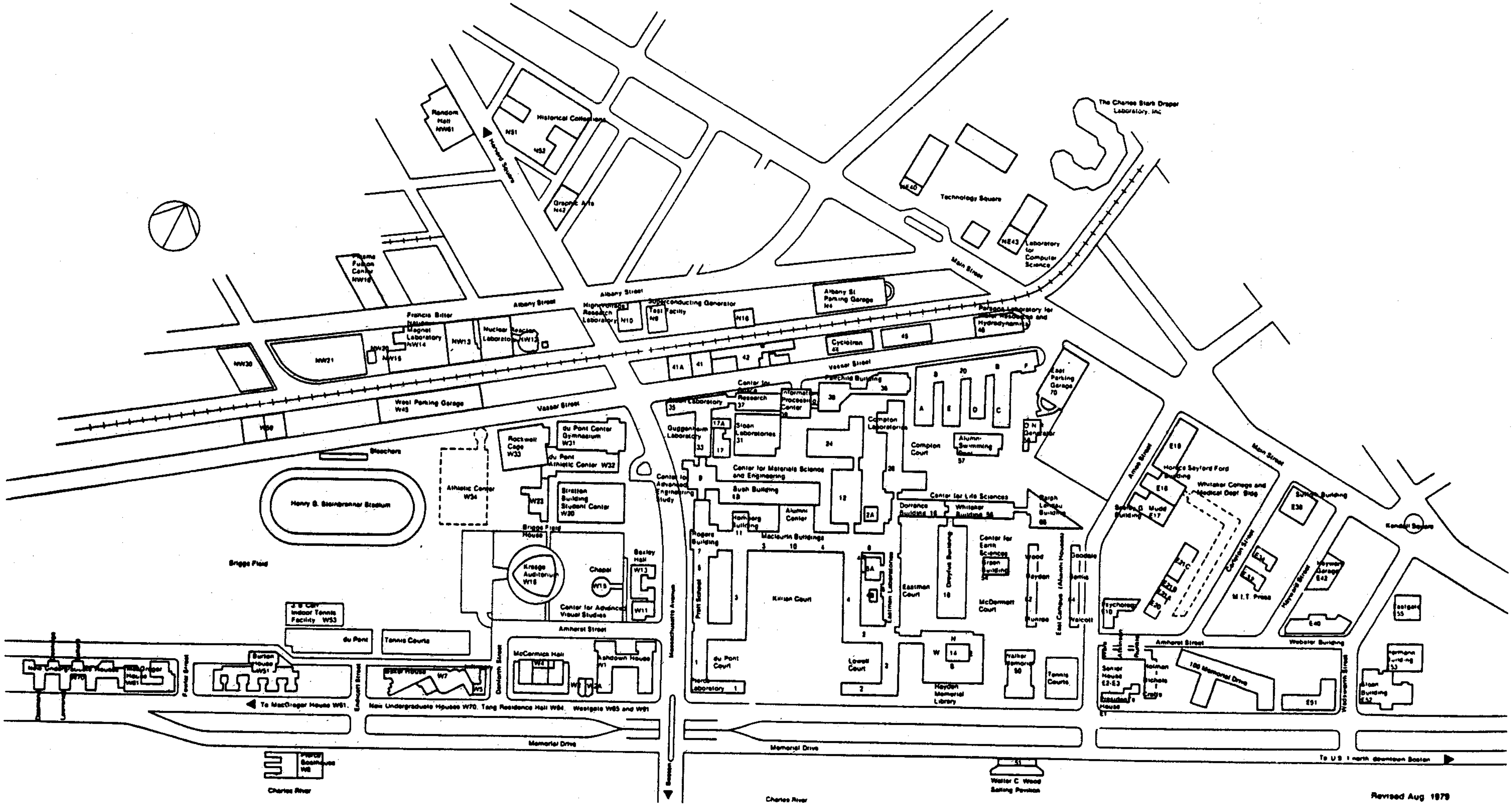

Figure 2. Area Map of MIT

PLASMA FUSION CENTER

I. APPLIED PHYSICS RESEARCH DIVISION

RONALD C. DAVIDSON, ACTING HEAD

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.

GROUPS:

- Tokamak Systems Experimental Research
  G. Bekefi and M. Porkolab, Co-Leaders
- Mirror Systems Experimental Research
  Louis D. Smullin, Leader
- Advanced Fusion Concepts
  Lawrence M. Lidsky, Leader
- Fusion Theory and Computations
  Jeff Freidberg, Leader
- Theory of Thermonuclear Plasmas
  Bruno Coppi, Leader
- MACSYMA
  Joel Moses, Leader
- Diagnostics and Laser Development
  Daniel Cohn, Leader
- Intense Charged Particle Beam Research
  George Bekefi and Ronald Davidson, Co-Leaders

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

1. TOKAMAK SYSTEMS EXPERIMENTAL RESEARCH GROUP

George Bekefi and Miklos Porkolab, Co-Leaders

A. OBJECTIVES:

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

B. RESEARCH PROJECTS:

- DC current generation with lower hybrid waves
- RF heating at the lower hybrid frequency
- RF heating at the electron cyclotron frequency
- Development of plasma diagnostics for tokamak discharges

C. PERSONNEL:

Faculty:

G. Bekefi, M. Porkolab

Research Staff:

S. Luckhardt,

Technical Support Personnel:

E.W. Fitzgerald, K.-I. Chen

Visiting Scientist

C. Celata

Graduate Students:

A.S. Fisher, T. Gentile, K.E. Hackett,
D. Hinshelwood, S. Knowlton, M.J. Mayberry,
S. McDermott, B. Richards, R.R. Rohatgi

Undergraduate Students:

S.M. Amador, C.L. Enloe, K.J. Pinto,
A. Saperstein

Secretary:

V. Kaloyanides

D. SPECIAL EQUIPMENT AND FACILITIES:

Experimental Facilities:

- Versator II Tokamak (a=13 cm; R=40.5 cm; B_T=15kG)

E. TECHNICAL PROGRAM SUMMARY:

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

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

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

- Bolometers
- UV and visible spectroscopy for T_i diagnostics

Parameter	Value
a (Minor Radius)	15 cm
R (Major Radius)	40.5 cm
B_T (Toroidal Field)	15 kG
$\hat{n}$ (Average Density)	$2\text{-}4\times10^{13}\,\mathrm{cm}^{-3}$
τ_p (Pulse Length)	20-40 msec
I_p (Plasma Current)	40 kA
T_{eo} (Central Electron Temperature)	500 eV
T_{io} (Central Ion Temperature)	120 eV

Table 1. Versator II Characteristics

The Versator II research program consists of four major components:

- A feasibility study of current drive using lower hybrid waves (800 MHz, 150 kW)
- RF heating of tokamak plasmas at the lower hybrid frequency
- Electron cyclotron heating (36 GHz, 100 kW)
- Development and testing of diagnostic techniques in the study of hot plasmas

Current-drive studies with lower hybrid waves are now in progress. The work is expected to continue for the next eighteen months. Lower hybrid ion heating experiments using the available lower hybrid power have begun, and electron cyclotron heating experiments will begin in the near future using the high-power gyrotron developed by the Naval

Research Laboratory. These experiments are planned to continue for a period of approximately eighteen months. The development of novel diagnostics is an ongoing program and is likely to continue for a number of years.

Assuming favorable experimental results from the current drive studies, a new experimental device, Versator III, will be proposed in late FY 1981. In addition to the current drive, Versator III will be used to investigate relativistic electron beam heating of tokamak plasmas as discussed elsewhere in this report. For this reason, it is required that the new electron beam facility and Versator III be housed adjacent to one another in the PFC Nabisco Facility in a large experimental area capable of accommodating both devices.

2. MIRROR SYSTEMS EXPERIMENTAL RESEARCH GROUP

Louis D. Smullin, Leader

A. OBJECTIVES:

Study stability properties of mirror-confined plasmas in the Constance II facility. Study ion heating phenomena in plasma guns in Constance I.

B. RESEARCH PROJECTS:

- Comparison of ECRH and beam-plasma techniques for generating hot electrons for stabilization of the DCLC instability in Constance II
- Study of plasma gun and stream properties
- Study of plasma trapping in static mirrors
- Optimization of electron guns for beam-plasma interactions

C. PERSONNEL:

Faculty:

L.D. Smullin

Research Staff:

J. Irby and R.E. Klinkowstein

Technical Support Personnel:

R. Davco, K. Rettman

Graduate Students:

A. Ezzedine, R. Garner, M. Mauel, and S. Voldman

Undergraduate Students:

S. Bradley, T. Evans, R. Hu

D. SPECIAL EQUIPMENT AND FACILITIES:

Experimental Facilities:

- Constance I Mirror Device (3 kG midplane; 2 : 1 mirror ratio)

- Constance II Mirror Device (5 kG midplane; 2 : 1 mirror ratio)
- Electron Beam Facility (10 - 20 kV; 100 - 500 kW)

E. TECHNICAL PROGRAM SUMMARY:

Magnetic mirror systems may have practical reactor advantages over closed toroidal systems. Until recently, however, plasma confinement in magnetic mirror configurations has been severely limited by the drift-cyclotron loss-cone (DCLC) instability. The detrimental effect of this instability was significantly reduced in experiments on 2X-IIB at Lawrence Livermore Laboratory (LLL) by injecting a cool plasma component. However, this had the unfortunate side effect of significantly cooling the electrons. In the Soviet Union, electron cyclotron resonance heating has been used to produce a disk of warm electrons ($\sim$ 300 eV) that stabilize the DCLC instability. In large-scale high-density plasma experiments, however, the Soviet technique is not applicable.

In the Constance I mirror experiment at MIT, it has been demonstrated that a powerful electron beam injected into the plasma, through oscillations stimulated in the plasma, produces a low-density, hot-electron population that stabilizes the DCLC instability. Moreover, the electrons are distributed throughout the entire plasma volume, unlike those in the Soviet experiments. Electron cyclotron resonance heating has also been demonstrated to be effective in stabilizing the DCLC instability even though $\omega_p \simeq 2\text{-}3\omega_{ce}$ in the center of the plasma. The effect appears to be comparable to that in the electron beam experiments.

The principle objectives of the present program are to expand upon these first results, and to compare the relative effectiveness of producing the stabilizing hot electrons by beam-plasma interaction or by electron cyclotron resonance heating. These experiments are being carried out in Constance II, a minimum B mirror facility. The minimum B field is produced by a pulsed, 4-pole Ioffe bar system, mounted inside the vacuum chamber on a 10" diameter circle. (A 6-pole array is now being designed to insert in the same location.) The plasma is produced by a plasma gun mounted in a guide magnetic field about 2 meters from the mirror. In order to produce a strong DCLC instability, the plasma must be relatively collisionless and thus the ions must be hot, i.e., more than a few hundred eV. By a process not yet understood, the washer-type plasma gun produces ions with the desired temperature. Since the heating mechanism is not yet understood, it is not known how to optimize the heating, or how to insure its reliability. The heating varies inversely with the gas pressure in the gun, and pulsed-gas injection guns are being studied, with and without the washer stacks. In addition, a hot cathode discharge device is being constructed similar to the one used by Ioffe and Nezlin. Finally, to alleviate a total dependence on the gun-heating mechanisms, a 150kW pulsed power source has been built for ion cyclotron resonance heating in the frequency range 5-8MHz. The transmitter is now being tested, and will be ready for use by August, 1980.

The design of an electron gun for optimum beam-plasma interaction is obviously a matter of importance. Computations of the electron trajectories in a space-charge-limited magnetron injection gun have been initiated, so that the perveance and the ratio of perpendicular to parallel velocities in the beam (for arbitrary axisymmetric electrode shapes and magnetic fields) are now able to be predicted. A question that has not been satisfactorally answered is the importance of beam perveance. For a given power $P=IV$, at what perveance $K=IV^{3/2}$ is the most effective heating attained? We will begin by numerically exploring the linear dispersion equations for the interaction. Depending on the results of these studies, special experiments may be initiated in Constance I to compare a high-perveance (10^{-5}) magnetron injection gun with a low-perveance (10^{-6}) Pierce gun, operating at similar power levels of 50-100 kW.

Finally, assuming favorable experimental results, we plan to investigate the problem of continuously heating the plasma of a mirror endplug by ICRH combined with a fueling system that may be either an axially injected ion beam or radially injected pellets. Such a scheme would, conceptually, replace the present neutral beam heating system with its many very difficult technical problems. This program would require a larger facility that would be better accommodated in the PFC Nabisco Facility than in the present Building 36 space.

3. ADVANCED FUSION CONCEPTS GROUP

Lawrence M. Lidsky, Leader

A. OBJECTIVES:

Develop fusion reactor designs consistent with the best available models of plasma physics and the technological requirements of the eventual reactor users. Investigate potential of advanced fuels in systems capable of exploiting their particular properties.

B. RESEARCH PROJECTS:

- Torsatron reactor conceptual design
- Modularized field coils for stellarator/ torsatron systems
- TOREX experimental design study
- ISHTAR design study

C. PERSONNEL:

Faculty:

L.M. Lidsky, P.A. Politzer

Research Staff:

R. Potok

Graduate Students:

J. Aspinall, J. Johnson, T. Uchikawa

Staff Assistant:

C.A. Lydon

D. TECHNICAL PROGRAM SUMMARY:

Until recently, fusion reactor design studies have attempted to extrapolate particular plasma confinement geometries to reactor scale. On such a scale, these designs have encountered several technological and economic penalties. This result is not surprising. The boundaries of acceptable engineering are more sharply drawn than those of potential plasma confinement schemes and there is no a priori reason to expect them to overlap.

It was concluded that the most efficient search scheme required an inversion of the usual process. A list of desirable reactor properties (steady-state, ignited, etc.) was developed, and a search of the literature was made for a confinement scheme compatible with these requirements. The most promising output of this search is the torsatron configuration but the technique of applying "desirability-weighted" technology criteria is also proving useful in assessing other candidate confinement schemes and fuel cycles.

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

4. FUSION THEORY AND COMPUTATIONS GROUP

Jeffrey P. Freidberg, Leader

A. OBJECTIVES:

Develop basic theoretical understanding of plasma heating and confinement properties of high-temperature fusion plasmas. Interpretation of experimental data required for formulating self-consistent scaling laws and for meaningful planning of experiments.

B. RESEARCH PROJECTS:

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

C. PERSONNEL:

Faculty:

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

Research Staff:

R. Berman, M. Gerver, V. Krapchev, K. Ko, J. Kulp, R. Potok, A. Rechester, D. Tetreault

Visiting Scientists:

V. Fuchs, A. Ram, E. Villalon, D. Sherwell, M.L. Xue

Graduate Students:

T. Boutros-Ghali, K. Cogswell, L. Harten, K. Hizanides,
G. Svolos, K. Swartz, D. Thayer, K. Theilhaber

Secretarial Staff:

C. Barkei, J. Cooper, C.A. Lydon

D. SPECIAL EQUIPMENT AND FACILITIES:

Computer Equipment:

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

E. TECHNICAL PROGRAM SUMMARY:

The main objective of fusion theory research is to provide the basic physics understanding necessary for interpreting 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 A and Versator II. Theory of nonlinear waves in plasmas, and induced stochasticity in particle dynamics by coherent waves.
- Confinement properties of fusion plasmas. These studies include: MHD equilibrium and stability properties of tokamak and torsatron/stellarator configurations; microinstabilities and anomalous transport in high-temperature plasmas; and formulation of self-consistent scaling laws needed for meaningful experimental planning.
- Nonlinear and turbulent phenomena. The purpose of these investigations is to develop the basic understanding of a wide variety of nonlinear and turbulent phenomena, including stochastic magnetic fields, clumps and nonlinear saturation of linear instabilities.
- Stability and transport properties of toroidal and linear fusion systems, including investigations of the effects of ambipolar fields on transport and stability properties of toroidal plasmas, high-beta

stability properties of the tandem-mirror configuration, and microstability and transport properties of mirror systems with emphasis on applications to Constance I and II.

During FY81 and FY82, theoretical research in these project areas will intensify with a continued emphasis on increasing theoretical support in critical problem areas for the Alcator, Versator and Constance experimental programs. It should be emphasized that well-formulated theories with sound experimental confirmation are able to 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 difficult to achieve otherwise. 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 Laboratory. In order to provide the maximum effective access to the NMFECC, we have recently established a computational support activity to provide computation-related services to the entire PFC user community. The responsibilities of this activity include the implementation and maintenance of local facilities for connecting to the NMFECC via existing network ports and the local computer network (CHAOS). In addition, the computational support activity provides a centralized administration of the PFC time allocation at the NMFECC and maintains and distributes documentation for users. Because of the importance of computing in both experimental and theoretical programs, it is imperative that PFC researchers have convenient and efficient access to the NMFECC.

During FY 80, a computer terminal facility is being developed to provide a more effective computational support for the Alcator and technology programs. This facility will include the following features: (a) a small processor capable of supporting displays for approximately eight users, (b) a network connection for this processor to the local CHAOS network which runs at an 8 Mbit rate, (c) a graphics/document quality hardcopy device, (d) a bit-map TV display system with 16 display memories, (e) distributed console access (TV monitors and keyboards located in offices, movable on carts), and (f) display, hardcopy, and network software. The basic system will have been acquired by the end of FY 80.

5. THEORY OF THERMONUCLEAR PLASMAS GROUP

Bruno Coppi, Leader

A. OBJECTIVES

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

B. PERSONNEL:

Faculty:

T. Antonsen and B. Coppi

Research Staff:

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

Visiting Scientists:

S. Atzeni, B. Basu, G. Bertin, T. Chan,
F. Pegoraro, J. Ramos

Graduate Students:

B. Chike-Obi, G. Crew, A. Ferreira, B. Lane,
L. Sugiyama

Secretarial Staff:

C. LoRusso

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

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

Since the fusion program depends on the evolution of a variety of disciplines and can benefit significantly from ideas developed in other fields, collaborative efforts are maintained with members of the scientific community in the Cambridge area whose scientific interest can impact this research program. In particular, fruitful connections have been established with the MIT Applied Mathematics Department, the Center for Theoretical Physics, the Center for Space Research, the Center for Astrophysics at Harvard, American Science and Engineering, and Raytheon. Two of these institutions have now developed their own direct contracts with DOE.

Another function that has been emphasized is to encourage and maintain a flow of visitors from and in collaboration with overseas institutions. As a result of this, several of the numerical codes currently used have been developed in collaboration with the Institut 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, through direct participation in research projects, advising, and the teaching of courses on the physics of thermonuclear plasmas. An active exchange of ideas is maintained with the major U.S. laboratories and universities engaged in fusion research.

D. TECHNICAL PROGRAM SUMMARY:

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

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

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

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

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

A set of physical factors has been identified, mainly the significant dependence of both the poloidal magnetic field and the rate of magnetic shear on the poloidal coordinate, that enhance the stability of an axisymmetric toroidal configuration when the parameters $G \equiv \beta R q^2/r_p$, with $1/r_p \equiv -d\ell np/dr$, becomes finite. Thus an expanded "first ideal-MHD-stability region" has been found that roughly corresponds to $G<G_c^{(1)}(s)$ with $s \equiv d\ell nq/d\ nr$, and a "second stability region" that corresponds to $G>G_c^{(2)}(s) > G_c^{(1)}(s)$. The first oral presentations of these results were given at the Sherwood Theory meeting in 1978 and then at the 1978 Gordon Conference in Santa Barbara.

These first reports were received with interest but also with some objections. However, the fact that the relevant stability problem involves an equation with nonlinear coefficients in G, rather than a linear coefficient in G as it was previously thought, was soon confirmed by the analytical work of other authors and later by the numerical study of flux-conserving finite-beta equilibria. These studies were carried out both by this group and by other major U.S. theoretical groups. By now, relatively high values of beta are commonly accepted. Meanwhile, given the interest of other groups in the subject, the MIT activity has been limited to the development of an analytical representation of the main results.

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

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

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

6. MACSYMA GROUP

Joel Moses, Leader

A. OBJECTIVES:

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

B. RESEARCH PROJECTS:

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

C. PERSONNEL:

Faculty:

Joel Moses, Richard Zippel

Research Staff:

R. Bryan, E.Golden, J. Golden, R. Greenblatt, R. Kerns, D. Moon, J. O'Dell

Graduate Students:

B. Trager

Secretarial Staff:

A. Schmitt, M. Marcucci

D. SPECIAL EQUIPMENT AND FACILITIES:

MACSYMA Consortium Facility

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

Computer Equipment:

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

E. TECHNICAL PROGRAM SUMMARY:

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

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

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

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

7. DIAGNOSTICS AND LASER DEVELOPMENT GROUP

Daniel Cohn, Leader

A. OBJECTIVES:

Develop new millimeter and submillimeter wave technologies for diagnostics of tokamaks and other fusion devices which operate in the 10^{14}cm^{-3} - 10^{15}cm^{-3} density range. Study laser-plasma interactions.

B. RESEARCH PROJECTS:

- Development of submillimeter laser ion Thomson scattering system
- Use of submillimeter heterodyne receiver for cyclotron emission measurements

C. PERSONNEL:

Research Staff:

D. Cohn, B. Lax, B. Mulligan, H. Praddaude, P. Woskoboinikow

Visiting Scientist:

I. Falconer

Engineering Assistant:

F. Tambini

Technical Support Personnel:

F. Shefton

Secretary:

D. Diehl, R. Montane

D. SPECIAL EQUIPMENT AND FACILITIES:

Computer Equipment:

1 Digital Equipment MINC minicomputer

E. TECHNICAL PROGRAM SUMMARY:

This activity includes the development of new plasma diagnostics, relying strongly upon advanced submillimeter laser and detector technology.

To summarize recent accomplishments, a system for the accurate measurement of plasma density in the $10^{14}cm^{-3}$ - $10^{15}cm^{-3}$ range has been developed by using newly developed optically pumped submillimeter laser technology. This system, which involves 119 μm CH_3OH lasers, was first implemented on Alcator and is now being adapted by other tokamak laboratories such as the Princeton Plasma Physics Laboratory. A heterodyne receiver which uses Schottky barrier diode detectors has been employed to make measurements of cyclotron emission in Alcator over a range of frequencies from 300 to 800 GHz. These measurements of cyclotron emission are considerably more sensitive than measurements obtained with other techniques.

The concept of using high-power submillimeter lasers to measure ion temperature in magnetically confined plasmas by Thomson scattering has been extensively investigated, and a high power (500 kW - 1 MW) 385 μm D_2O laser and a special heterodyne detection system have been developed. The spatially resolved measurements of ion temperature, impurities and collective effects which should be possible with this system will ultimately play a significant role in diagnosing the properties of high-temperature plasmas. The development of the appropriate optically pumped laser technology has led to an increased understanding of the quantum electronics of optically pumped lasers. Moreover, the associated heterodyne receiver development has led to the development of fast, sensitive Schottky barrier diode detectors which are finding additional applications.

To summarize future plans, the ion Thomson scattering diagnostic will be tested on Alcator C and developed into a practical diagnostic tool. In addition, new diagnostic techniques for increased spatial and temporal resolution of plasma density and temperature and measurement of the plasma current profile will be developed.

8. INTENSE CHARGED PARTICLE BEAM RESEARCH GROUP

George Bekefi and Ronald Davidson, Co-Leaders

A. OBJECTIVES:

Experimental study of the dynamics of relativistic E-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
- Relativistic magnetron design
- Raman back scattering 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. Davidson

Research Staff:

J. Chen, W. McMullin, A. Palevsky and H. Uhm (part time)

Technical Staff:

I. Mastovsky

Graduate Students:

A. Dimos, D. Hinshelwood, K. Jacobs, O. Langdon, R. Shefer

Undergraduate Students:

S. Reber, R. Close

Secretarial Staff:

J. Cooper, V. Kaloyanides, C. Robertson

D. SPECIAL EQUIPMENT AND FACILITIES:

Experimental Facilities:

- Physics International Pulserad 110 A high-voltage Electron Beam Facility (1.5 MV, 20 kA) including control panel, x-ray shielding and vacuum system
- Nereus high-voltage Electron Beam Facility (0.5 MV, 100 kA) including control panel, oil storage tank and vacuum system

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 autoresonant accelerator and the electron ring accelerator that utilizes the intense self fields on an electron cluster to trap and accelerate ions, (c) studies of the relativistic electron flow in high-voltage diodes, (d) research on the propagation and trapping of intense ion beams and layers with both light-ion and heavy-ion applications, and (e) basic experimental studies of the equilibrium and stability properties of magnetically confined nonneutral plasmas in uniform and mirror magnetic field geometries.

Experimental electron beam research is being carried out in two critical problem areas:

- Generation of intense microwave and submillimeter radiation
- Study of the dynamics of intense relativistic electron beam diodes

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

Tokamak heating by means of relativistic electron or ion beams is a relatively novel area of research under consideration at MIT. There are few beam heating experiments at this time and the entire question of plasma heating by intense electron beams remains unanswered. If paper studies and experiments show promise during the next few years, we plan to undertake a serious experimental and theoretical program in this field. For this purpose we would use the Versator III facility discussed elsewhere in this report.

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) studies of the negative-mass and tearing-mode stability properties of an intense ion layer with arbitrary degree of field reversal in a background plasma, (b) investigations of the basic thermal equilibrium properties of intense ion and electron beams with both azimuthal and axial directed motion, (c) 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, (d) investigations of the equilibrium and stability properties of intense relativistic electron beam-plasma systems using a kinetic (Vlasov) description to correctly incorporate thermal effects, (e) the development of a self-consistent theory of the cyclotron maser instability in intense hollow and solid electron beams, (f) investigations of the influence of kinetic effects and beam quality on cyclotron maser stability behavior, (g) investigations of the influence of mode structure and beam geometry on maximizing microwave emission, and (h) the development of a weakly nonlinear (quasilinear) theory of mode saturation. Theoretical research will continue in each of these problem areas with particular emphasis on (a) the equilibrium, stability, radiation and nonlinear properties of intense nonneutral electron beams, and (b) the equilibrium and stability properties of intense ion beams and layers propagating through a background plasma.

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

PLASMA FUSION CENTER

II. CONFINEMENT EXPERIMENTS DIVISION

RONALD R. PARKER, HEAD

A, OBJECTIVES:

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

B. GROUPS:

- Equilibrium, Stability and Operations
  D. Overskei, Leader
- Confinement Studies
  A. Gondhalekar, Leader
- Plasma-Wall Interaction
  E. Marmar, Leader
- RF Heating
  M. Porkolab, Leader
  J. Schuss, Assistant Leader

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

- Alcator A
- Alcator C

Professors Ronald Parker and Bruno Coppi are overall Alcator program Principal Investigators.

C. ALCATOR RESEARCH GROUPS AND PROJECT AREAS:

1. EQUILIBRIUM, STABILITY AND OPERATIONS GROUP

David O. Overskei, Leader

a. Objectives:

Optimize and extend tokamak parameters and performance. Investigate and develop methods of control of MHD stability and equilibrium. Direct day-to-day operation of Alcator A and C in order to achieve goals set by the Alcator Experimental Objectives Committee.

b. Projects:

- Alcator A Operations
- Alcator C Operations

c. Personnel:

Research Staff:

D. Gwinn, M. Greenwald, B. Lipschultz, D. Overskei, P. Politzer, R. Parker

Engineering Staff:

M. Besen, P. Besen, G. Chihoski, F. Dawkins, K. Fertl, D. Grearson, D. Howes, P. Maruzzi, B. Montgomery, C. Park, N. Pierce, R. Rosomoff, J. Rose, F. Silva

Technical Support Personnel:

T. Bakucz, R. Childs, R. Danforth, J. Gerolamo, R. Griffith, M. Iverson, J. Maher, J. Moscaritolo, B. Oliver, W. Parkin, S. Rich, H. Shriber, L. Storace, E. Sudenfield, E. Thibeault, R. Woodworth

Visiting Scientist:

R. Petrasso

Graduate Students:

S. Fairfax, R. Granetz, J. Moreno, J. O'Rourke, P. Pribyl

Secretary:

J. Guberman

2. CONFINEMENT STUDIES GROUP

Awinash M. Gondhalekar, Leader

a. Objectives:

Conceive and carry out measurements which determine confinement properties of ohmically heated and RF heated Alcator plasmas. Provide interpretation of experimental results in the context of confinement theory.

b. Projects:

- Alcator A Confinement Studies
- Alcator C Confinement Studies

c. Personnel:

Research Staff:

B. Coppi, C. Fiore, A. Gondhalekar, M. Greenwald, D. Gwinn, D. Overskei, D. Pappas, A. Rechester, R. Temkin, P. Waskoboinikow, R. Watterson, S. Wolfe

Engineering Staff:

G. Chihoski, N. Pierce, F. Tambini

Technical Support Personnel:

B. Doherty

Visiting Scientists:

R. Slusher, C. Surko

Graduate Students:

W. Fisher, S. Kissel, T. Moran, J. Parker, A. Pachtman, D. Schissel

Secretary:

J. Guberman

3. PLASMA-WALL INTERACTIONS GROUP

Earl S. Marmar, Leader

a. Objectives:

Study interactions of Alcator 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 and quantity of light and heavy impurities
- Determination of wall and limiter power flows
- Impurity deposition and wall retention experiments

c. Personnel:

Research Staff:

E. Marmar, J. Rice, J. Terry

Engineering Staff:

G. Chihoski, N. Pierce

Technical Support Personnel:

T. Bakucz, R. Childs, H. Shriber, E. Thibeault

Visiting Scientists:

M. Gerassimenko, E. Källne, R. Petrasso, F. Seguin

Graduate Students:

M. Foord, B. Labombard, M. Pickrell, A. Razdow

Secretary:

J. Guberman

4. RF HEATING GROUP

Miklos Porkolab, Leader
Jack Schuss, Assistant Leader

a. Objectives:

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

b. Projects:

- Alcator A Ion Cyclotron Heating
- Alcator C Lower Hybrid Heating
- Alcator C Ion Cyclotron Heating

c. Personnel:

Research Staff:

B. Blackwell, R. Parker, M. Porkolab, J. Schuss

Engineering Staff:

M. Carracino, K. Fertl, W. Harrison, H. Israel, K. Rice, J. Rose

Technical Support Personnel:

C. Holtjer, D. Lavoie

Graduate Students:

M. Gaudreau, T. Gentile, M. Sansone, D. Shulsinger, Y. Takase, S. Texter

Secretarial Staff:

J. Guberman, A. Kotsopoulos

D. SPECIAL EQUIPMENT AND FACILITIES:

Experimental Facilities:

- Alcator A tokamak (a=9.5 cm; R=54 cm; B_T= 100 kG)
- Alcator C tokamak (a=16 cm; R=64 cm; B_T=140 kG)
- Rector research tokamak (35 cm × 70 cm minor cross section; R=58 cm; B_T=3.5 kG)

Major Facility Support Equipment:

- Power Equipment:

  Utility power substation:

    13.8 kV/30 MW

  Generators:

    220 MVA PFC Motor/generator (13.8 kV AC)

    2-16 MW, pulsed, 250 V, DC flywheel NML generators

  Rectifier/Invertors:

    Alcator C TF—200 kA, 750 V (4, 50 kA Robicon modules)

    Alcator C OH—50 kA, 750 V (2 Transrex units)

    Alcator A—40 kA, 150 V (American Rectifier)

    Alcator A—5 kA, 650 V (Transrex)

    Alcator A—50 A, 30 V (Sorenson)

  Rector Power Supplies:

    2.5 kV, 50 μF capacitor bank (TF)

    8 kV, 32 μF capacitor bank (OH)

    1 kV, 15 μF capacitor bank (OH)

    0.8 kV, 125 μF capacitor bank (OH)

- Plasma Heating Equipment:

  16 power supply/modulator outputs (65 kV, 15 A, 500 msec)

  100 kW, 2.45 GHz RF power for LHH (Alcator A)

4 MW, 4.6 GHz RF power for LHH (Alcator C)
15 MW, 175-225 MHz power for ICRF (Alcator A and C)
300 A, 30 kV, 100 μF capacitor bank for ICRF
50 A, 15 kV, 200 μF capacitor bank for ICRF
RF transmission, control, monitoring and data acquisition systems

- Cryogenic Facilities:

2, 8000 gallon LN_2 storage facilities
Liquified gas handling and transfer facilties

E. TECHNICAL PROGRAM SUMMARY:

The objective of the Alcator confinement program is to study plasma confinement and heating under conditions approaching those which will prevail in the magnetically-confined plasmas of a fusion reactor. The program consists of two major facilities: Alcator A, a high-field tokamak in operation since 1972, and Alcator C, a new high-field tokamak which began operation in mid-1978. Associated with the Alcator devices are two major radio-frequency heating experiments. One is at a frequency near the lower hybrid frequency. The other is in the vicinity of the ion cyclotron frequency. The lower hybrid heating experiment was funded at a $6M level by DOE in early 1978. The ion cyclotron program was made possible by the donation of the FPS-17 radar by the United States Air Force. Recent results, present status and goals of the Alcator A and C programs are described below.

Alcator A: The Alcator A is a relatively small (minor radius = 10 cm, major radius = 54 cm) tokamak in which the disadvantages of small size are more than compensated for by the extremely high toroidal field strengths of up to 100 kG. Two results of major importance to the worldwide controlled fusion effort have been achieved. The first is the discovery that plasma confinement improves as the plasma density is increased.

The second is the discovery of techniques for producing high-temperature plasmas with impurity content (i.e., non-hydrogenic components) in the $10^{-3} - 10^{-4}$ range required for reactor operation. The experimentally determined confinement behavior has been exploited to achieve the world-record value of $n\tau_E = 3 \times 10^{13}$ sec-cm^{-3}, just below that required for fusion breakeven at higher temperatures.

The Alcator A program continues to provide basic information pertinent to high-temperature plasma behavior. Specific programs now in place are aimed at the understanding and control of plasma-wall interactions. Important results have been obtained during the past year on the problems of impurity transport and removal of particles by interaction with the limiter.

An additional major program on Alcator A is a modestly powered (100 kW) RF heating experiment near the ion cyclotron frequency, which for Alcator A is about 100 MHz. The experiment is providing information on the physics of wave penetration, heating mechanisms, and efficiency, as well as information on the technological problems of vacuum window and RF coupler design. This experiment may be considered prototypical of the much higher power experiment planned for Alcator C, and the results are being integrated into the design of that program.

Alcator C: Alcator C is an upgrade of the A device, in which the minor radius has been increased to 16 cm, the major radius to 64 cm, and the maximum toroidal field strength to 140 kG. This machine is powered by the 220 MW PFC alternator. The alternator is 25 years old, having supplied power for this length of time in the Consolidated Edison system. Due to poor economy of the steam turbine drive, the system was retired and the alternator donated to MIT.

As a result of the C design, parameters even closer to those required for fusion are expected to be achieved. During the first phase, in which the only power to the plasma will be supplied by the ohmic heating system, $n\tau_E$ values of approximately 10^{14}sec-cm^{-3} and temperatures approaching 2 keV are expected to be achieved. This value of $n\tau_E$ is well above the minimum required for energy breakeven, although actual breakeven requires higher temperatures. Plasma equilibrium, stability, fueling, and purity are the main physics issues investigated during this phase.

At present, Alcator C has been operated at toroidal fields in the range 60 kG - 100 kG and plasma currents up to 525 kA. These represent about 75% of the design capability. The maximum $n\tau_E$ values are now equal to the best achieved on Alcator A, and an increase up to $n\tau_E \simeq 5 \times 10^{13}$cm^{-3} is expected during the summer of 1980.

RF Heating: Further improvement of plasma parameters in Alcator C will require additional energy input. Phase II of Alcator C has as its objective the increase of plasma temperature from 2 keV, to 4 keV or more. For this purpose, two radiofrequency heating methods will be explored and are being developed in parallel. The first will use 4 MW of power at the lower hybrid frequency, which is about 4.6 GHz in Alcator C. The second will employ up to 8 MW of power at the second harmonic of the ion cyclotron frequency. Key physics issues in both programs are: RF wave penetration into the plasma, heating mechanisms, efficiency, and the effect on plasma stability and confinement. Technological issues are concerned with RF power transmission through vacuum interfaces, power densities achievable, and practical RF coupler design.

Lower hybrid heating is the primary method selected for heating the plasmas of Alcator C. However, the ICRH program, which has been initiated on Alcator will be emphasized on

Alcator C in the event that this method proves more successful. Successful completion of this phase will set the stage for a followup experiment to Alcator C. Although plans for the next step are still being formulated, the most ambitious step after Alcator C would be the world's first D-T ignition experiment. During FY 81, RF heating and ohmic heating experiments on Alcator C are expected to have reached a level of achievement which will give a clear direction for Alcator D. To support this anticipated decision point, tokamak design activities have been initiated and will be continued in 1981. Assuming a clear scientific opportunity exists, FY 82 will see the start of major device fabrication and site preparation. Final design activities will be carried out at MIT and with industrial contractors. The manufacture of long-lead-time items such as toroidal field components and the vacuum chamber will start in FY 82, and smaller scale prototype work will be carried out in FY 81.

As indicated earlier, the design activity for the next step in the Alcator program has been initiated and will be intensified as the Alcator C results evolve. They should lead to possible construction of Alcator D in FY 82. This activity is exploring two alternative paths. The first design approach is examining the optimum upgrade of Alcator C that can take full advantage of the RF heating capabilities associated with the lower hybrid and ICRH Shemya equipment. The full 10 to 15 MW of ICRH capability cannot be utilized in Alcator C due to limited access. An upgraded TF coil design with more ports will be examined as a replacement of the present coil. The increased neutron yield for such a device will require location in a shielded installation in the PFC Nabisco facility.

The second, more aggressive approach is examining compact high-field designs that lead to an early ignition experiment. This device may be RF heated and utilize limited compression. Such an ignition experiment could be located in a large containment dome at the PFC Nabisco facility.

In addition to upgrades of Alcator C, a modification of Alcator A beginning in FY 81 is also planned. The purpose of the modification is to develop a facility which would allow detailed stability studies with emphasis on development of techniques for control of disruptions. Presently, a medium-field (B=5T) device intermediate in size between Alcator A and C and fitted with helical windings is envisioned. The time scale for the modification is about 2 years.

PLASMA FUSION CENTER

III. FUSION TECHNOLOGY AND ENGINEERING DIVISION

D. BRUCE MONTGOMERY, HEAD

OBJECTIVES:

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

GROUPS:

- Advanced Design
  John E.C. Williams, Leader
- Superconducting Magnet Development
  Mitchell O. Hoenig, Leader
- Superconducting Materials Development
  Simon Foner, Robert Rose and Brian Schwartz, Co-Leaders
- Divertor Development
  Tien-Fang Yang, Leader

The Fusion Technology and Engineering Division provides advanced design to support the Magnetics Branch activities of the Engineering Test Facility (ETF) and the proposed Garching high-field Ignition Test Reactor. Engineering support is also provided for next-step planning activities in the MIT confinement program.

Major experimental programs are also carried out in the development of conductors for superconducting fusion magnet projects. A helium refrigerator and 2 meter Dewar are the principal facilities. A supercritical helium-cooled conductor conceived and developed by the magnet group has been selected by Westinghouse for the 2 × 3 meter niobium-tin coils for the Large Coil Project, and for the 12 T advanced magnet project at Livermore.

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

Advanced design is being carried out in the area of magnetic divertors to support the ETF and advanced reactor designs. An experimental program which could be carried out on a national scale to support the development of magnetic, target and particle handling concepts is being planned.

1. ADVANCED DESIGN GROUP

John E.C. Williams, Leader

A. OBJECTIVES:

Carry out engineering functions in support of advanced design projects.

B. PROJECTS:

- ETF Engineering
- ITR Engineering
- Engineering support of next-step planning in the MIT confinement program
- 12 T program support

C. PERSONNEL:

Research Staff:

H. Becker, E. Bobrov, J.M. Davin, R. Derby, E. Erez, J. Lettvin, N.T. Pierce, J. Schultz, C. Weggel, J.E.C. Williams

Draftsmen:

P.R. Maruzzi, A. Rabasco

Secretary:

D. Marble

D. SPECIAL EQUIPMENT AND FACILITIES:

Computer Equipment:

- 5 teleray computer terminals, accessing MIT facilities and the NMFECC

E. TECHNICAL PROGRAM SUMMARY:

The fusion engineering advanced design group provides critical support for the magnet systems for the Engineering Test Facility (ETF), for the proposed Garching high-field Ignition Test Reactor (ITR), for the 12 Tesla coil program, and for the next steps in the high-field tokamak program beyond Alcator C.

ETF Magnetics Design:

The PFC Fusion Technology and Engineering Division has been selected to take responsibility for the Magnetics Branch of the ETF Design Center activities. This work is carried out in close cooperation with the ETF Design Center Headquarters at ORNL, which has overall responsibility for systems integration and management of ETF design activities.

The activities of the Magnetic Branch consist of preconceptual design of the magnet and cryogenics of two systems, differentiated by their poloidal field systems.

One of the most important tasks of the Magnetics Branch is effective interfacing with the National Fusion Community. The Fusion Community has a broadly based magnetics capability. Some of these resources have been utilized on the TNS studies, others are represented by the present generation device projects, and yet others in the development of superconducting technology. Activities outside the fusion program, such as MHD magnet development activities, the large scale cryogenic systems applications in high energy physics, and the widely scattered cryogenics materials evaluation programs, are all of potential value to the ETF program. These programs are both national and international, and are located in national laboratories, universities, and in industry. We view the coupling of these activities to ETF as a major responsibility of the ETF Magnetics Branch.

A second important activity in the early phases of the Design Center has related to overall parametric systems studies. It has been the responsibility of the Magnetics Branch to supply these magnetics modeling codes necessary for the overall systems analysis activities.

Ignition Test Reactor TF Magnet Design:

A design effort for a copper high-field Ignition Test Reactor (ITR) is being carried out in collaboration with the Max Planck Institute for Plasma Physics at Garching. The MIT Plasma Fusion Center will act as the lead laboratory for US participation in this collaboration and will coordinate the technical inputs from the various US laboratories that are involved. Technical activities of the Advanced Design Group center around the design of the toroidal field magnet system based on the Bitter magnet concept. The toroidal field magnet must be designed to facilitate extended DT operation of the device. Extensive tests of the mechanical properties of the copper, steel and insulator components of the magnet are being carried out.

Alcator A Modification:

It is proposed to modify Alcator A for the purpose of studying MHD activity in high density and high temperature tokamak plasmas, with particular emphasis on understanding and controlling major disruptions. In order to pursue this effort we propose the replacement of the Alcator A Bitter magnet by a Bitter magnet intermediate in size between Alcator A and C, incorporating helical windings. The helical windings will be capable of adding a transform of 0.2 to the transform generated by the toroidal current. The size, magnetic field and plasma current will be chosen in order to enable direct comparison with Alcator C and prior Alcator A performance. This modification allows exploration of stable, low q ($\sim$1.5) operating regimes. It will also allow much better control than is presently available over startup of tokamak discharges. It will incorporate diagnostics (e.g., large diode arrays) capable of giving detailed information on the structure and evolution of magnetic surfaces and island chains.

It is expected that this modification will take two years, beginning with detailed magnet design early in FY 81, leading to operation at the end of FY 82.

Alcator D Design:

By the end of FY 81, RF heating and confinement experiments on Alcator C are expected to have reached a level of achievement which will give a clear direction for a follow-on device. To support this anticipated decision point, a tokamak design activity was initiated in FY 79 and has continued in FY 80.

Assuming a clear scientific opportunity exists, FY 82 would see the start of major advanced manufacturing and site preparation work. Major final design activities would be carried out at MIT and with industrial contractors. The manufacture of long-lead-time items, such as toroidal field components and the vacuum chamber, would start in FY 82. Smaller scale prototype work will be carried out in FY 81.

2. SUPERCONDUCTING MAGNET DEVELOPMENT GROUP

Mitchell Hoenig, Leader

A. OBJECTIVES:

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

B. PROJECTS:

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

C. PERSONNEL:

Research Staff:

E. Erez, M.O. Hoenig, A.G. Montgomery, M. Olmstead, M. Steeves

Technical Support Personnel:

R.V. Wardenaar

Visiting Scientist:

V. Arp

Graduate Student:

S. Shanfield

Secretary:

M. Charbonneau

D. SPECIAL EQUIPMENT AND FACILITIES:

Special Facilities:

- 2 meter LHe cryostat
- 1 × 2 meter Dee Coil Facility with 7.5 T, 15 cm diameter field coil
- 1 m × 0.2 Race Track Structural Test Facility (6T)
- CTI 1400 liquifier/circulator
- 12 T, 15 cm bore Bitter coil
- 8 T, 25 cm bore Bitter coil
- 7 kA, 20 V DC Power and Supply

E. TECHNICAL PROGRAM SUMMARY:

Major experimental programs are carried out in the development of conductors for superconducting fusion magnet projects. A helium refrigerator and 2 meter Dewar are the principal facilities. The supercritical helium-cooled ICCS* conductor developed by the magnet group has been selected by Westinghouse for the 2×3 meter niobium-tin coils for the Large Coil Project, and is being used by the MIT group for the 12 T advanced magnet project at Livermore. The ICCS concept was conceived and develped 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.

In Phase I of the program, a basic computer program was developed to analyze the stability of various conductor

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*ICCS: Internally cooled, cabled superconductor configurations. In Phase II, experimental results for NbTi cables were correlated with computer analyses. During Phase III tests were performed using commercial cable configurations. During the course of these experiments, a significant discovery was made. The stability of an ICCS is essentially independent of bulk flow. Local heating generates a pressure wave, which causes sufficient local turbulence in even quiescent fluid to assure stability. During subsequent phases (FY 77), work was initiated on a one-meter scale D-coil test facility, and in 1976 and 1977, "bundle conductor" type MF-Nb_3Sn cabled conductors were examined. Since 1978, efforts have been directed at the design, development, fabrication, and testing of a 12 T MF-Nb_3Sn coil. At the present time, a three-year program is being carried out which includes test operations at the High Field Test Facility at the Lawrence Livermore Laboratory.

The magnet group has also explored a joint project with JAERI regarding a project on the 12 T Japanese Cluster Test Facility. JAERI will build 1 m × 2 m background test coils and has expressed an interest in the U.S. providing a forced-flow Nb_3Sn test module coil for structural tests on this facility.

The group has also participated in an MHD-sponsored experiment, in which an ICCS, with double wall thickness is allowed to move under magnetic pressure. Embodied as a 1 m long oval "Football" test coil, the experiment will be performed in MHD's 6T split racetrack facility at the Magnet Laboratory facility.

3. SUPERCONDUCTING MATERIALS DEVELOPMENT GROUP

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

A. OBJECTIVES:

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

B. RESEARCH PROJECTS:

- Development of In Situ Materials
- Development of Powder Metallurgy Materials
- Development of Ultrafine Filamentary Composites
- Development of Fine Filament Modeling Programs

C. PERSONNEL:

Faculty:

R. M. Rose

Research Staff:

R. Akihama, W.R. Cimino, S.F. Cogan, J.L. Fihey, S. Foner, R. Murphy, M. Ries, R. Roberge, B.B. Schwartz

Technical Support Staff:

I. Puffer and R. Andrews

Graduate Students:

S. Arney, J.D. Klein and S. Pourrahimi

Undergraduate Students:

D.S. Holmes (S.B. thesis); UROP students: J. Bowen, N. Dudziak, J. Parse, G. Warshaw

Secretarial Staff:

M. Filoso and L. Lawrence

D. SPECIAL EQUIPMENT AND FACILITIES:

Special Facilities:

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

E. TECHNICAL PROGRAM SUMMARY:

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

The program involves several activity components:

- Development and Characterization of "In Situ" Multifilamentary Superconducting Materials
- Development of Cold Powder Metallurgy Process for Multifilamentary Superconducting Materials
- Composite Micromechanics and Fatigue Models
- Development of Microfilamentary Composites
- Ultrafine Filamentary Materials
- 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. All the 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 all the facilities at MIT. The initial scale up runs for the fast casting technique have been carried out at Prof. Flemings' laboratory at MIT. In addition to MIT's excellent facilities, the metallurgical capabilities of IREQ in Canada (Roberge) and the facility of the University of Geneva (Flükiger) have been used to prepare additional as well as specialized materials.

During FY 1979 and FY 1980, a mechanical testing capability has been developed at the Magnet Laboratory in cooperation with the National Science Foundation funded magnet facility. An Instron machine with an extendable arm has been developed which can be placed in a high magnetic field. Testing of wires to 18.5 Tesla can be done routinely and is being used as a facility for the superconducting materials development community from universities, federal laboratories and private industry.

4. DIVERTOR DEVELOPMENT GROUP

T.-F. Yang, Leader

A. OBJECTIVES:

To develop divertor designs and divertor technology suitable for ETF, and to design and construct specific divertor systems.

B. RESEARCH PROJECTS:

- Develop Magnetic Divertor Concepts
- Development of a National Plan for Divertor Technology
- Design and Construction of the ISX-B bundle divertor
- Scoping study of ISX-C Bundle Divertor
- Develop Divertor designs for ETF

C. PERSONNEL:

Faculty:

L. Lidsky, B. Mikić, N. Todreas

Research Staff:

D. Blackfield, B. Montgomery, G. Rappaport, J.Tracey, T. Yang

Graduate Student:

P. Gierszewski, P. Roemer, A. Wan

Draftsman:

C. Milonas

Secretary:

A. Kotsopoulos

D. SPECIAL EQUIPMENT:

Pilot experimental work on a suitable plasma source for divertor simulation is being undertaken utilizing facilities available in the Research Laboratory for Electronics. Large power supplies for future magnetic component testing are available through the confinement experimental program. Much of the divertor development component testing will be carried out in various test facilities throughout the country. The limiter test will be carried out on Alcator.

E. 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. An improved mousetrap divertor has also been conceived. However, the engineering difficulties have to be solved before being considered for practical application. The study of a hybrid divertor is underway.

The bundle divertor for the ISX-B tokamak at ORNL is being designed and constructed at MIT. The 5MW, 6 Tesla copper coils require careful thermal and stress analysis. The sophisticated mounting structure also requires careful finite element analysis and numerically controlled machining. The divertor housing is near completion. A complete and magnetically tested divertor will be delivered in November, 1980, as scheduled. An ISX-C bundle divertor scoping study has also been initiated.

The divertor design program in support of ETF was initiated in FY 80. Designs for poloidal and bundle divertors are being supplied to the magnetics branch at the ETF Design Center for integration into the ETF design. Design work is also being carried out in support of the INTOR activities.

The Divertor Technology program was initiated in FY 80 to conduct a planning exercise to formulate a National Divertor Development Program to be initiated in FY 81. A series of discussions and workshops are being held to evolve such a plan.

Current impurity control strategies for ETF call for inclusion of a divertor in the design. However, at the present time there is no divertor concept which results in an overall system which satisfies both the physics and engineering constraints. It will therefore be necessary to develop both concepts and components in any divertor development program.

The basic strategy of the divertor development program will be to (1) develop iterative design concepts for integration into the evolving ETF system designs, (2) to utilize data from PDX and ISX-B to the maximum extent possible, and (3) to construct and/or modify "off-line" test facilities to aid in the development of components and novel concepts.

IV. FUSION SYSTEMS DIVISION

DANIEL R. COHN, HEAD

OBJECTIVES:

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

GROUPS:

- Safety and Environmental Studies
  Mujid Kazimi, Leader
- Tokamak Systems Studies
  Daniel Cohn, Leader
- Blankets and Structures
  John Meyer and Borivoje Mikić, Co-Leaders
- Gyrotron and Advanced Millimeter Source Development
  Richard Temkin, Leader

PROJECTS:

- Millimeter and Submillimeter Wave Detector Development
  Harold Fetterman and Peter Tannenwald, Co-Leaders

The purpose of the system studies programs in the Fusion Systems Division is (a) to contribute to the conceptual design basis for the construction of the next generation of major tokamak devices, (b) to deepen understanding of the potential features of power producing fusion reactors and to develop new design concepts, and (c) to provide guidance in the development of fusion energy technology. Present system studies programs include reactor physics studies, safety and environmental studies, blanket and structure analysis, and overall tokamak reactor design. Next generation, DT burning machines which are being studied include ignition test reactors (ITR) and the engineering test facility (ETF). The ITR would be used to study ignition physics and burn control and would employ unshielded copper magnets. ETF would utilize superconducting magnets and would serve as a test bed for fusion technology.

There are two advanced component development programs in the Fusion Systems Division. High frequency ($\sim$ 140 GHz) gyrotron designs will be developed and 100 kW level, 10 μsec pulsed devices will be built and tested. The purpose of this program is to provide a basis for the production of devices for millimeter wave plasma heating. Advanced millimeter and submillimeter wave Schottky barrier diode detectors will be produced by Lincoln Laboratory for use by DOE Laboratories in a variety of plasma confinement studies. This program will also involve further refinement of these detectors.

1. SAFETY AND ENVIRONMENTAL STUDIES GROUP

Mujid Kazimi, Leader

A. OBJECTIVES:

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

B. PROJECTS:

- Develop methodology for radiological hazard assessment
- Lithium fire modeling and mitigation
- Tritium modeling assessment
- Comparison of consequences of reactor accidents in various designs.

C. PERSONNEL:

Research Staff:
M. Kazimi, L. M. Lidsky, N. C. Rasmussen

Graduate Students:
D. Hanchar, P. Krane, S. Piet, M. Tillack

Undergraduate Student:
V. Gilberti, G. Suh

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.

To summarize recent accomplishments, a methodology has been proposed to provide system reliability criteria based on an assessment of the potential radiological hazards associated with fusion reactor designs and on hazard constraints which prevent fusion reactors from being more hazardous than light water reactors. The probabilistic consequence analyses, to determine the results of radioactivity releases, employed the Consequences Model developed to assess the risks associated with light water reactors for the Reactor Safety Study. The calculational model was modified to handle the isotopes induced in the structural materials of two conceptual Tokamak reactor designs, UWMAK-I and UWMAK-II. It was determined that the radiological hazards associated with induced activity in these reactor designs imply reliability requirements comparable to those estimated for light water reactors for most probable accidents. The consequences of estimated maximum possible releases of induced activity, however, are substantially less than the maximum light water reactor accident consequences.

The total power cycle environmental risk of fusion has been compared to other fuel cycles including coal, fission, solar and wind. The results to date indicate that fusion reactors, if designed to eliminate public consequences of accidents, will be associated with the most favorable power cycle from the standpoint of environmental effects. Work in this area is continuing.

In addition, a lithium pool combustion model has been developed to describe the physical and chemical processes which occur during a hypothetical lithium spill and fire. The model (LITFIRE) was used to study the consequences of lithium fire within a typical containment. Calculations show that without any special fire protection measures, the reference containment may reach pressures of up to 32 psig when one coolant loop is spilled inside the reactor building. These consequences are found to diminish greatly by the incorporation of a number of design strategies including initially subatmospheric containment pressures, enhanced structural surface heat removal capability, initially low oxygen concentrations, and active post-accident cooling of the containment gas. It has been shown that low volume "racetrack" containment structures have significant advantages.

Research is currently in progress to assess the factors that contribute to the uncertainty level of the predicted consequences of tritium releases from fusion reactors to the environment. The assessment includes various models that have been reported in the literature as well as their data base.

Future plans, within the next five years, include the following activities: (a) Verification of the lithium fire models by comparison with experimental results in the ongoing effort at HEDL. (b) Inclusion of a best estimate tritium release model in the CRAC code to be applied to fusion plant probabilistic safety assessment. (c) 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 temperature). (d) Completion of safety evaluation of reactor concepts other than the lithium-cooled tokamak reactors.

2. TOKAMAK SYSTEMS STUDIES GROUP

Daniel R. Cohn, Leader

A. OBJECTIVES:

Develop new system and subsystem concepts for tokamak reactors.

B. RESEARCH PROJECTS:

- High field ignition test reactor design
- Coordination of U.S. participation in the ZEPHYR design
- Reactor physics studies
- ETF plasma systems studies
- Tokamak power reactor studies

C. PERSONNEL:

Research Staff:

H. Becker, E. Bobrov, L. Bromberg, D. Cohn, E. Erez, J. Davin, J. Fisher, J. Lettvin, R. Potok, J. Schultz, J. Williams

Visiting Scientist :

A. Erison

Secretary:

D. Diehl, R. Montane

D. SPECIAL EQUIPMENT AND FACILITIES:

Computer Equipment:

- 1 Texas Instrument 745 portable terminal

E. TECHNICAL PROGRAM SUMMARY

This activity involves the development of new concepts and engineering designs of tokamak reactors. Considerable emphasis is placed upon reactor physics studies. Investigations include: (a) near-term ignition test reactors (ITR) which would study the physics properties of ignited plasmas, (b) the Engineering Test Facility (ETF), which would serve as a test bed for fusion technology, and (c) demonstration power reactors.

To summarize recent achievements, designs have been developed for both compression-boosted, neutral-beam-heated and RF-heated ignition test reactors. Modes of ignited operation have been investigated and passive and active means of burn control have been studied. In addition, the Plasma Fusion Center is serving as coordinator for the U.S. participation in the ZEPHYR ignition test reactor design study at the Max Planck Institute für Plasmaphysik in Garching, Federal Republic of Germany. Recent achievements also include the determination of methods of optimizing operation of RF current-driven steady-state tokamak reactors and the development of a tokamak power reactor design which is heated with high frequency gyrotrons. Finally, MIT is participating in plasma system studies for ETF.

To summarize future plans, MIT will continue to participate in the ZEPHYR design study in the areas of ignition physics and burn control, magnet design, materials studies, diagnostic and experimental planning and coordination of the U.S. participation in ZEPHYR. The ETF plasma systems studies will involve investigations of possible operating regimes, burn control and heating options. In addition, an advanced fuel study program has been proposed to investigate options for improved designs of D-D reactors using high-field magnet technology.

3. BLANKET AND STRUCTURES GROUP

John Meyer and Borivoje Mikić, Co-Leaders

A. OBJECTIVES:

Investigate problems of blanket and first wall design. Develop new design concepts. Develop criteria for structural design requirements. Participate in national blanket and first wall design and testing activities.

B. RESEARCH PROJECTS:

- Development of blanket and first wall design concepts
- Determination of structural design constraints

C. PERSONNEL:

Research Staff:
P. Griffith, J. Meyer, B. Mikić, N. Todreas

Graduate Student:
P. Gierszewski, J. McMurray

D. TECHNICAL PROGRAM SUMMARY:

Activities in the Blanket and Structures Group in the area of blanket and first wall design concepts include studies of stagnant liquid lithium blankets and the development of novel design features aimed at reduction of thermal stress in the first wall. Design windows have been developed for a stagnant lithium blanket considering three different coolants (lithium, helium and flibe). In the area of first wall design it has been found that copper cladding can significantly reduce the peak stress for a 316 stainless steel radiation shield tube. Another first wall concept which has been studied is a relatively thick first wall to serve as a protective "armor" with coolant tubes welded or brazed to the near surface.

Three main areas have been studied in the area of structural design of the first wall. These include: (a) development of methods of calculating stresses (including U-cell, canister, tubular and passage-in-wall cases), (b) determination of design criteria for acceptable stress levels, (c) development of methods to quantify judgments concerning first wall material selection (including plasma/wall interactions and coolant corrosion effects).

Plans for future work include (a) investigation of blanket design issues such as natural convection effects for liquid lithium and flibe blankets and helium bubble formation, (b) continuation of first wall design studies, (c) continuation of the development of structural design criteria and first wall materials evaluation, and (d) participation in national programs in the design and testing of blankets and first wall materials.

4. GYROTRON AND ADVANCED MILLIMETER SOURCE DEVELOPMENT GROUP

Richard J. Temkin, Leader

A. OBJECTIVES:

Design and test advanced high frequency gyrotron devices. Develop optically pumped laser sources in the millimeter and submillimeter region.

B. RESEARCH PROJECTS:

- Development of 140 GHz, kW pulsed gyrotron
- Theoretical study for gyrotron design
- Study of optically pumped laser sources

C. PERSONNEL:

Research Staff:

D. Cohn, R. C. Davidson, B. Lax. W. Mulligan, R. Temkin, P. Woskoboinikow

Visiting Scientist:

C. E. Chase

Graduate Students:

D. Biron, B. Danly, K. Kreischer

Secretary:

D. Diehl, R. Montane

D. TECHNICAL PROGRAM SUMMARY:

This development activity involves the design and testing of advanced gyrotron devices operating at high frequencies (∿ 140 GHz). High-order resonator modes (e.g., TE_{031}) will be used to achieve high power levels. Mode competition will be investigated. Whispering gallery modes (TE_{M11}, M large) will be studied. An important goal of the program is to develop 100 kW devices with pulse lengths of 1-2 μsec and repetition rates up to 10 Hz. These devices would be used as a basis for the design and eventual production of long pulse or CW, high-power, high-frequency gyrotrons. These gyrotrons would be used for plasma initiation and heating in tokamaks, bumpy tori and mirror devices.

An additional effort (funded by NSF) involves the development of new optically pumped laser sources in the millimeter and submillimeter region.

To summarize recent accomplishments, a linear analytic gyrotron theory has been developed which predicts frequency detuning, describes characteristics of all TE cavity modes, and can be used to determine characteristics of multimode operation. In addition, a preliminary design for a high-mirror-ratio electron gun has been developed, and a preliminary power supply design has been completed.

To summarize future plans, the final design for a high-mirror-ratio electron gun will be developed by industry and a Bitter magnet, provided by the National Magnet Laboratory, will be modified for gyrotron experiments by the end of FY80. The fabrication of the electron gun will be completed by the middle of FY81. Experiments will begin in the middle of FY81, and there will be a continued effort in gyrotron theory aimed at optimizing the design of high frequency devices.

5. MILLIMETER AND SUBMILLIMETER WAVE DETECTOR PROJECT

Harold Fetterman and Peter Tannenwald, Co-Leaders

A. OBJECTIVES:

Supply state-of-the-art Schottky barrier diode detectors to a number of DOE laboratories. Further develop these detectors, and participate in Plasma Fusion Center research activities that require the expertise of Lincoln Laboratory in advanced millimeter and submillimeter wave detection.

B. LINCOLN LABORATORY PERSONNEL:

Research Staff:
B. Clifton, H. Fetterman, P. Tannenwald

Technical Support Personnel:
W. Macropolis, S. P. Nida, C. Parker

C. SPECIAL EQUIPMENT AND FACILITIES:

Epitaxial crystal growth; photolithography and mask making; proton bombardment; ion implantation; diode packaging

D. TECHNICAL PROGRAM SUMMARY:

Advanced Schottky barrier diode detectors for use in 300 GHz - 3 THz range will be produced for designated DOE laboratories. These detectors will be used in a variety of applications including measurements of plasma density by laser interferometry, cyclotron emission studies and submillimeter laser scattering experiments. In addition to this simple replacement of field units as needed, it is anticipated that modifications will be introduced to upgrade performance.

Detector research and development will also be carried out. Emphasis will be placed on obtaining sensitive heterodyne mixers using planar, surface-oriented diodes. The planar diodes have already proved to be more rugged mechanically and electrically than the state-of-the-art whisker diodes. Moreover, the planar diodes are readily adaptable to detector array configurations and solid state local oscillators.

PLASMA FUSION CENTER

OFFICE OF PLANNING AND ADVANCED PROJECTS

DANIEL R. COHN, HEAD

A. OBJECTIVES:

Coordinate planning activities for major next step confinement devices. Facilitate MIT participation in national and international fusion program planning. Coordinate MIT activities in international collaboration.

B. PRESENT ACTIVITIES:

- Study of possible next steps for MIT confinement program.
- Joint German - US collaboration in the design study of a high-field tokamak ignition device for alpha particle heating and burn control studies.
- Participation in national Engineering Test Facility design study.
- International fusion program planning for INTOR.
- Planning of joint programs for collaboration with Japan, including torsatron research, the construction of magnets for the Japanese Cluster Test Facility, and the development of technical exchange programs.

C. PERSONNEL:

G. Bekefi, A. Bers, L. Bromberg, D. Cohn, R.C. Davidson, L. Lidsky, J. McCune, D.B. Montgomery, R. Parker, P. Politzer, D. Rose, J. Williams

PLASMA FUSION CENTER

OFFICE OF RESOURCE MANAGEMENT

JOHN L. COCHRANE
ASSISTANT TO THE DIRECTOR FOR ADMINISTRATION

A. OBJECTIVES:

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

B. SUPPORT SERVICES AND OPERATIONS AREAS:

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

C. PERSONNEL:

Headquarters Operations and General Support Services:

John Cochrane, Assistant to the Director for Administration

Staff:

J. Cooper, S. Kenneally, M. Langton,
C. Robertson, J. Sieckarski, A. Anderson

Fiscal Office:

Paul Smith, Fiscal Officer

Staff:

E. Bermudez, B. Doran, R. Goodridge, A. LeBlanc, D. Magnuson, K. McMahon, J. O'Toole

Purchasing Office:

Kenneth Wisentaner, Manager

Staff:

M. Bacon, L. Clark, P. Garrity, R. Newcomb, M. Silva, R. Stevens

RLE Administrative Support:

Barbara McCarthy, RLE Administrative Officer

Don Duffy, RLE Fiscal Officer

Staff:

B. Barron, C. Bella, K. Hall, V. Lauricella, J. Peck