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Magnetic Fusion Energy and Computers

*The Role of Computing in Magnetic Fusion
Energy Research and Development*

Published October 1979

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U.S. Department of Energy
Office of Fusion Energy

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PREFACE

This report was sponsored by the Office of Fusion Energy of the Department of Energy.

On July 19-20, 1979 a panel was convened at the Magnetic Fusion Energy Computer Center, Lawrence Livermore Laboratory for the purpose of organizing the report and editing the many contributions. The panel also produced the requirements graphs and tables of the last section and unanimously agreed on the three recommendations presented in the first section.

The panel consisted of David Nelson (Office of Fusion Energy, DOE), J. Manickam (Princeton Plasma Physics Laboratory), Jack Byers and Brendan McNamara (Lawrence Livermore Laboratory), Wayne Pfeiffer (General Atomic Company), Dennis Hewett (Los Alamos Scientific Laboratory), Charles Maynard (University of Wisconsin), Arthur Mirin and John Killeen (MFECC).

Contributions to the report were received from all of the above and from John Hogan and Martin Peng (Oak Ridge National Laboratory), Leon Shohet (University of Wisconsin), George Miley (University of Illinois), Nelson Byrne (Science Applications, Inc.), Kenneth Marx, Dalton Schnack and John Fitzgerald (MFECC).

The report was prepared by Louise Beite and Deanna Bright of MFECC.

JOHN KILLEEN
Director, National MFE
Computer Center
August 1979

1. INTRODUCTION AND SUMMARY OF RECOMMENDATIONS

This report examines the role of computing in the Department of Energy magnetic confinement fusion program. The main emphasis is on the use of the most powerful scientific computers to solve the mathematical problems arising in the modeling of fusion reactors.

Numerical calculations have had an important role in controlled fusion research since its beginning the early 1950's. In the last few years the application of computers to plasma physics has advanced rapidly. This is due to the increasing sophistication of the mathematical models which made more realistic numerical simulation of plasmas possible by taking advantage of the increased speed and memory of computers. In the next few years there will be a substantial increase in the development and use of numerical models in order to meet the needs of the fusion power program.

In June 1973 an Ad Hoc Panel on the Application of Computers to Controlled Thermonuclear Research was convened. The recommendations of the Ad Hoc Panel (WASH 1296) and their subsequent implementation have had a dramatic effect on fusion computing. A recommendation of the Panel was the establishment of a computing facility dedicated to the magnetic fusion program. The National Magnetic Fusion Energy Computer Center (MFECC) was organized in 1974 at Lawrence Livermore Laboratory and service began in late 1975.

Another recommendation of the Ad Hoc Panel was a significant expansion in the development and use of computer models in the fusion program. They identified five categories of computer models of magnetically confined plasmas and discussed their importance to the program. A significant increase in the use of macroscopic models was called for in order to simulate existing and planned experiments.

The present status of the MFECC and its associated network is described in the second part of this report. The third part of this report examines the role of computer models in the main elements of the fusion program and discusses their dependence on the most advanced scientific computers.

A review of requirements at the National MFE Computer Center was conducted in the spring of 1976. The results of this review led to the procurement of the CRAY 1, the most advanced scientific computer available, in the spring of 1978. The utilization of this computer in the MFE program has been very successful and is also described in the third part of the report.

A new study of computer requirements for the MFE program was conducted during the spring of 1979 and the results of this analysis are presented in the fourth part of this report. The MFE program has grown considerably and major directions have emerged e.g., TFTR, MFTF, EBT and the proposed Engineering Test Facility (ETF). The computing requirements are necessarily much larger and the models more varied and demanding. In the fourth part of this report the needs for additional computing capacity at the MFECC are projected through 1985. The need for the most powerful scientific computers available is emphasized.

The required resources that are identified lead to the following:

RECOMMENDATIONS

1. To meet the near term needs of the MFE program (Figures 4.5 and 4.6) a second Class VI computer should be installed at the National MFE Computer Center during FY 1981.

This machine should have CPU execution speeds as fast or faster than the CRAY 1 and preferably a fast memory of 2 to 4 million words.

2. To meet the longer term MFE requirements for both capacity (Figures 4.5 and 4.6) and capability, a Class VII computing system should be installed at the National MFE Computer Center during FY 1984.

It is expected that by 1984 a new class of computers will be recognized in the large scale computing industry. Such a machine should have execution speeds several times that of a Class VI and fast memory of 4-16 million words.

3. The User Service Centers and the National MFE Network should continue to enhance their capabilities.

In concert with the installation of the Class VI and Class VII computers, the User Service Centers at the major fusion laboratories should be upgraded in computing capacity, memory, graphics, and other services needed to utilize the central resources most efficiently. The existing communication network should be upgraded in bandwidth, where needed, in order to take full advantage of increased computing power available at the Center. Additional dedicated data communication lines to the Network should be provided for those user groups that require substantial and regular computing at the MFE Computer Center.

2. NATIONAL MFE COMPUTER NETWORK

The purpose of the MFE Computer Network is to provide to all fusion researchers the full range of available computational power in the most efficient and cost effective manner. This is achieved by using a network of computers of different capability tied together and to the users via dedicated data lines and dial up telephone lines. The existence of this nationwide computer network allows projects to be sited anywhere in the country without regard to local computer availability, and therefore increases enormously the flexibility of the fusion program.

The largest scale computation is provided by the National Magnetic Fusion Energy Computer Center (NMFECC). The concept of a centralized computer facility for MFE was proposed in July 1973 (The Application of Computers to Controlled Thermonuclear Research, WASH 1296) as one of three options for meeting long-term MFE computer requirements. Subsequently selected as the option with the most benefits, a site for the centralized facility was selected, funds were provided, and equipment was procured within two years. The Lawrence Livermore Laboratory (LLL) was selected to develop and operate the new center.

By 1975 the Center began first operations using a CDC 6600 loaned by the LLL Computer Center. In October 1975 the Center installed its own CDC 7600 computer, and by March 1976 significant transmission over the dedicated Data Communication Network was taking place. By that time the new CDC 7600 was already saturated.

In May of 1978 the Center installed a new high speed CRAY-1 computer with one million words of memory. Together with the original CDC 7600 the CRAY-1 has become an invaluable computational resource to the entire MFE computing community. It is currently operating at full capacity around the clock seven days per week.

In addition to the CDC 7600 and the CRAY-1, the center provides a CDC 6400 for managing a multilevel file storage system which incorporates high performance disk units, a CDC 38500 mass storage system (.5 trillion bit capacity), and an automated archival storage system.

At the next level of capability are User Service Centers (USC's): DEC-10 computer systems with direct high-speed access to the national center through PDP-11/40 remote communications control processors. There are now five (Fig. 2.1) operational USCs in the field located at Princeton Plasma Physics Laboratory (PPPL), the Los Alamos Scientific Laboratory (LASL), the Oak Ridge National Laboratory (ORNL), General Atomic (GA), and LLL (for the

NATIONAL MFE NETWORK 1979

Figure 2.1

mirror confinement program). A sixth USC, used in Center operations, is located at the MFECC itself. The USC's are further connected to experimental data acquisition computers, to array processors, and other special purpose equipment.

Under these "tiered" arrangements smaller problems and processing of local experimental data can be handled at the USCs, while large problems can be sent to the national center. Computational results from the national center are returned to the USCs for display or printout. The advantages of these arrangements include local availability, cost-effective equipment utilization, and an interactive computing network among the various user service centers. Interactive timesharing is available to users on the DEC-10 systems, on the CDC 7600 system, and on the CRAY-1 computer.

Dial up capabilities providing MFECC services are also available to universities and other laboratories engaged in MFE research. When user requirements at a given site exceed what can be provided via dial-up, a Remote User Service Station (RUSS) may be installed. To date twelve sites have been approved by the Office of Fusion Energy for RUSS installation. An RUSS Station implies a dedicated telephone line to the nearest node (USC) on the wide band communication network. (Fig. 2.1)

The enormous growth of the number of users since the network became operational attests to the user acceptance of the network concept. The utilization of common software among so many users enhances the availability and transportability of the full spectrum of computer codes employed in the MFE programs. Moreover, the centralization of the supporting staff makes possible the development of advanced computer software tailored to the needs of the MFE community. An outstanding example of this is the rapid development of a time-sharing system for the CRAY computer.

The inherent flexibility in the MFE Computer Network allows easy adaptation to new computers, new users, and new applications. For example, recent improvements in the network software enable a user at any terminal attached to the network to log onto any computer in the network and to send files from any node to any other node. This facilitates sharing of special purpose hardware, software, and data files, wherever they are located on the network.

How Computers are Used in the MFE Program

There are many ways to categorize computer applications. One approach is to characterize the following basic tasks that computers perform.

- MODELING AND ANALYSIS:** The digital computer's ability to perform rapid and accurate arithmetic and logical operations has literally revolutionized certain branches of science, engineering, and economics by providing solutions to problems heretofore intractable.
- "Calculator"
- INFORMATION PROCESSING:** Computers are capable of manipulating vast amounts of data and information very rapidly and efficiently.
- "Filing System"
- SYMBOLIC MANIPULATION:** A small but-growing application is in symbolic manipulation to do plasma theory, numerical analysis, and automatic program writing.
- CONTROL OF MACHINES AND PROCESSES:** The speed, storage capacity, and communication capabilities of modern digital computers allow "on-line" control of laboratory, industrial, commercial, educational, and biological processes.
- "Intelligent Controller"

All of the above tasks find extensive applications in the MFE program and require a range of computer resources from the smallest microprocessors to the largest scientific computer systems.

The first task, which fusion theorists refer to as computer simulation, accounts for the largest requirement for computer capacity and capability. Computer simulation consists of using a computer model to represent whatever physical processes are of interest, for example, those taking place in a tokamak. Simulations can thus further one's understanding of ongoing experiments and provide guidance for future ones. Indeed, simulations and experiments complement each other as shown in the sketch below.

Computer simulations, however, have one major advantage over physical experiments. Simulations are much cheaper. More extensive parameter scans can thus be done by simulation than by experiment. Consequently, great advances in understanding are possible, despite budget constraints, through a judicious combination of experiment and simulation. These applications of computing make use of the facilities of the National MFE Computing Center.

In order to discuss the implications of new computer acquisitions, we introduce the concepts of computer capability (power) and capacity.

Capability (power) is a measure of the size or complexity of a job a computer system can process within some specified time. In practice, this period of time can be from several seconds to several days.

An increase in capability implies an ability to solve more difficult problems: problems requiring computer models with higher dimensionality, finer resolution, better physics, or other improvements which tax computing power.

Capacity is a measure of the throughput of a computer system, i.e., the number of jobs of a given type that can be accommodated within some specified time.

An increase in capacity implies the ability to do more of the same type of job. The capacity of a computing facility may be increased by the addition of similar computers, or by the provision of computers with greater capability.

A faster computer provides additional capacity and capability (power). Both are important. However, most often, it is increased capability--the ability to tackle harder problems with better tools--that provides the major payoff to the fusion program. Much of this report focuses on the implications of acquiring new computer capabilities.

Figure 2.2. A Faster Computer Provides Increased Capability and Capacity

3. THE ROLE OF COMPUTER MODELS IN MFE RESEARCH AND DEVELOPMENT

Large-scale digital computers are playing an increasingly important role in controlled fusion research. The behavior of a plasma confined by a magnetic field is being simulated by a variety of numerical models. Some short time scale models give detailed knowledge of the plasma on a microscopic scale, while other longer time scale models compute macroscopic properties of the plasma dynamics.

The 1973 report THE APPLICATION OF COMPUTERS TO CONTROLLED THERMONUCLEAR RESEARCH (WASH 1296) identifies five categories of computer codes used to model the physics of fusion devices. A brief description of these categories follows.

a) Time Dependent Macroscopic (Fluid) Codes

There is a natural division among time dependent fluid codes--those which simulate the fast time scale and those which operate on the transport time scale. Fast time scale magnetohydrodynamic (MHD) codes are typically used to investigate the time dependent behavior of instabilities. The main question to be answered is whether or not a particular MHD mode will be unstable, and if so, how fast it will grow and whether it will saturate before spoiling the plasma confinement.

Transport codes are used to simulate the time evolution of a plasma in a magnetic confinement device over most of its lifetime. Diffusion coefficients, thermal conductivities, and electrical resistivities are usually obtained from the best available transport theories although sometimes empirical models are used. Up until the last few years the primary effort was devoted to the development of one-dimensional (radial) transport models for toroidal plasmas. Recently the emphasis has been on the inclusion of neutrals and impurities and the extension of the models to non-circular tori. This latter problem has required the solution of one-dimensional transport equations in conjunction with a two-dimensional equilibrium equation.

b) Time Independent Macroscopic Codes

Time independent macroscopic codes are used to compute and study prospective plasma equilibria and to determine their stability using energy minimization principles. The computation of plasma equilibria involves the solution of an elliptic partial differential equation. For toroidal devices in which there is axial symmetry this is a two-dimensional calculation. Several containment schemes, including mirror devices, do not possess an ignorable coordinate. Three-dimensional codes have recently been developed for these cases.

The stability of equilibrium configurations is investigated by calculating eigenvalues of the linearized perturbed equations. Variational methods are employed, and finite elements and Fourier series are used to represent eigenmodes.

c) Vlasov and Particle Codes

Particle codes are fundamental in that they compute in detail the motion of particles under the influence of their self-consistent electric and magnetic fields as well as any externally imposed fields. These codes give phase-space distribution functions, fluctuation and wave spectra, and orbits of individual particles. They are ideal for providing detailed information on the growth and saturation of strong instabilities and the effects of turbulence.

Particle codes are usually classified as either "electrostatic" or "electromagnetic". In the first type only the self-consistent electric field is computed via Poisson's equation and the magnetic field is either absent or constant in time. This was the nature of the earliest particle codes, but in the last five years there has been a considerable development of electromagnetic codes. They are either relativistic and fully electromagnetic (the particle equations of motion are relativistic and the electric and magnetic fields are obtained from the full Maxwell equations) or they assume the nonradiative limit (the equations are nonrelativistic and displacement currents are neglected).

d) Fokker-Planck Codes

In the simulation of magnetically confined plasmas where the ions are not Maxwellian and where a knowledge of the distribution functions is important, kinetic equations must be solved. At number densities and energies typical of mirror machines, the end losses are due primarily to the scattering of charged particles into the loss cones in velocity space by classical Coulomb collisions. The kinetic equation describing this process is the Boltzmann equation with Fokker-Planck collision terms. The use of this equation is not restricted to mirror systems. The heating of plasmas by energetic neutral beams, the thermalization of alpha particles in DT plasmas, the study of runaway electrons and ions in tokamaks, and the performance of two-energy component fusion reactors are other examples where the solution of the Fokker-Planck equation is required.

e) Hybrid Codes

The term "hybrid code" refers to those codes that combine two or more basically different models, and hence two or more

basically different computational techniques. The most prominent example is a combination fluid-particle code. The advantage of a particle code is that it contains the most complete treatment of the physics. Its disadvantage also stems from this feature because it is forced to follow the development of the plasma on the fastest time scale and shortest space scale at which significant plasma phenomena occur. These scales are typically much shorter than the time and size scales in fusion devices. The feature of fluid codes which is attractive is that they treat the plasma on a coarser scale and hence need many fewer time steps and spatial points; however, the motion of certain classes of particles are often crucial. It is clear that proper treatment of such phenomena requires an accurate description of the important class of particles. On the other hand, it is possible to treat the rest of the plasma by means of fluid equations. Another useful hybridization is the coupling of a Fokker-Planck code to a plasma transport code.

The role of the above computational plasma physics models in the main elements of the fusion program--tokamaks, mirrors, alternate concepts, and reactor studies--is described in the remaining sections of this chapter.

THE TOKAMAK PROGRAM

Introduction

The tokamak program constitutes the mainline effort in MFE research. As stated in a previous program document (WASH-1295), there are three key milestones for the success of the tokamak program:

1. Demonstration of confinement and heating in the plasma physics regime of a fusion reactor.
2. Demonstration of thermonuclear burn sufficient to yield net energy gain.
3. Demonstration of the engineering elements necessary for a reactor.

To date most of the effort of the program has been directed toward achieving the first milestone, and great progress has been made. Significant work toward the next two milestones depends critically on the outcome of the first.

As part of the quest for the first milestone, there are several major experimental devices in operation or under construction at various laboratories. Prominent among these are PLT, PDX, and TFTR at the Princeton Plasma Physics Laboratory, Doublet III at the General Atomic Company, ISX-B at Oak Ridge National Laboratory, and Alcator-A and Alcator-C at MIT. Researchers at each of these laboratories, as well as at a number of others throughout the country, are actively involved in obtaining a better understanding of the physics of tokamak plasmas. Obtaining this understanding will require an intensive interplay between experimental results and computer modeling as discussed below.

Equilibrium and Stability

In the study of plasma confinement, the computation of potential plasma equilibria and their stability with respect to MHD modes is of paramount importance.

There are a great many parameters that go into defining an equilibrium; e.g., pressure and current profiles, external magnetic field configurations, limiters, etc. Understanding the role of the different parameters is essential to the successful design and operation of a tokamak. This is highlighted, for

example, by the early experiments in Doublet IIa, when doublet discharges could be maintained for at most 10 ms. After that the doublets would break into droplets or collapse into ellipses. Computer simulation involving a series of MHD equilibrium calculations were made and showed that by proper programming of selected field-shaping coils, doublets could be maintained for longer periods. Experiments were done utilizing such programming prescriptions, and doublets were indeed produced that lasted for 25 ms, i.e., essentially until the end of the discharge. In this instance computer simulation not only elucidated the cause of a troublesome operational problem, but also suggested a remedy.

Another example of the successful use of equilibrium codes is in the design of the ISX-B poloidal field system. Hundreds of thousands of dollars in power supplies and control circuitry were saved by combining the ohmic heating coils, vertical field coils, and D-shaping coils. The actual design was based on extensive optimization using equilibrium codes and resulted in a poloidal field system with great flexibility in producing different shaped plasmas for stability studies. Moreover, the current required as a result of optimization was cut in half. The accuracy and reliability of the design has been proven in the experiment.

Equilibrium codes are now used routinely in designing experiments and mapping out parameter space for optimal operation. (Fig. 3.1)

Once an equilibrium is found, the confinement is determined primarily by its stability to a host of gross MHD modes. The full MHD equations comprise a coupled system of eight nonlinear partial differential equations, the solution of which is a formidable task on any computer system. Approximations have often been made to simplify these equations, such as reduction in dimensionality, linearization, restriction to a particular geometry, ordering or regime, and the assumption of no transport or resistivity. Until a few years ago most MHD codes employed one or more of these assumptions. With the advent of the CRAY 1, models have appeared which solve the full set of equations in two and three space dimensions.

Great progress has been made over the last few years in understanding and predicting the effects of MHD instabilities on tokamak behavior, at least in the linear regime. Some examples follow.

An incipient problem associated with non-circular cross-section tokamaks such as PDX is the possible instability of axisymmetric modes (e.g., vertical displacements of the plasma column). The existence and growth rates of these instabilities depends sensitively on the exact location and circuitry of

Fig. 3.1 A typical MHD equilibrium calculated for Doublet III. The plasma, shown in cross section, is denoted by the dotted contours of constant magnetic flux. The solid, surrounding contour is the vacuum vessel, while the 24 parallelograms are field-shaping coils.

external poloidal field coils. Several multidimensional MHD codes have been used extensively to locate a stable operating regime for PDX free from this instability. A resistive form of this instability with a much reduced growth rate will exist even in the stable operating regime. Two-dimensional time dependent calculations with resistivity are now being performed to study the effectiveness of a feedback device to stabilize this instability over the much longer resistive time scale.

Ballooning modes have been studied analytically since the early days of the MFE program. Indeed they dominated the theoretical discussions in the IAEA Culham conference in 1965. The recognition that the modes studied analytically (which required a short wave length, high-toroidal-number assumption) were highly localized quickly led to the assumption that they would have little effect on the transport, and thereafter interest faded. Extensive computer calculations using a linear MHD stability code led to the recognition that (Fig. 3.2) low-azimuthal-number ballooning modes could form large radial channels that connect the interior of the plasma column to the edge. This led to renewed analytic activity. A study of the computationally determined eigenfunctions led back to the study of high- n localized modes, but with a better interpretation and understanding. The techniques developed in this study are now being applied to extend the theory of resistive ballooning modes, again with close interaction between analysis and computation. This understanding of the ballooning mode has in turn affected machine design. The present generation of noncircular tokamaks is based largely on the prediction that higher stable beta against ballooning modes can be achieved in such devices, as contrasted with those having a circular cross-section. In particular, ISX-B and PDX upgrade with enhanced energy input through neutral beams have been extensively studied to determine the high beta limits set by the ballooning mode.

Although linear MHD stability calculations have made a significant contribution to our understanding of plasma phenomena, they do not address the modes of real interest in present day devices; they merely set optimistic upper bounds on stable operating regimes. Nonlinear MHD problems including the effects of resistivity, by their very nature, defy analytic solution, and one is forced to rely totally on computers. (Fig. 3.3) In order to analyze nonlinear resistive instabilities, the time dependent MHD equations of motion must be solved. The most advanced resistive MHD stability codes are non-linear and three dimensional. This degree of generality is necessary in order to study the coupling of modes. Running times of typical problems are several hours on the CRAY because of the necessity of fine spatial resolution for plasmas with high values of S , the magnetic Reynold's number.

Fig. 3.2 Representation of a ballooning mode in a tokamak. The arrows indicate the direction of the flow in the plasma with the length proportional to the intensity. Note the strong flow from the interior to the exterior in the right half. This shows the disastrous effect of a ballooning mode as it transports plasma from the inside to the outside. Results were obtained from the PEST code.

$t = 1.93 \times 10^{-3}$

$t = 3.80 \times 10^{-3}$

$t = 4.88 \times 10^{-3}$

$t = 1.36 \times 10^{-2}$

Fig. 3.3 Helical flux contours during the evolution of a $m = 1$ magnetic island. The evolution is obtained by advancing the resistive magnetohydrodynamic equations in time.

The case of the disruptive instability is another example of the value of understanding the physical processes in detail. It is now believed that sawtooth oscillations, Mirnov oscillations, and major disruptions are all manifestations of resistive MHD instabilities. This knowledge allows the design of reactors which avoid disruptions. Numerical calculations have demonstrated the possibility of feedback stabilization. This represents a specific proposal to stabilize tokamaks against major disruptions. Specific coil currents and response times have been computed and await experimental implementation.

Detailed three-dimensional calculations are necessary in order to accurately follow prospective MHD modes (e.g., kink, tearing) completely to saturation, taking into account all of the relevant geometrical effects. It is virtually impossible to run such problems on the CDC 7600, except on very coarse meshes which offer inadequate resolution. On the CRAY 1, reasonably accurate simulations are being performed of low-shear systems in which low poloidal and toroidal mode number instabilities are being observed. Since the gradients are not strong, adequate resolution can be obtained. These simulations are giving much insight into the nonlinear processes which saturate MHD instabilities. However, it is still impossible to simulate the nonlinear development of high shear internal MHD modes because of resolution requirements. In the non-linear phase, unstable modes in a device with high shear develop sharp gradients. Adequate resolution of such instabilities (which are believed to be the most relevant experimentally) require an order of magnitude more in computer capability.

Plasma Transport

A plasma transport code provides a relatively complete simulation of plasma behavior on the slow, transport time scale. This entails solving a set of highly nonlinear, partial differential equations for the particle and energy balance. The most advanced codes consider equilibrium evolution, impurity effects, neutral gas puffing and reflux, auxiliary heating, and alpha particle effects. Inclusion of these important physical effects allows more realistic simulation but requires increased computer capacity and capability.

The direct approach to simulating existing tokamak experiments is to adjust the transport coefficients to obtain agreement between calculated and measured results. This approach is presently being used with considerable success to analyze PLT data. In particular, it is found that the electron thermal conductivity varies inversely with the electron density and temperature. However, to establish accurate parametric

dependences of the transport coefficients, it will be necessary to expand significantly the number of discharges analyzed beyond the small fraction that are currently being studied. In TFTR, where the number of tritium discharges will be restricted, it will be necessary to analyze in detail, if possible, every shot.

Transport codes have also proven to be quite useful in the design of experiments and the exploration of new operating regimes. For example, transport computations predicted that large impurity radiation levels could cause hollow electron temperature profiles in TFTR. The hollow profiles were later observed in PLT.

To effectively study tokamaks of noncircular cross-section, it is necessary to couple transport codes with plasma equilibrium codes. These hybrid equilibrium transport codes are already coming into their own, and they will prove to be invaluable in analyzing large tokamaks, such as PDX and Doublet III, on which current penetration is slow compared to energy transport. Thus, transient profiles of current density arise that would be hard to predict from a series of static equilibrium calculations.

Equilibrium-transport calculations have also been used to study plasma evolution in a neutral beam-heated tokamak. It is found that by reasonable adjustment of the vertical field and the current in the primary windings, the beta of the equilibrium can be raised from 1% to 23% without separatrix formation at the plasma edge, appearance of reversed current regions, or undesirable shape changes. However, unless the poloidal fields are properly adjusted, unexpected plasma compression or surface current may result.

To explore the stability limits of plasmas with noncircular cross-section or high values of beta, coupled equilibrium-stability-transport codes are required. A primitive version of such a code is already being used to study ISX-B. It includes ballooning stability calculations and transport effects of sawtooth and Mirnov oscillations. Based on comparisons between this code and experimental measurements, ballooning modes have been tentatively identified in ISX-B. Soft x-ray detectors and flux loops have observed high mode number, high frequency fluctuations localized in the region predicted to be ballooning unstable. Their onset corresponds with the transition to instability calculated by the code, and the mode structure agrees with theoretical predictions. A more complete code, including free boundary kinks and an accurate treatment of resistive modes, would give increased confidence in our physics understanding, but it is beyond the capability of present computers.

Auxiliary Heating

Ohmic heating alone is probably insufficient to attain ignition in a tokamak plasma. Consequently, auxiliary heating techniques are being actively investigated, with the most promising being neutral beam heating and heating by radio frequency (RF) waves.

An important step in the design of a neutral beam system is an analysis of the injector optics. Ion beam optics and extraction are modeled using the Maxwell-Vlasov equations in two or three space dimensions. Effects of various electrode configurations, accelerating potentials, apertures, and other parameters are studied. Discoveries from this modeling have already led to a 30% increase in PLT injection efficiency and a savings of more than a million dollars in beam lines. Examining one two-dimensional configuration requires several hours on a CDC 7600. The three dimensional code will require several tens of hours on the CRAY 1 to study one configuration, and will have to be run sparingly on the present computer system.

Several classes of configurations have been previously examined in two dimensions. Besides an examination of plasma electrode shapes which allows a reduction of aberrations, several inventions have been made which will find application in future neutral injectors. These include: a) sheath mitigated aberrations in two stage acceleration with high field ratio, b) reduction of aberration effect by application of a preacceleration potential, c) plasma elimination of aberrations in a single stage accelerator by application of reverse bias of that in case b), d) reduction of aberrations by the method of mutual exclusion.

Future studies include such interesting 3-D problems as cylinder operative displacement steering, the effect of a transverse source plasma density gradient on beam steering in cylindrical geometry (will also be studied in 2-D slot geometry), the effect of non-parallel electrodes and other tolerance effects on beam optics, effects on beam optics due to end effects in slots, and effects of adjacent beamlets on beam optics. Direct recovery studies with transverse magnetic fields for electron blocking will be studied.

The important role of computing in the area of neutral beam injection has been recognized for more than a decade. Multi-species Fokker-Planck calculations of the expected Q in mirror machines have played a driving role in the conceptual evolution of the mirror program. As a result, a developed computational base was available to tokamak researchers when the

first tokamak neutral beam tests were proposed in the early 70's. With the advent of the MFECC the models for neutral beam heating in tokamaks have been advanced to the stage where direct comparison with experiment is meaningful. A computationally demanding task is determining the spatial profile of energy deposition in the plasma due to neutral beam heating. A common approach to this problem uses a Monte Carlo code to obtain the hot ion birth rate and a Fokker-Planck code to follow the slowing down of these hot ions. Because of computer limitations, current Fokker-Planck codes utilize fewer than the six dimensions of physical phase space. The most advanced Fokker-Planck codes (Fig. 3.4) consider one space and two velocity dimensions. Extension to higher dimensions will require greater computer capability. Comparisons of computation and experiment have confirmed the utility of the classical model for fast ion thermalization. These models are heavily relied upon for the planning of the tokamak program. Some examples follow:

1. TFTR is expected to achieve break-even with D-T operation. This expectation is based directly on confidence in knowing the fast-ion distribution from computer calculations and on avoiding less reliable extrapolation in $n\tau$. Fokker-Planck/transport calculations for TFTR are used to justify this confidence.
2. In describing PLT results, the 100 watt D-D neutron output was reliably quoted as a 50 kwatt equivalent D-T output. This can be done only if there is confidence in knowing the fast-ion distribution.
3. At the time PLT attained record-setting temperatures, the experimentally measured neutron flux sharply disagreed with Fokker-Planck code predictions. This disagreement led to a thorough investigation, upon which it was discovered that the calibration was incorrect and that the measured neutron flux was 2 to 3 times greater than originally believed, thereby bringing the code predictions and experimental measurements into line.
4. In PLT, Ormak, and ISX direct comparisons of Fokker-Planck calculations with measured charge exchange spectra have been made, allowing the discrimination between bulk and fast-ion energy.
5. Counter-injection has been found, experimentally, to give worse results than co-injection. Little experimental time is lost in trying to optimize counter-injection, however, because of confidence in the

Figure 3.4

Three-dimensional computer-generated plots of deuterium distribution function for a typical PLT case, in which both parallel and anti-parallel 40 keV neutral beams are injected into a Maxwellian background plasma. In (a) only the energetic component is displayed, whereas in (b) the total ion distribution function (energetic + bulk plasma) is shown. The variable θ is the pitch angle (radians) and the variable X is normalized speed ($X = E(\text{keV})^{1/2}/15$).

theoretical/computational results which ascribe this behavior to unconfined, or poorly centered, fast-ion orbits.

6. Neutral beam deposition calculations for Doublet III have disclosed an important sensitivity to target plasma density, and have led to the Density Enhancement Program currently carried out on that device.
7. Control of strongly beam heated plasmas requires knowledge of the beam contribution to plasma pressure. As this cannot be directly measured, computational results are used as input to the planning of the feedback system. Moreover, the beam pressure is included in theoretical assessments of critical β , which are especially important in scenarios for low density heating to ignition.
8. Recently, attention has been drawn to the diminished n_T requirements for ignition in the "hot-ion" mode, in which $T_i \gg T_e$. Favorable prospects for actual operation in this mode are directly due to the convincing detail with which the hot ion component can be compared with (computed) theoretical expectations. No such detail is yet possible for the electron component, although recent progress in analytic theory (turbulent destabilization of drift modes) and in nonlinear resistive MHD has narrowed the gap.
9. Neoclassical ion confinement theory for tokamaks, when incorporated with multi-process transport codes, has been a reliable guide to predicting the outcome of neutral beam heating experiments since their beginning, lending credence to the mainline tokamak program.

Plasma heating through RF waves has also attracted considerable attention. Recently, experiments were done on Doublet IIA to evaluate the effectiveness of RF heating. At first, no significant heating occurred regardless of the antenna and plasma parameters tried. Then a zero-dimensional analytic theory was derived that showed the existence of an operating window in the wave number/plasma temperature parameter space. This operating window was subsequently corroborated and refined by computer simulation using a one-dimensional transport code. Bolstered with this new theoretical insight, the experimental operating conditions were modified, and significant RF heating was observed.

One dimensional theory is not able to adequately explain experimental results at the higher intensities which are more

typical of those needed for heating large plasmas to fusion temperatures. Two dimensional nonlinear effects are now being investigated. One study involves solving a two-dimensional Fokker-Planck equation, containing a quasilinear electron Landau diffusion term, to compute the effects of an applied dc electric field and electron transport due to a braided magnetic field on lower hybrid heating and current drive. This two-dimensional nonlinear Fokker-Planck problem requires a high resolution mesh, and to achieve the desired accuracy, it must be run on the CRAY 1. Another two-dimensional study employs an electrostatic particle simulation code, which requires several hours per run on the CDC 7600.

Boundary Effects and Impurities

The role of impurities in tokamak behavior is complicated by the need to add sophisticated atomic physics calculations to the already difficult problem of transport. Here the role of the computer becomes central to an understanding of the problem; for example, partially ionized tungsten with fifty bound electrons has a complicated level structure with thousands of possible transitions. Compared with simple estimates, the computations predict radiation levels that are sixty times stronger. Such calculations have predicted high radiation levels in tokamaks with high-Z limiters made of materials such as tungsten; this was later confirmed by the experimental results on PLT and ORMAK. Subsequently the tungsten limiters were replaced by low-Z limiters, resulting in reduced radiation losses and higher central temperatures.

This area of physics will become increasingly important as we head into the reactor phase, and newer, highly sophisticated numerical techniques will have to be developed to solve the problems.

Microinstabilities and Turbulence

A very important area is that of kinetic instabilities, which will play a key role in determining confinement times and establishing scaling laws. Only now, computational capabilities in kinetic instabilities, particularly trapped particle and drift modes, are beginning to approach those in fluid models. (Fig. 3.5) The reason, of course, is that handling the additional velocity space dimensions is extremely difficult.

An example of an application of these models is provided by the recent PLT results, where at the highest neutral beam powers and ion temperatures, enhanced fluctuations have been observed by

Fig. 3.5 Absolute magnitude of the eigenfunction $\tilde{\phi}(\theta, s)$ of the perturbed electrostatic potential for the trapped-electron mode. The eigenfunction was obtained from a two-dimensional linear eigenfunction-eigenvalue code, using an artificial set of tokamak equilibrium profiles with non-constant equilibrium gradients. Here θ is the angle the short way around the torus, with magnetic field minima at $\theta = 0$ and at $\theta = 2\pi$, and a magnetic field maximum at $\theta = \pi$. Also r is the toroidal minor radius, r_0 is the radius of a reference mode-rational surface, and Δr_s is the spacing of mode rational surfaces.

Figure 3.5

microwave scattering diagnostics. These modes have been tentatively identified by means of the codes mentioned above as being combinations of the usual trapped-ion and trapped-electron modes, driven by a strong ion temperature gradient. (Fig. 3.6)

The importance of understanding kinetic instabilities is brought out by the surprise that PLT was able to achieve 6 keV temperatures in the collisionless regime without the loss of confinement due to trapped particle modes that were predicted by crude analytic theory. It can be just as bad to design experiments to avoid nonexistent instabilities as to lose confinement due to the appearance of an unexpected instability.

Computational work in the area of turbulence is fairly young, although there is clear experimental evidence that many phases of tokamak discharges are turbulent. Both linear and nonlinear stability codes show the formation of convective cells when instabilities saturate. The effects of these on plasma confinement are not well understood. Various analytic theories--strong or weak turbulence, quasilinear theory, ergodic theory--have been developed to study these processes, but the many assumptions required makes them suspect in practice. A larger class of computer will probably be required to make much headway in these areas.

Particle simulation codes are potentially very powerful in leading to an understanding of the physics of microinstabilities in tokamaks. A particle simulation model consists of representing the physical domain in one to three dimensions as a grid of points where interesting field quantities, such as the electrostatic scalar potential, electric field, magnetic vector potential, etc. are evaluated and maintained. This domain is filled with particles--electrons and ions--whose individual positions and velocities have to be calculated. The mass ratio of ions to electrons influences the time scale, and hence frequencies, of the modes observed in the system.

Particle simulation codes have grown from simple one-dimensional electrostatic models to three-dimensional electromagnetic models. The three-dimensional models are still quite limited. Grid sizes have not changed significantly. Mass ratios have changed from the earlier 100 or so to more realistic values like 2000. This means that we can simulate full three-dimensional electrostatic models with plasmas of dimensions up to about 100 ion gyroradii (in the range of ATC to PLT). Time steps are determined by the ion plasma or cyclotron frequency. It is impractical to work on the faster time scales associated with electron motion, which means that we cannot look at electromagnetic instabilities such as drift-Alfven or drift-tearing modes. An electromagnetic model requires much more

Fig. 3.6 Temperature dependence of the real frequency ω_r and the growth rate γ for a hybrid of the trapped-ion mode, the trapped electron mode, and the ion-temperature-gradient-driven drift mode. The equilibrium density and temperature profiles used are typical of the neutral-beam-heated PLT tokamak. Their shapes are held fixed while the ion temperature at the magnetic axis $T_i(r=0)$, is varied. These results are computed using a two-dimensional linear eigenfunction-eigenvalue code.

Figure 3.6

memory since there are more field variables. To accommodate these field variables requires reducing the number of grid points, thereby making the problem less useful.

Nevertheless, particle simulations are beginning to demonstrate their usefulness in elucidating anomalous transport. For example, the strong turbulence spectrum observed in tokamak experiments has been shown by three-dimensional computer simulations to be associated with the drift wave instabilities that generate convective cells and strong plasma turbulence. (Fig. 3.7) This discovery is important for the scaling of plasma diffusion. As another example, the anomalous diffusion observed in octupoles at General Atomic and the University of Wisconsin is in complete agreement with the convective cell diffusion studied in detail by means of computer simulation and theory. Without the simulation results, the diffusion scaling observed in octupoles might not have been explained.

Fig. 3.7 This figure indicates the orbits of a set of test particles sampled in a three-dimensional particle simulation of collisionless drift instabilities. Each dot represents the guiding center location of an ion sampled initially to form a ring half way to the wall from the center of a plasma column. It can be clearly seen as the instability develops in time that the ions form vortices or convective cells associated with the nonlinear motion. Anomalous cross field diffusion is greatly enhanced once vortices are formed which gives a diffusion larger than the quasilinear diffusion associated with the drift instabilities. Nonlinear plasma theory was developed to explain the excitation of vortices from the drift instabilities and is in good agreement with the numerical simulations.

THE MIRROR PROGRAM

Introduction

The mirror research program in the U.S. is rapidly expanding, based on the success in producing high β , high energy plasmas in 2XIIB at Lawrence Livermore Laboratory (LLL) and the computational understanding of the machine's performance arising from the Fokker-Planck models including quasilinear diffusion. The various technologies of 2XIIB are being scaled up, leading to a powerful and flexible experiment, the Mirror Fusion Test Facility at LLL. Theoretical and computational understanding of a single mirror cell has reached a very high level with good descriptions of 3D equilibrium, particle orbits, plasma stability, losses, and neutral injection. However, the single mirror cell leads to a marginal fusion reactor.

The tandem mirror idea uses a high energy mirror cell, at each end of a long solenoid, to electrostatically confine a nearly Maxwellian, fusing plasma in the center. (Fig. 3.8) Since this plasma is close to thermal equilibrium, the physics is quite similar to that of tokamak plasmas but the multiple mirror configuration separates ions and electrons into several groups and makes the models more elaborate. Present efforts are directed towards combining the physics of single cell mirrors, thermal plasmas, and the new features introduced by strong electrostatic fields. These combinations are leading to larger and more complex codes than previously used.

A second major product of the 2XIIB experiment is the development of neutral beam supported, reversed field mirror plasmas. The 2XIIB experiment reached plasma pressures almost sufficient to reverse the external magnetic field at the plasma center. Experiments at Los Alamos have generated such configurations in a θ -pinch, and ion and electron ring experiments at Cornell and NRL have also achieved field reversal. In order to achieve the same with neutral beams, the Beta II experiment at LLL will produce a reversed field ring from a plasma gun, catch the ring in a mirror, and use it as a target for neutral injection. The physics of these plasmas is comparable with toroidal plasmas but there is no externally produced toroidal field, the β is predicted to be high, the aspect ratio is around 1, and many high energy ions will have Larmor orbits comparable with the ring size. The reversed field computational effort is growing and is guiding the experimental effort.

COMPUTATIONS FOR TANDEM MIRRORS

1. Design of accelerators, neutralisers, and ion sources for neutral beams
2. End losses, Secondary electron emission, $T_e(Z)$
3. High β , particle & MHD equilibria
4. Baseball and other coil design — stresses & fields
5. Neutral beam penetration, heating, & buildup

6. Radial penetration of cold neutral gas
7. Neoclassical radial transport, based on banana orbits
8. Cyclotron R.F. instability simulation
9. Stochastic heating of low energy ion by R.F. in end plug
10. Circuit & power supply design
11. Self consistent quasilinear diffusion & Fokker Planck

Figure 3.8

The computer models now actually in hand or being actively developed represent a considerable advance over those used even a year ago, and the demands for computer time are going up accordingly, e.g. a 3-D time dependent MHD project. Particle models are now being extended into new regimes by long-time-orbit average techniques and by three-dimensional linearized codes. The following sections give more technical detail of all of the larger computational efforts, and some of the fundamental physics which can be addressed by simple codes, for the MFTF, Tandem and Reversed Field Mirror programs.

MHD Equilibria and Stability

The calculation of equilibria for mirror configurations is more complicated than that for toroidal devices. It is not possible to obtain an adequate description of an equilibrium with a simple MHD model. Single cell mirror equilibria have been described using a guiding center model. This requires the iterative solution of magnetic differential equations and an elliptic equation, all in three dimensions.

Another type of equilibrium calculation is obtained by running a particle code to steady state. Such calculations do not require any assumptions as to the size of gyro-orbits, and are hence more realistic in that sense. This is currently being done in mirror calculations in a two-dimensional domain by assuming axisymmetry. It should be emphasized that this is a limitation imposed by the memory and available computer time on the existing CRAY-1, and could be relieved by additional computer capability.

There are two different approaches to MHD stability calculations. In the first, one simply follows the evolution of a perturbation in time, using a standard (three-dimensional) MHD code. The application of this approach to mirror machines is progressing rapidly. It is clear that runs to follow a single mode will require of the order of 2-3 hours of 7600 time. The 3-D MHD code MALICE has been adapted to field reversed θ pinch and FRM geometries. It has been used to model both the stable state of nonrotating equilibrium and the ensuing $m=2$ instability that occurs when rotation is induced. (Fig. 3.9) The other type of stability calculation is a variational calculation to determine whether a given equilibrium represents a minimum in potential energy (and is therefore stable). This technique is well-developed for toroidal configurations and is under development for mirrors.

Fig. 3.9 Final state of the nonlinear evolution of the ideal MHD, rotational, $m = 2$ instability is shown in an end-view of a 3D calculation. The computational grid distorts near the plasma. Marker particles, loaded proportionally to the initially circular density profile, follow the plasma motion. The spiral arm structure is an effect of the conservation of angular momentum. This simulation replicates the breakup of the FRX-A plasma in experiments at LASL, and is a collaboration of the LLL and LASL computational physics group, made possible by the MFE Computer Center.

11.4 MSEC.

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Figure 3.9

Kinetic Instabilities - Particle Simulation Codes

Previously the SUPERLAYER particle code, an ion-only, 2-D, magneto inductive code was used to model the buildup by neutral injection of a high β plasma in 2XIIB. The code included an accurate neutral beam deposition model, including both ionization and charge exchange, and a Monte Carlo model for the quasilinear velocity space diffusion. The code agreed with the experiment in certain features such as the ion velocity distribution, thus demonstrating the importance of the quasilinear diffusion. The virtue of the code is that it can accurately calculate self-consistently the effects of large ion orbits, a task which is impossible with analysis alone. Even so, to simulate realistic experimental runs in 2XIIB required a large acceleration of time scales. New techniques of orbit averaging over long times now promise to remove this limitation and to greatly extend the applicability of this model. In this form the code should be able to accurately model the interaction of ion-cyclotron RF with a finite beta (non-reversed) plasma using a direct application of a coherent RF electric field, thus extending our knowledge of stochasticity and superadiabaticity.

With the advent of the orbit averaging, the SUPERLAYER code will also be applicable to certain models of tandem mirror physics, including the interaction of a stream plasma, the ambipolar field (prescribed), and RF in the plug. The new idea of thermal barriers, an important recent advance in tandem mirror theory, can also be simulated.

In order to examine the stability of field reversed mirrors, a 3-D linearized particle code, in the form of a quasi-neutral Darwin model using particle ions and fluid electrons is being developed. In this form the model is a kinetic MHD model and it displays a rich variety of physics, including ion kinetic instabilities as well as lower frequency MHD-like modes with finite Larmor radius effects automatically included.

In order to examine the effects of realistic nonlinear micro-instabilities the one dimensional (x, v_x, v_y) particle simulation code ESI has been extended to higher dimensions $(x, y; v_x, v_y)$ and more recently $(x, y, z; v_x, v_y, v_z)$ for purposes of studying driftwave microinstabilities. The new codes use a hybrid description, cold fluid electrons and particle ions, and solve Poisson's equation for the self-consistent electrostatic field. The first of the two new codes has been applied to the study of linear and nonlinear drift-cyclotron and drift-cyclotron-loss-cone (DCLC) instabilities. DCLC has been experimentally shown to control particle and energy confinement in conventional mirror experiments, while drift-cyclotron is a

residual instability in mirrors and is thought to be quite dangerous for the central cell of the Tandem Mirror Experiment. The newest of these codes includes ion-bounce motion in a nonuniform applied magnetic field $B_0(z)$ and allows the investigation of DCLC and ion-bounce-mode instabilities. This code represents a significant advance in computer simulation of mirror experiments in that essential physics aspects, e.g. quasilinear velocity-space diffusion, superadiabaticity and stochasticity, anisotropy, mirror losses and stream stabilization, are incorporated in a self-consistent manner.

Rather than detail the computer time and memory requirements for each particle code, the needs for one major code, which has been highly optimized, can be described. The main points are: 1) long runs are common, some even exceeding 60 hours of 7600 time, 2) extension to more complex problems will require core memory of 2 or 4 million words and addition of a very large, high-bandwidth serial-access memory.

Energy and Particle Balance in Tandem Mirrors

The proposition that a stable mirror plasma will yield net thermonuclear power hinges critically on the rate at which particles are lost out the ends of the device. In the absence of turbulence and at number densities and energies typical of mirror machines, the endlosses are due primarily to the scattering of charged particles into the loss cones in velocity space by weak, classical Coulomb collisions. The kinetic equation describing this process is the Boltzmann equation with the Fokker-Planck collision term.

The numerical solution of the Fokker-Planck equation has long been a basic tool of mirror research. Multispecies codes of both one and two dimensions in velocity space have been used to determine endlosses, distribution functions and fusion energy production rates under a wide variety of hypothetical reactor conditions for both D-T and D-D systems (including reaction products). These calculations have led to a much greater understanding of the behavior of a reacting plasma and have bolstered confidence that breakeven can be attained.

In order to model the 2XIIB experiment at LLL, Fokker-Planck codes have been modified to include the effects of RF diffusion due to quasilinear turbulence. (Fig. 3.10) Such calculations have played a vital role in explaining 2XIIB results on a daily basis and have provided a general understanding of 2XIIB operation with a cold plasma stream. Predictions of behavior in MFTF are now underway.

THE DISTRIBUTION FUNCTION AT $T = 3.507E-05$ $F_{MAX} = 4.6031E-02$

Fig. 3.10. Ion distribution function $F(V^2, R)$ during a buildup of a 2XIIB plasma with gun plasmas and neutral beam injection. A peak at $V^2 = 0$ represents the stream and other two peaks at $V^2 = 8$ keV and 18 keV are neutral beams, broadened by quasilinear diffusion due to plasma turbulence. The calculation used the most fundamental description of plasma scattering in velocity space - the Fokker Planck model - modified by a quasilinear model of plasma turbulence at the ion cyclotron frequency. Radial and energy variations of the plasma distribution can be checked experimentally, and such codes are essential in design of future machines.

Fokker-Planck codes have played an important role in understanding tandem mirror scenarios. For this it has been necessary to represent reacting ions in the central solenoid along with ions in the two end plugs, and to properly couple these regions. Additionally, the modeling of complicated velocity-space loss regions, the computation of a consistent ambipolar potential profile (Fig. 3.11), and consideration of disparate timescales in the plugs and solenoid have made this a formidable task.

In a tandem mirror device minimum-B (nonaxisymmetric) mirrors at either end of a solenoidal central cell provide electrostatic plugging for ions in the solenoid. Recent work has shown that the presence of nonaxisymmetric (quadrupole) field components in the transition regions at the ends of the solenoid can lead to significant radial transport of solenoid ions. This transport can be particularly large when there is a resonance between the azimuthal drift and bounce motions. Estimates have indicated that resonant radial transport should be small in comparison with axial endloss in the LLL Tandem Mirror Experiment (TMX), but may, depending on parameter choices, be significant in a reactor.

Radial transport codes designed to investigate this phenomenon are already operational. These codes are currently one-dimensional and quite simple. However they consider only a narrow aspect of the total particle and energy balance in a tandem mirror device, and more sophisticated versions will be necessary. For example, more detailed treatment of azimuthal asymmetries due to the endplugs will increase the dimensionality to two spatial dimensions, as well as increasing the amount of physics detail treated. Another development is the coupling of a Fokker-Planck treatment of energetic particles to the transport equations in order to study the effects of neutral beam heating. This will add two velocity space dimensions to the problem. In addition it will be necessary to consider the transport of neutrals arising from processes such as gas puffing, recycling and neutral beam injection. Because of the complicated geometry, a Monte Carlo code will be required. It is expected that tandem mirror transport calculations will require a significant amount of computer power.

Adiabatic and Transport codes for Field Reversed Mirrors

The translation, trapping, heating, and decay of a field reversed plasma ring in the BETAIL experiment can all be described by axisymmetric codes. The appropriate models eliminate analytically the fastest time scales of Alfvén and sound wave propagation, to leave adiabatic equations which

Fig. 3.11 Self-consistent axial profiles of electron density, ambipolar potential, and electron temperature for 2XIIB at two gas box currents as calculated from the electron Monte Carlo code. The gas box is located at $Z = -0.8\text{m}$. The peaked electron temperature for the low current case shows the thermal isolation which occurs in mirror machines due to electrostatic confinement for long mean-free-paths. The temperature profile for the large current case shows a situation dominated by axial thermal conduction at moderate mean-free-paths.

Figure 3.11

describe a sequence of connected equilibria which slowly decay by transport and charge exchange. These fluid codes are mathematically complex and follow the time dependent plasma flows, constrained to be in 2-D equilibrium, coupled to 1-D radial plasma loss across the magnetic field. The radial transport model is the same as that for the tandem mirror for collisional plasmas. As the plasma is heated by neutral injection, the collision frequency eventually drops below the bounce frequency of individual particles in the magnetic field and the transport properties become non-local. The neoclassical transport theories take account of these effects, and need to be evaluated for each new plasma-field configuration.

The gun injection and pinching off of a field reversed plasma for BETA II is being modeled by a two dimensional MHD code. (Fig. 3.12)

(a) Location of gun electrodes and aperture

Fig. 3.12 This is a 2D Eulerian MHD calculation of field-reversed plasma ring formation. The muzzle of a Marshall-type plasma gun is placed 25 cm behind a conducting aperture. A pulsed coil inside the aperture is modeled by time dependent boundary conditions on the vector potential A_θ . Poloidal magnetic flux lines are plotted after the coil has been turned on and magnetic field line reconnection has occurred under the coil.

ALTERNATE CONCEPTS

Introduction

The importance of alternate concepts to the national fusion energy program has recently been emphasized by the recommendations of the Foster Committee. In this section the impact of computational physics on both past and future efforts in these areas will be briefly discussed.

The discussion is broadly divided into sections by device or concept along the lines of the recent Concept Review Committee report on Proof-of-Principle experiments. The first section is concerned with EBT (ELMO Bumpy Torus), which has been recommended for a major Proof-of-Principle (POP) experiment. Since this program will be the scientific equivalent of PLT, it seems clear that a major computational effort will be required in the near future. The second section deals with the Reversed-Field-Pinch (RFP). This concept was judged potentially eligible for a POP experiment if present experimental and/or theoretical work should prove successful. Again, the resolution of these problems will depend critically on an accelerated computational effort. The third and final category contains concepts whose readiness for a POP experiment is not established on technical grounds, but which nonetheless may involve fundamental physics and engineering questions. These include the Reversed-Field-Theta-Pinch (RFTP), the Fast Liner Experiment (FLX), and devices based on the Stellarator concept. Here the need for extensive computational work is perhaps the greatest in order to address questions which cannot be answered experimentally due to lack of funding.

EBT

EBT offers a number of features that may lead to an attractive fusion reactor. Among these are: steady state operation, modularity, easy access for maintenance, simple magnetics, absence of axial current (i.e., removal of one source of free energy), absence of disruptions, and potential availability of several heating options. Potential disadvantages of an EBT reactor are: scaling laws which may preclude small unit sizes (i.e., less than 750 MWe), possible difficulties with ash and impurity control which could preclude steady state operation, and the necessity of driving the rings continuously. The EBT reactor shows promise for overcoming some of the alleged disadvantages of tokamak reactors, namely pulsed operation, poor

access, and difficult maintenance. For these reasons EBT has been designated as a proof-of-principle (POP) experiment. Since a POP experiment can be considered the scientific equivalent of PLT in the tokamak program, a greatly expanded computational effort will be required. The most important areas of investigation are discussed below.

Particle Orbits

Energy containment, equilibrium, stability, and transport in EBT all depend essentially on individual particle orbits. Because the magnetic configuration is a closed line torus with no rotational transform or resultant flux surfaces, particle containment relies on the drift velocity produced by the bumpy fields. This essential difference between the tokamak or stellarator and the EBT means that an independent assessment of single particle confinement is required for EBT. Computation of particle orbits must be fully 3-D because EBT lacks axisymmetry. Knowledge of orbits in fields generated by different coils, hot plasma, and divertor configurations is required for optimal machine design and for general physics understanding of EBT-P. Particle orbits in EBT are affected by the plasma diamagnetic currents, ambipolar electric fields, and toroidal effects. For example, a particle which is mirror confined to a single cell on the inside of the torus may, after drifting in the poloidal direction, become a passing particle as it moves to the outside of the torus.

An extensive computational effort is in progress to investigate particle orbits in EBT for determining optimal confinement and as an input for calculating transport coefficients. An important impact which this effort has already made on the EBT program is the concept and design of aspect ratio enhancing (ARE) coils. Confinement improves with large aspect ratio, but since this leads to a larger, more expensive device, it is impractical beyond approximately 40-1. ARE coils modify the magnetic field of a simple bumpy torus to approximate the confinement of an otherwise larger aspect ratio torus. Computer designed ARE coils will be tested on EBT-S in FY80. If they perform as expected they will increase the effective aspect ratio by over 50%, at a very modest cost.

Thermal particles orbits are determined sufficiently accurately by using a small gyro-radius approximation (guiding center model), which saves considerable computer time. The simplest codes include only the vacuum fields from the external coils, but to follow accurately some classes of particles it is essential to include the field modifications due to finite beta plasma currents as well as the ambipolar fields.

For the relativistic electron rings it is essential to compute the exact particle orbits (including the gyro-motion) because the large gyroradii do not allow a guiding center approximation. Such codes require an order of magnitude more computer time than a guiding center code, but they have already shown that confinement of the hot electrons is not adequately modeled by the guiding center approximation. This fact has implications for the microwave heating requirements in a reactor.

Equilibrium and Stability

Although EBT does possess mirror symmetry along the magnetic axis, it is not toroidally symmetric. As a result, EBT (Fig. 3.13) equilibria cannot be analyzed as a two-dimensional problem. While this precludes the use of existing tokamak equilibrium codes, three-dimensional techniques have been developed and have been brought into use via the MFECC Network. Equilibrium solvers for straight bumpy cylinders are also useful. Although toroidal effects are absent in these solvers, these simpler codes are sufficiently economical to permit broad exploration of high-beta effects, particularly in the large aspect ratio range relevant to the EBT-P experiment.

Macroscopic stability theory requires investigations of both ideal and non-ideal MHD and guiding center fluid models. Some codes are already in place which can be used for this purpose either as they now are constituted, or they can be upgraded to include additional effects in the near future. Some studies will require new codes.

Codes of this type are costly in terms of memory requirements and running time. The resulting computational effort will put a strain on existing facilities. Computing one 3-D equilibrium requires approximately one hour of 7600 time, depending on required resolution. Optimization or parameter studies require many equilibria.

Comparable computational effort is required in the area of microstability. Judicious modeling will allow a continuously improving understanding of microstability with a capability for impact on the interpretation of data not only from EBT-I and EBT-S, but from EBT-P. This research may be vital to understanding the transport scaling of EBT should the neoclassical model fail to account for observations in EBT-P.

Fig. 3.13 Magnetic field configuration of ERT. The dotted lines represent magnetic field lines, and the solid lines represent surfaces of constant B . $\beta = 0$ corresponds to vacuum conditions (no plasma in cavity) and $\beta = 0.5$ corresponds to a hot electron annulus whose pressure is equal to half the vacuum magnetic field pressure. This shows the effect of the hot annuli on the field. The rings in the center enclose a region of minimum magnetic field, which is favorable for confinement of the plasma.

Transport

Given the existence of macroscopically stable equilibrium for steady state EBT operation, transport processes will ultimately determine the economic feasibility of the concept as a reactor. In the more immediate future, an understanding of the possible transport mechanisms in EBT will be essential to interpreting data from EBT-S and EBT-P.

One of the more controversial issues in the recent past has centered around the transport scaling of EBT. Available theories predict that if the dominant transport loss is neoclassical, then EBT possesses very favorable scaling properties. The desirability of EBT as a reactor concept resides, in large measure, on the hope that such a favorable scaling will in fact prevail. On the other hand, the possibility exists that there may be microinstabilities in EBT which cause anomalous transport to be an important contributing mechanism at higher temperatures. If this should be the case, the advantages of an EBT reactor over other reactor concepts may be marginal. Existing experiments and the available data base are consistent with neoclassical losses but are inadequate to permit confident extrapolation to hotter and more dense versions of EBT.

In order to assist in the accurate identification of the dominant transport mechanism and to exploit the implications of the observed scaling, such as reactor dimensions and profile control requirements, an increased effort in transport theory and computation is underway. The major thrust of this effort is in neoclassical transport. However, possible anomalous transport mechanisms must also be considered. These programs involve the calculation of transport coefficients for both ions and electrons. The neoclassical effort includes the effects of non-Maxwellian distributions and Fokker-Planck calculations. These efforts will ultimately require input from particle orbit and equilibrium codes.

Transport simulation and fueling theory initially utilized 1-D and 1-1/2-D codes. Classical macroscopic transport codes in two and three dimensions are being developed. Kinetic modeling is aimed at the need for reliable estimates for electron transport in the presence of a microwave (heating) field. This field provides enhanced scattering, as well as producing a high energy tail on the electron distribution. Present codes solve for a simplified form of the poloidal variation of the distribution function. Codes which include pitch angle variations will be required in the future. This problem is marginally within the present computational capability.

Recent success in extending transport computations into the collisionless regime have increased confidence that EBT is neoclassical. The agreement between experiment and computation on the ambipolar electric field has been a key test of the theory. The importance of the wall particle reflux in determining the gross transport behavior of the plasma, first discovered by computation, complements an experimental program to study the plasma-wall interface. This study also has implications for long pulse tokamaks and mirrors, whose wall interaction will more closely approximate that of the steady state EBT.

Heating

Past EBT experiments have operated at toroidal plasma ion and electron temperatures limited to approximately one hundred eV and several hundred eV, respectively. These experiments utilized ECRH (electron cyclotron resonance heating) to both drive the annular rings and heat the toroidal plasma. ECRH power generation technology and overall power requirements limited both the operating density of these experiments and the power available. It is expected that EBT-P will be limited by similar considerations. An understanding of ECRH (coupling of input power to other plasma modes) is thus fundamental to the understanding of EBT physics. A major computational and theoretical effort is underway in this area. The basic technique is the use of geometrical optics (ray methods) to follow the electric field into the plasma through various regions of absorption, reflection, and tunneling. The geometry and field are derived from finite 3-D equilibria, although these are not as yet self-consistent with the heating profile.

Additionally, it is possible that other heating mechanisms may be necessary if EBT-P is to achieve the temperatures required for successful demonstration of the EBT concept. Codes which model neutral beam injection and other forms of RF heating, such as ion cyclotron, lower hybrid, and Alfvén wave, will thus be required.

In summary, the computational program in support of EBT has led to better and cheaper experimental design, has given confidence in the physics involved, and has led to discoveries which will improve EBT-P and EBT reactors.

RFP

An RFP reactor has certain attractive features such as the possibility of ohmic heating to ignition, batch burn capability

(which eases refueling and ash removal), low stresses on the superconducting coils, better accessibility than tokamaks, and low probability of disruptions. However, there are some difficulties that need to be resolved. There are no demonstrated alternatives to ohmic heating for supplemental or backup heating at this time, an efficient energy storage and transfer scheme is required, and the possibility exists that plasma feedback control will be needed during the formation stage. Computational studies are now underway which address these and related questions. The net result is that, while the RFP reactor may offer some significant alternatives, it may not offer substantial engineering advantages over tokamaks. This assessment obviously could change if RFP physics experiments (such as ZT-40 at LASL) or the results of computational and theoretical studies prove very successful.

The RFP, however, is of considerable interest from a physics viewpoint. Specifically, the RFP configuration is near a minimum energy state for the combined plasma/magnetic field system and may well provide important, fundamental information on axisymmetric toroidal confinement configurations (of which the tokamak is one) which could change our approach to reactor designs for such systems. In light of this, and the fact that a large proof-of-principle RFP experiment will not be built in the U.S. at this time, large scale computational efforts would seem to be the most cost-effective means of gaining understanding of basic RFP physics. Specific areas for such research are described below.

Transport

A considerable part of the computational support of the RFP program involves the development and understanding of the necessary electrical circuitry required during the start-up phase of the pinch. A one-dimensional hybrid simulation code is being employed to ascertain the plasma profiles due to various combinations of external fields. Rise times are of particular importance. Zero- and one- dimensional codes have been very useful in the simulation of the behavior of present experiments and in the prediction of the behavior of future ones.

To explain the observed rate of field diffusion during start-up, anomalous transport is necessary. This requires a knowledge of the basic plasma physics of RFP devices. Such efforts have received increased computational support as the ability to model general microscopic plasma phenomena has grown. These calculations not only support analytic theory but also provide macroscopic transport parameters for transport codes.

The lower hybrid drift instability simulations which have been performed recently provide an excellent example of such basic plasma physics research made possible only by numerical methods. These simulations provided nonlinear saturation levels for this instability by following the evolution of the associated turbulence as it grows from perturbations in the initial equilibrium. This work used the particle-in-cell model for both ions and electrons, and consequently required time integration on the electron time scale. For such work to remain feasible in terms of computation time, artificially small values of the mass ratio were used and gradient length were made nonphysically short. This sort of computational scale modeling provide qualitative understanding of the mechanisms which are causing these instabilities. With this understanding and scaling behavior obtained from several runs, extrapolations are made to determine the consequences of the instability in more realistic parameters. The accuracy of such extrapolation is much improved by reducing the extrapolation distance. Such reductions are possible only with increased CPU speed and memory.

MHD Stability

Analytic work on ideal MHD stability clearly demonstrates the existence of stable high β configurations with significant vacuum regions out to a conducting wall. However, as much of the analysis has been in one-dimension, and in view of the fact that some future experiments may operate with a relatively low aspect ratio, it seems desirable to employ existing linear stability codes (e.g., PEST/ERATO) to investigate the stability of toroidal free-boundary RFP's at high β . The three-dimensional non-linear evolution of these modes can be studied with existing codes.

Past experience has shown that stability against ideal modes may not be sufficient, and that resistive instabilities must also be considered. Several codes, based on both initial value and eigenvalue concepts, are currently in existence and have shed light on stability boundaries imposed by these modes on RFP's. Additionally, the nonlinear evolution of these modes has been simulated using a two-dimensional resistive MHD code. (Fig. 3.14)

Recent analysis has shown the existence of RFP equilibria which are stable to resistive instabilities at zero β (i.e., tearing modes) and to localized ideal interchanges (i.e., Suydam modes) at finite β . However, computer calculations found them to be unstable to resistive interchanges, or "g" modes. As these modes may ultimately be β -limiting, their nonlinear evolution is of considerable interest. The results of 2-D simulations have indicated that certain of these modes can cause significant degradation of the discharge. More extensive calculations should

Figure 3.14

be carried out in the future to determine more precisely the limitations imposed by these modes.

Among the most fundamental and important questions to be addressed is the spontaneous generation of a stable reversed field state during start up. This relaxation phenomenon has been predicted theoretically based on minimum energy arguments. Time dependent, three dimensional simulations of this process in a highly resistive plasma have been useful and are in good agreement with fast RFP experiments. These calculations show that a reversed field state can remain indefinitely if the plasma current is held constant. The key question which remains is whether the level of instability required to maintain the reversal leads to acceptable containment. Additionally, the computations should be extended to significantly lower levels of resistivity. Such 3-D calculations presently require great amounts of computer time but answer fundamental questions concerning the Reversed Field Pinch.

FIELD REVERSED θ -PINCH (F RTP)

The F RTP has demonstrated macroscopic stability far in excess of that expected from ideal MHD theory. One of the intriguing questions in F RTP research is: Why does this configuration survive much longer than expected? Three dimensional time dependent simulations have failed to show long wavelength MHD instabilities, and codes based on the energy principle are now being applied to short wavelength modes. Both of these studies are being carried out as a collaboration between the MFE groups at Livermore and Los Alamos. Such collaborations are greatly facilitated by the existence of the MFE network which allows the rapid interchange of computer codes and results. (Fig. 3.9) Additionally, the apparent stability against resistive modes is not well understood and linear and nonlinear 2-D codes with finite resistivity will be applied to this problem.

Final destruction of the F RTP configuration may be brought on by a rotationally driven $m=2$ mode. Recent work suggests that the rotation may be a result of selective loss of particles with one sign of angular momentum. To verify this idea, a macroscopic code which correctly includes finite Larmor radius effects will be used. Such a code is presently being developed which includes finite Larmor radius effects by treating the ions by particle-in-cell techniques but avoids the restrictive electron time scales by treating the electron components as a thermal fluid. It is still possible that anomalous diffusion due to microturbulence rather than collisional effects are responsible for the selective loss of particles with the same sign in angular

momentum. This question can also be addressed and quantified with such hybrid codes.

FAST LINER EXPERIMENT (FLX)

The FLX has greatly benefited from numerical simulation as a guide to experimentalists in the design of the liner itself. One-dimensional hydrodynamics codes employing equation-of-state tables to describe different liner materials have proven invaluable in this regard. Recent extensions of these codes have been able to include an MHD model of the contained plasma--thereby providing a more complete model. Diagnostics of the latest shots of the FLX have demonstrated plasma and liner trajectories and velocities which are in very good agreement with simulation predictions.

A fast liner implosion which reaches velocities of 10^6 cm/sec still requires some concern for the axial flow of plasma out the ends. Obviously, the next step in simulating liner dynamics is to increase the dimensionality of the technique from 1-D (R) to 2-D (R-Z). This improvement entails a substantially more complex code, if similar physics is retained, as well as significantly greater computer requirements.

STELLARATORS

Stellarators offer potential advantages over tokamaks, including steady state operation, absence of disruptions, larger stable aspect ratio, and absence of anomalous transport due to current driven driftwaves. Stellarators are not presently part of the U.S. experimental program; machines are operational in Europe, Japan, and the Soviet Union. A modest theoretical and computational effort is underway in the U.S. to investigate key issues and to support design studies. Because stellarators are inherently 3-D, computations of particle orbits, equilibrium, stability, and transport are time-consuming. The two existing equilibrium codes require approximately one 7600 hour per run. These codes are being used to study beta limits and to optimize coil design. The results are encouraging: 5% beta stable equilibria have been found by careful coil design, and the insight gained may lead to better coil configurations and higher marginal beta.

A serious problem in stellarator reactors has been superbanana diffusion; asymmetries in the stellarator fields can cause collisionless particles to execute large drift orbits and be very poorly confined. This would be particularly serious for energetic neutral beam ions or for alpha particles, and it could

preclude ignition in a stellarator reactor. Very recent calculations of particle orbits in torsatrons (a type of stellarator) have shown that in this configuration superbananas may not be a serious problem. Earlier approximate calculations assumed the existence of certain particle path invariants and predicted large superbananas. The recent exact calculations have shown that these invariants do not always exist, and as a consequence the superbananas are not formed. While time-consuming, these calculations may radically change our assessment of stellarators as reactors, and enhance their attractiveness as an alternate concept.

Neutral beam injection into toroidal stellarators is being studied using a Monte-Carlo injection code with full 3-D deposition and guiding center orbits. Additional areas of expanded computation include 3-D transport, additional RF heating and wave launching, magnet design, force and stress calculations, and design and placement of diagnostics.

FUSION REACTOR DESIGN STUDIES

As the fusion program has grown, concern with the end product, a fusion reactor, has increased. Early reactor studies have attempted in varying detail to estimate what a reactor might look like based on the concept at hand. These studies include calculations carried out in assessing the technical, economic, and environmental feasibility of various devices proposed as fusion power sources. These range from parametric surveys to bring out specific features of a fusion concept, to detailed design calculations for a particular conceptual power plant which must be built for conditions very unlike current experimental systems.

In addition, from the reactor studies have emerged the methods and requirements for the serious reactor design efforts that will be the basis for most activities in a mature fusion program. It seems probable that the program is entering a transition phase where the emphasis will shift rapidly from one of analyzing the physics to one of analyzing facility performance. This will cause a shift in calculational efforts to more traditional areas such as shielding and mechanical design. It will also cause a shift in emphasis in the traditional physics areas as well.

For discussion purposes the types of calculations required can be classified as

- a) plasma engineering
- b) nucleonics
- c) mechanical design
- d) magnetic field analysis
- e) systems studies
- f) thermal hydraulics
- g) tritium handling
- h) safety and environmental studies

Plasma engineering will require computer programs that evolve from the present plasma physics programs, but with an emphasis on the requirements of the device rather than on the physics. For example, they may use a crude treatment of the plasma profile supported by other models in this area, but with great detail on the time evolution of fuel, alpha, and impurity densities as needed in setting transformer and vacuum pumping requirements. In another case, a program may require more detailed modeling for numerical reasons than the physics involved would justify. There is an analogy here between the fusion and the more mature fission programs. Neutron physics played the role of plasma physics and reactor physics the role of what we are calling plasma engineering. The large three-dimensional

few-group diffusion programs used to determine neutron flux distributions offer little aid in understanding neutron physics, but are essential to the reactor designer in evaluating reactor performance. In contrast, the detailed modeling available in current neutron transport Monte Carlo programs could not be justified for physical understanding. It is reasonable to expect that plasma engineering programs will become the key calculational tools in reactor design and the consumer of the largest single block of computer resources. The history of the fission program would support the idea that these calculations will not replace the traditional ones, but cause a growth in total usage and a gradual displacement in importance.

The second class of calculations are for the transport of neutrons and gamma photons, and the resulting radiation damage, energy deposition, and transmutations. These calculations are in many respects far more difficult than the corresponding calculations in fission systems. Nothing comparable to diffusion theory can be used due to the localized nature of the neutron source and the extreme anisotropy of scattering at source energies. The most expensive of these calculations will likely be those determining radiation streaming through blanket and shield penetrations. The shielding of equipment at the ends of these ports and the regions behind them will be expensive and complex. Thus, large numbers of very expensive calculations, mostly via Monte Carlo, will be required. These will be necessary for every facility including and beyond the ETF.

Calculations of mechanical stresses have not received great attention to date. However, the stresses and their importance increase with the size of the facility. High capital costs and the accompanying necessity of a high duty factor will force extremely detailed analysis of all failure mechanisms. The stress studies required will be among the most demanding ever undertaken by the technical community. This area will probably show the greatest increase of computer usage in the fusion program. These calculations will need to be coupled to models of structural swelling and embrittlement produced by the radiation environment.

Magnetic field calculations are moderately expensive in design studies for current experiments. In future designs, error and backfitting costs will increase rapidly. As a result these calculations will require very detailed modeling, including transient effects that are often ignored at present.

Systems studies are increasingly important in all technical fields. Their introduction into fusion reactor work by ANL and the degree of use made of their systems model indicates it will play a significant role in future design work.

Thermal-hydraulics models have thus far been extremely simple in most fusion conceptual studies. This is due at least in part to the low power density in fusion concepts to date, which implies there is no threat to feasibility of the concepts. It may turn out that the first systems can simply be overdesigned. However, if a liquid metal coolant is chosen, it is hardly likely to be accepted without detailed analysis which would involve magnetohydrodynamic modeling and studies of thermal conduction and induced stresses.

Tritium migration and recovery has been studied with very simple models to date. The emphasis has been on a mechanism for adequately extracting the blanket generated tritium and of recycling the exhaust tritium. In so far as these problems are concerned, the models may be adequate. However, the question of loss pathways and associated environmental and licensing problems may demand a much more exhaustive analysis.

Safety and environmental issues have been addressed briefly in a number of studies. As yet, no standard analysis procedures and requirements have evolved, although some work in this area was necessary in connection with TFTR. However, facilities like the ETF will certainly be required to face these issues. Whether large computing demands will result in the near term is unclear. The current public concern over hazards has resulted in incredibly large and complex modeling tasks in the fission area. At least some activity of this type is likely to be required of fusion system modelers.

The question of the eventual dominance of engineering concerns is not actually the issue here. Our concern is one of timing and degree. The time frame of 1981-82 is the basis for this report. The contention is that these concerns and needs will significantly affect the fusion program on this time scale. The reason is that engineering concerns have already begun to play a major role in the design of TFTR and MFTF. Moreover, future devices may be designed primarily by engineers. The calculations described above will require a large amount of computer time. Some require the use of class IV machines: The largest problems such as Monte Carlo transport problems for penetrations are more comfortably carried out on a class VI machine. The large burn codes that will be needed shortly will certainly require a class VI machine to make routine runs feasible.

ENGINEERING TEST FACILITY

Fusion reactor studies before FY 1977 by-and-large emphasized scoping considerations which required only a relatively modest amount of computing. During the FY 1977-78 TNS studies, it became necessary to carry out physics/engineering trade-off studies and reactor systems analyses in some detail. The trade-off studies relied heavily on the large progress made in the fusion experiments and theory. A significant number of up-to-date computing codes were applied, both in the physics and engineering areas. However, the application of these tools was limited to a few areas, such as plasma magnetics and poloidal field systems, one-dimensional transport estimates of the neutral beam or RF plasma heating to ignition, and toroidal field coil studies on ripple, size, and cost.

The thrust of the design studies has recently shifted toward the considerations of an Engineering Test Facility (ETF), with the goal of producing a conceptual design in sufficient detail to support a decision in 1984 toward Title I design and construction. It is clear that an integrated study of the plasma system and the engineering systems (e.g., electrical systems, magnetic systems, nuclear systems, and systems engineering) is called for. A significant increase in detailed analyses and realism over the TNS study is expected. Concurrent to the ETF design activities, a commercial reactor design study is also being pursued.

ETF will be the first fusion device that has engineering objectives at least as significant as physics objectives. The present conception of ETF, which is naturally consistent with the vast experience in designing and building physics-oriented experimental devices, may not be desirable when the engineering objectives are fully accounted for. Although the present emphasis is in tokamaks, studies of mirror and EBT ETF designs will be initiated when proof of scientific feasibility in these concepts is assured.

Dramatic progress of understanding fusion physics is expected in the coming years. The ETF plasma system design studies should benefit from the advances in understanding and in expertise behind it. To carry out a credible design study, it is necessary to develop, modify, and utilize the state-of-the-art calculating tools to incorporate our knowledge into the design studies in a realistic fashion. The integration of plasma system study with the engineering considerations will require in general extensive trade-off and sensitivity studies. Significant amounts of computing support will thus be required.

The plasma system studies can be put in five general areas: energy and particle transport, plasma heating, equilibrium and stability control, impurity and particle control, and startup, burn, shutdown scenarios.

Energy and particle transport in ETF due to electron and ion thermal conduction, particle diffusion, direct losses of energetic particles, ripples in the magnetic field, neutrals, and various forms of instabilities will be modeled. Sensitivities of plasma and device parameters to uncertainties in transport models will be quantified to aid in assessing the margins and flexibilities in the ETF design.

Plasma heating in ETF by neutral beam, RF and fusion α particles should be computed to estimate the heating power and duration required. Understandings in ion drift orbits, beam ion slowing down, ripple effects, neutral halo effects, impurities and geometric effects need to be accounted for.

Equilibrium and stability control in ETF will deal with plasma magnetics and plasma shaping calculations that take account of engineering constraints and the anticipated plasma behavior during a discharge. Based on the latest understanding of plasma stability properties, the optimal shape profiles will be estimated for highest β and tearing mode stability. Extensive computer simulations of the plasma disruption process in ETF will be necessary to assess the critical time scales and characteristics as input to devising and designing stabilization methods.

Impurity and particle control in ETF will be an area of major concern. State-of-the-art codes and models will be used to estimate the ETF plasma tolerances to accumulated impurities and ash, imperfect impurity unloading, and screening coefficients. The required performance of the impurity control on the uncertainties and parameters of the scrape-off layer and impurity production mechanisms will require extensive calculations.

Startup, burn, and shutdown scenarios in ETF are expected to have a wide range of desirable possibilities. These possibilities need to be simulated to trade between physics and engineering requirements to arrive at the most attractive designs. A large number of simulations are needed.

As indicated in the Tokamak Program section, the code developments in the applied physics area have already made impressive advances. They permit realistic applications to credible ETF plasma system designs. Continued advances in the area are expected in the coming years, and progressively more extensive utilization of these computer models in the ETF design efforts is anticipated.

4. NEEDS ANALYSIS AND RESOURCES REQUIRED

In June of 1979 the following utilization levels were experienced on the MFECC Cray-1 and the CDC 7600.

Figure 4.1

The strictest possible utilization yardstick is applied to computers. Less than 24 hours per day, 7 days per week productive use of a lathe or a milling machine would not raise concern but we have come to demand nothing less from our computing equipment.

Although it is satisfying to see utilization statistics as high as those shown above they also represent a warning that increased loading may degrade system performance. Prime daytime computing conditions are especially sensitive to degradation of performance caused by over demand. Unfortunately the hours that people normally work amount to less than a third of the

computer's work week as shown below. (As a national resource, operating in three time zones, MFECC is able to expand the prime daytime computing hours by one third as shown.).

Figure 4.2

A COMPUTING WEEK - 168 HOURS

The quality of performance during the prime daytime hours is vital to over-all computing effectiveness. These are the hours when users interact with the machine to do code development and to prepare programs and data which will run in production at night or on weekends. If system response is brisk, users will succeed in staging their problems for maximum beneficial use of night and weekend time. Conversely, degraded performance during prime hours will not only waste the user's time with excessive delays but may also result in wasted production time.

It is MFECC's goal to provide hardware and software that will maximize the effectiveness of the user's computing efforts, and it is a sound economic policy to provide needed capacity enhancements before system performance is degraded by the crush

of demand. With over 1000 active users on the MFENET, small delays in system response and job turn around can multiply to represent an enormous loss of manpower effectiveness. In a short time the real cost of this will dwarf the cost of providing the capacity required to restore quality computing conditions. In the final analysis, program mission accomplishment is the product of both manpower and machine resources. The cost of technical manpower is rising by at least 10% each year. Fortunately computers with greater capability continue to be developed and each successive innovation has produced declining costs per unit of computing capability as is shown in the following graphs.

Figure 4.3 Growth of Scientific Computer Capability in DOE

Figure 4.4 Cost Per Unit Capability of Scientific Computers

An additional economic consideration is the fact that use of computers and computer modeling can significantly reduce the use of other expensive and limited resources. Exploring a promising fusion concept by computer simulation is much cheaper than constructing a physical experiment. Furthermore, experiments actually constructed will be based on a better understanding of

the physical processes and therefore have a higher probability of success.

In the months immediately preceding the installation of the CRAY 1 machine, MFECC users were adversely affected by the over subscribed CDC 7600 system. Work was diverted to the CDC 7600 at LBL but an acute capacity shortage persisted until CRAY 1 came on line in May 1978. In a few short months the prodigious capacity of the CRAY 1 was near full utilization. The rapid conversion of user programs to the CRAY 1 is a credit to the resourcefulness of the MFECC user community and system's staff but there was never a doubt about the need for a four fold increase in capacity.

The top curve on the following graph indicates current data on MFECC user requirements from 1980 thru 1985. The curves below the demand curve represent installed capacity and requested capacity during this period.

Figure 4.5

The following graph and table show the composition of the demand curve by magnetic fusion project.

Figure 4.6

TABLE 1
MFE Requirements in NSU's (thousands)

	FY80	FY81	FY82	FY83	FY84	FY85
Tokamak	44.3	51.6	61.3	71.1	79.6	91.8
Mirror	23.9	26.3	30.2	35.5	43.4	51.2
Alternative	16.8	20.7	22.5	24.9	28.9	32.5
Engineering	6.0	9.4	13.0	19.5	27.1	37.5
	-----	-----	-----	-----	-----	-----
	91.0	108.0	127.0	151.0	179.0	213.0

Computer modeling for tokamak concepts creates the largest element of demand and accounts for about half of the total NSU requirements in each of the years FY80 thru FY85. Mirror research accounts for about 25% of the total followed by alternative concepts at about 5% in each year. The greatest percentage growth will be in engineering applications which is expected to grow from a modest 6,000 NSU in FY80 to about 37500 NSU in 1985. This is in anticipation of design and construction of demonstration reactors during this period.

How much will all of this capacity cost? Fortunately, technology advances will exert a favorable influence on costs. If MFECC were a business the capital acquisition of mainframes would not be shown in a single year but would be amortized over the life of the machine. Using seven year life and straight line depreciation the annual resource costs would be:

Table 2

MFECC ANNUAL COSTS (M\$)

	79	80	81	82	83	84	85
	--	--	--	--	--	--	--
Operating	8.3	9.0	10.6	12.9	13.8	14.9	13.8
Annual							
Depreciation	1.8	1.9	2.0	1.3	1.3	1.7	2.7
of Capital	----	----	----	----	----	----	----
Assets	10.1	10.9	12.6	14.2	15.1	16.6	16.5

Operating costs for the Center include lease of major mainframes, manpower, maintenance of hardware at the central facility and in the network, the cost of data communications, and other supplies and expenses associated with the central computing facility.

A plot of the cost per NSU with capital depreciation included in the operating cost is shown in Figure 4.7.

Figure 4.7

It should be pointed out that this represents much more than simply the cost of operating major mainframes. Included is the cost of an expanding data network, data storage, user training and consultation, documentation, engineering services at remote sites, and access to the finest of mathematical and graphics libraries. To borrow a phrase from gasoline station jargon, this is a "full service" NSU delivered to the customer's site.

The ability to purchase more capacity at roughly the same price has a substantial leverage on the cost of computing. The MFECC NSU, and all associated services, can be delivered to the customer for a lower unit price.

The preceding discussion presents the quantitative advantages of more powerful computers. An equally important aspect is the need for more capable computers and software to handle the sophisticated computer models under current development. Some characteristics of such codes are discussed in the following section.

The Need for More Powerful Computers

This section examines three of the major types of codes which are being used in the MFE program. These are, MHD normal mode codes, time dependent MHD codes, and particle codes. This list is representative of those larger, more time-consuming programs for which a Class VI or larger machine is necessary.

a) MHD Normal Mode Codes - One approach to the determination of MHD behavior is the calculation of linear normal modes; that is, natural modes of oscillation of small perturbations away from equilibrium. This has been carried out in very detailed fashion by the PEST and ERATO codes, which calculate an equilibrium and then obtain the structure and frequencies of these normal modes. These codes have made vital contributions to the understanding of the dangerous kink and ballooning instabilities, as well as other MHD modes in tokamaks. This has permitted the much more accurate determination of limits on the plasma beta, the ratio of the plasma pressure to the magnetic field pressure. The PEST code has had a major impact on experimental design, in that the coils for the PDX experiment were rewired on the basis of equilibrium and stability studies showing that beta could be several times higher than previously thought. Both codes run approximately ten times faster on the Cray-1 than on the CDC 7600. This substantial decrease in running time results not only from the fact that the Cray-1 is a much faster machine, but also because its fast access core is substantially larger, thereby permitting more efficient coding. Even so, both PEST and ERATO and other codes of their type will require a great deal of computer time in the future. Each computer run takes about thirty minutes on the Cray-1; several runs are required to analyze one equilibrium; and hundreds are required to discover trends. Such stability calculations will be vital in the investigation of future experiments and reactor configurations.

b) Time-dependent MHD Codes - Another principal technique for determining plasma instabilities along with their growth rates is through the solution of the time dependent MHD equations of motion. The full set of MHD equations comprise a coupled system of eight nonlinear partial differential equations, the solution of which is a formidable task on any computer system.

In order to make these computations tractable, approximations have often been made, including reduction in dimensionality, linearization, restriction to a particular geometry, ordering, or regime, and the assumption of no transport or resistivity. To explain complex phenomena such as the major disruption in a tokamak requires a three dimensional resistive code. It is of utmost importance to understand the major disruption, for if it occurs it will cause the tokamak walls to vaporize. A 3-D resistive code at ORNL has been converted to the Cray-1 very successfully. As in the case with Normal Mode calculations, part of this speed gain is due to the higher throughput of the Cray-1, but just as important is the fact that the increased size and speed of the memory of the Cray-1 have allowed the problem to be cast in a more optimal fashion. This tremendous improvement allows the consideration of cases in which the magnetic Reynolds number is two orders of magnitude higher than that considered before, and that has been helpful in analyzing plasmas typical of PLT. However, it is not yet possible to simulate the nonlinear development of high shear internal MHD modes because of resolution requirements. Adequate resolution of such instabilities (which are believed to be the most relevant experimentally) will require an order of magnitude more in computer capability.

c) Particle codes - In many cases fluid models are not adequate to describe plasma behavior, for it is necessary to consider microscopic effects, i.e., the effects of the way particles are distributed in velocity. Numerically this is most often accomplished through particle codes. As an example of the kind of increased computer capability needed, we refer here to a two space dimensional, three velocity dimensional, electromagnetic particle code, ZOHAR, which has been used for several years at Livermore. A similar code, WAVE, currently is used at LASL. These codes are typical in size and scope to particle codes now being used throughout the MFE community. The following points should be emphasized: (1) Even present-day problems can be extremely long-running; the authors of ZOHAR have occasionally made runs of up to sixty hours on a CDC 7600. Clearly a Class VI machine is essential to make such runs feasible on a regular basis. (2) For anticipated new physics problems even the Cray-1 is somewhat limited. To remedy this it is desirable to have a fast access memory from two to four million words and to add a large high-bandwidth serial-access second level memory.

Acquisition of the Cray-1 has expanded the scope of problems for which particle codes may be effectively used. It is now possible to run full 3-D electrostatic models using a reasonable ion-to-electron mass ratio to simulate plasmas about the size of PLT. However, computational time scales correspond to the ion

plasma or cyclotron frequency. It is currently not possible to adequately simulate electromagnetic instabilities such as the drift-Alfven or drift tearing modes due to the faster timescales associated with electron motion and to the fact that an electromagnetic model requires much more memory.. Such simulations will require a more powerful computer.

The following idea should be kept in mind. Experience has shown that a computer simulation should take no longer than seven to ten days if it is to be performed efficiently. Given the normal restrictions of a shared resource, this corresponds to five to ten hours of computer time. A longer turnaround time often results in a drop of efficiency, due in part to the psychological difficulty of maintaining active interest in what appears to be a dormant situation, and to the massive accumulation of data to be analyzed. Also, the scientist must have the ability to interact with the code and use information from an earlier run to guide his next run. For this form of feedback to occur in a useful way, turnaround times must be as short as possible. Thus, if a problem requires substantial computing, the correct solution is to increase the speed and scope of the computer, if at all possible. In the case of the CRAY-1, this has proven to be a cost-effective measure.

Software Needs

Good basic software is as essential to computing as electricity and paper. Interactive systems are found to greatly enhance the productivity of a computational physicist by fast-debugging and the ability to view calculations and interact with the physics. The installation of CTSS on the CRAY-1 by MFECC was a singular achievement for the speed of the operation and the flexibility and reliability of the system.

The Center runs a network, file storage system, microfilm recorder, and many other devices, each of which requires its own supporting specialist. The critical mass of systems programmers and the close interaction among the subgroups are essential to the high level of reliability of the total system. This represents a powerful argument for centralized computing, accessed by a network, and the expectation that the major growth needs of the magnetic fusion community will best be met by additions to the central facility.

In order to use the MFE Computer Center effectively, a remote user must have reliable, high speed access. Any upgrade of the central site must be accompanied by improvements in the Network, USC's, and Remote User Service Stations. Each part of

the system has required software support, which must be maintained at the highest level.

There has been a steady effort at MFECC, and among users, to enhance the man-machine interface with high quality software tools. Most of the facilities are compatible between the 7600 and CRAY-1, and even with the USC DEC-10's. This has been an invaluable aid to utilizing the CRAY-1 fully. In essence, the MFECC community and the MFECC are capable of substantial independence of manufacturers software, which is generally aimed at a broader market than scientific computing. This capability enabled MFECC to bring the CRAY-1, which was delivered with a compiler, loader, and basic batch system, on stream with a full time-sharing system in less than four months. It is clearly essential to maintain this level of performance in the area of software support in any new acquisitions.

Summary

Since the economic and technical advantages of more powerful scientific computers accrue to so many DOE research endeavors, the Department has a unique stake in encouraging large scale machine development. As larger super-computers become available, MFECC will be in an advantageous position to help fusion researchers across the nation fully exploit their capability and economy. If programmatic priorities shift from site to site the resources of MFECC can be easily shifted to achieve maximum impact on high priority projects.

The concept of centralizing large scale computing for MFE has been validated as cost effective. In addition to the favorable economics of sharing computer resources among major fusion laboratories the Center has provided smaller DOE/MFE contractor laboratories and universities with computer resources that were formerly available only at the national laboratories. The theoretical tools are now available to pursue fusion research on the broadest possible front. Magnetic fusion researchers require more computer support than is currently available. Expanded use of computer models in the theoretical and design stage will provide substantial leverage in reducing the total cost of eventually constructing a fusion reactor.

RECOMMENDATIONS

1. To meet the near term needs of the MFE program (Figures 4.5 and 4.6) a second Class VI computer should be installed at the National MFE Computer Center during FY 1981.

This machine should have CPU execution speeds as fast or faster than the CRAY 1 and preferably a fast memory of 2 to 4 million words.

2. To meet the longer term MFE requirements for both capacity (Figures 4.5 and 4.6) and capability, a Class VII computing system should be installed at the National MFE Computer Center during FY 1984.

It is expected that by 1984 a new class of computers will be recognized in the large scale computing industry. Such a machine should have execution speeds several times that of a Class VI and fast memory of 4-16 million words.

3. The User Service Centers and the National MFE Network should continue to enhance their capabilities.

In concert with installation of the Class VI and Class VII computers, the User Service Centers at the major fusion laboratories should be upgraded in computing capacity, memory, graphics, and other services needed to utilize the central resources most efficiently. The existing communication network should be upgraded in bandwidth, where needed, in order to take full advantage of increased computing power available at the Center. Additional dedicated data communication lines to the Network should be provided for those user groups that require substantial and regular computing at the MFE Computer Center.