FUSION THEORY AND COMPUTATIONS

17. TASK DESCRIPTION

It is proposed to carry out theoretical studies of the equilibrium, stability, transport and heating properties of high-temperature fusion plasmas. Continued emphasis will be placed on the effective interface of fusion theory and computations with the local Alcator, Versator, Constance and Torex experimental programs. The proposed research includes but will not be limited to the following types of studies: (a) Investigation of RF heating of toroidal plasmas with applications to Alcator A and C and Versator II, including theoretical studies of nonlinear waves in plasmas, and induced stochasticity in particle dynamics by coherent waves. (b) Investigation of the MHD equilibrium and stability properties of tokamak plasmas. Study of microinstabilities and anomalous transport in high-temperature plasmas. Investigation of ignition physics and alpha particle heating in fusion plasmas. (c) Develop the basic understanding of a wide variety of non-linear and turbulent phenomena, including stochastic magnetic fields, clumps and nonlinear saturation of linear instabilities. (d) Investigate the effects of ambipolar fields on transport and stability properties of toroidal plasmas. Investigate high-beta stability properties of tandem-mirror systems. (e) Investigation of the MHD equilibrium and stability properties of Torsatron/Stellarator configurations. Microinstabilities and anomalous transport in tokamak/torsatron/mirror configurations, including formulation of self-consistent scaling laws needed for meaningful experimental planning.

DISCLAIMER

The following pages are an exact representation of what is in the original document folder.

SUBTASK #1

RF HEATING AND NONLINEAR WAVES IN TOROIDAL PLASMAS

Abraham Bers, Principal Investigator

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RF HEATING AND NONLINEAR WAVES IN TOROIDAL PLASMAS

19. DETAIL ATTACHMENTS

Purpose

The general objective of this research is to explore the use of externally applied electromagnetic power (generically, "RF power") for the supplementary heating and confining of toroidal plasmas. Particular studies are being carried out to determine the heating of tokamak plasmas with microwave power in the lower-hybrid range of frequencies, and the results are applied to current experiments on Alcator A and Doublet II-A, as well as to experiments in the near future on Versator II and Alcator C.

RF HEATING AND NONLINEAR WAVES IN TOROIDAL PLASMAS

Publications for Calendar Years 1977 and 1978

1. Two-Dimensional Selfmodulation of Lower Hybrid Waves in Inhomogeneous Plasmas
   G. Leclert, C. F. F. Karney, A. Bers and D. J. Kaup
   Submitted to Phys. Fluids, May 1978

2. Comments on "Propagation and Mode Conversion of Lower-Hybrid Waves Generated by a Finite Source"
   V. Krapchev and A. Bers
   Phys. Fluids 21, 2123 (1978)

3. Stochastic Ion Heating by a Lower Hybrid Wave
   C. F. F. Karney
   Phys. Fluids 21, 1584 (1978)

4. Confining a Tokamak Plasma with rf-Driven Currents
   Nathaniel J. Fisch
   Phys. Rev. Lett. 41, 873 (1978)

5. Parametric Decay in a Finite Width Pump, Including the Effects of Three-Dimensional Geometry and Inhomogeneity
   A. Reiman
   Phys. Fluids 21, 1000 (1978)

6. Two-Dimensional Depletion of a Lower Hybrid Pump by Quasi-Mode Excitations
   A. Sen, C. F. F. Karney, and A. Bers
   Phys. Fluids 21, 861 (1978)

7. Waveguide Array Excitation of Lower Hybrid Fields in a Tokamak Plasma
   V. Krapchev, A. Bers
   Nucl. Fusion 18, 519 (1978)

8. Three-Dimensional Effects in the Non-Linear Propagation of Lower-Hybrid Waves
   A. Sen, C. F. F. Karney, G. L. Johnston, A. Bers
   Nucl. Fusion 18, 171 (1978)

9. Nonlinear Development of Lower Hybrid Cones
N. R. Pereira, A. Sen, and A. Bers
Phys. Fluids 21, 117 (1978)

10. Complex Modified K-DV Equation and Nonlinear Propagation of Lower Hybrid Waves
A. Sen, C. F. F. Karney, A. Bers, and N. R. Pereira
Proceedings of The Third Topical Conference on Radio Frequency Plasma Heating, California Institute of Technology, Pasadena, California, January 11-13, 1978

11. Ponderomotive Effects in a Magnetized Plasma
V. Krapchev and A. Bers
Proceedings of The Third Topical Conference on Radio Frequency Plasma Heating, California Institutc of Technology, Pasadena, California, January 11-13, 1978

12. Current Generation by High Power RF Fields
N. J. Fisch and A. Bers
Proceedings of The Third Topical Conference on Radio Frequency Plasma Heating, California Institute of Technology, Pasadena, California, January 11-13, 1978

13. A Steady State Toroidal Reactor Driven by Microwave Power in the Lower-Hybrid Range of Frequencies
A. Bers and N. J. Fisch
Proceedings of The Third Topical Conference on Radio Frequency Plasma Heating, California Institute of Technolgy, Pasadena, California, January 11-13, 1978

14. Theory of Plasma Heating in the Lower Hybrid Range of Frequencies (LHRF)
Abraham Bers
Proceedings of The Third Topical Conference on Radio Frequency Plasma Heating, California Institute of Technology, Pasadena, California, January 11-13, 1978

15. Parametric Excitation of Kinetic Waves--Ion-Bernstein Waves by a Lower Hybrid Pump Wave
Duncan C. Watson and Abraham Bers
Phys. Fluids 20, 1704 (1977)

16. Stochastic Ion Heating by a Perpendicularly Propagating Electrostatic Wave
C. F. F. Karney and A. Bers
Phys. Rev. Lett. 39, 550 (1977)

17. Theory of the Runaway Electron Tail
Kim Molvig, Miloslav S. Tekula, and Abraham Bers
Phys. Rev. Lett. 38, 1404 (1977)

TECHNICAL PROGRESS (latter part of FY '78 and FY '79 to date).

In this past period our studies have continued to focus on problems relevant to lower-hybrid heating of tokamak plasmas in general, and to understanding the recent results of lower-hybrid heating on Alcator A in particular. The two most prominent results from Alcator A are the observed nonlinear effects in the coupling of the RF power and the strong ion heating observed in a narrow range of plasma densities. In the following we describe first three studies directly relevant to understanding these experimental results, followed by three studies that are also of broader interest to RF heating of tokamak plasmas.

Nonlinear Coupling.

It has been recognized for some time that in lower-hybrid heating the electric field amplitudes will be large so that nonlinear plasma dynamics effects will be prominent. The nonlinear effects are characterized by the ponderomotive force,[1] and typically by the parameter $(v_{ind}/v_T)^2$ and/or $(\varepsilon_o E^2/nT)$. In the central region of the plasma, where the temperature is high, these parameters are small enough so that nonlinear effects can be treated as perturbations of the linear propagation characteristics of the plasma. Such studies, involving selfmodulation and parametric excitations, have been quite common in the last few years both in our group[2,3,4,5,6,7] and elsewhere.[8,9,10,11,12] The major conclusions are: (a) parametric excitations should be quite prominent; (b) the excitation of a narrow $n_{||}$-spectrum of waves, with $n_{||}$ well above accessibility, should be able to propagate with negligible effects due to selfmodulation; the density and temperature gradients strongly inhibit selfmodulation; (c) the excitation of a broad $n_{||}$-spectrum, with $n_{||}$'s extending near to accessibility and below, may undergo strong selfmodulation and generate internally reflected waves; the effects of inhomogeneity in this case are not yet known.

On the other hand, near the plasma edge the nonlinearity parameter $(v_{ind}/v_T)^2 \approx (\varepsilon_o E^2/nT)$ becomes larger than unity and the above-mentioned studies do not apply. The nonlinear effects are no longer small and cannot be described by perturbation theory techniques. An unrealistic analysis of the edge dynamics in one-dimension and time[13] indicates that the plasma is pushed, by the RF, away from the wall, across $\bar{B}_o$, and thus reduces the coupling and that a steady-state near the wall may not be reached. Recent electrostatic simulations of lower-hybrid wave excitation by phased-plates at the plasma edge do not corroborate the latter.[14] The wave excitation by plates, in these simulations, introduces large amplitude oscillating sheaths that result in ion-heating at the periphery of the plasma.

In the case of lower-hybrid excitation by waveguide arrays, which is of more practical interest, such sheaths would be less prominent. Instead, the electric field near the plasma edge varies appreciably along the direction of $\bar{B}_o$ and is enhanced in the vicinity of the waveguide walls and along the resonance cones emanating from these regions.[15] Based upon this, we have recently pointed out that at the plasma edge ponderomotive effects parallel to $\bar{B}_o$, coupled with the nonlinear bunching of the electrons there, can explain the experimentally observed nonlinear effects in the external coupling of lower hybrid energy to the plasma, as e.g. seen in Petula, JFT II, and Alcator A.[16] The ponderomotive force in the direction of $\bar{B}_o$ produces plasma density modifications in that direction that are independent of the phasing of the waveguides; this is due to the fact that the ponderomotive force is proportional to $|E|^2$. For example, in the recent Alcator A experiments $(v_{ind}/v_T) \sim 10\text{-}20$ at the plasma edge, giving rise to density depressions $n_o \exp(-v_{ind}/2v_T)$ of three orders of magnitude. This has two consequences. First, the electron bunching near the edge, which is responsible for the lower-hybrid excitation in the plasma, is shifted to shorter wavelengths. Second, since the ions cannot follow instantaneously the electron density depressions, oscillating sheaths parallel to $\bar{B}_o$ are set up; for the power levels of 100 kW in Alcator A, the electric fields in these sheaths is about a few hundred eV's and these can stochastically heat the ions at the edge. More importantly, however, at these power levels the applied electric fields at the edge are such that the electron bunching is nonlinear; thus one finds that $(\omega_B/\omega) = (k_{||}v_{tr}/\omega) = (v_{ind}/v_{ph})^{1/2} \sim 0.3$. This, together with the ponderomotive rippling of the plasma surface leads to a shift of the applied $k_{||}$-spectrum to larger $k_{||}$ by a factor of 2-3, which is consistent with observations of heating and CO_2 laser scattering in Alcator A.[17,18]

Ion Heating.

In relation to the observed ion-heating in Alcator A there exist three possible mechanisms: (a) by the parametrically excited waves; (b) by stochastic heating of the lower-hybrid wave or its parametrically excited waves; (c) by linear ion-cyclotron harmonic damping of the lower-hybrid wave or its parametrically excited waves. The theory of stochastic heating by lower-hybrid waves is by now relatively well advanced.[19,20] In the recent past we have concentrated on understanding the possible relevance of linear ion-cyclotron-harmonic damping in an inhomogeneous magnetic field, and the nonlinear heating aspects of quasi-mode parametric excitations. The first requires $(k\,\rho_i)^2 \gtrsim (\omega/\Omega_i)$ which can only be satisfied near wave conversion occuring at the center of the plasma. However, at the large field amplitudes of interest, and with the above condition satisfied, stochastic heating is effective and linear theory is not appropriate. The relevance of parametric excitations in ion heating is less clear. Parametrically excited spectra are observed in all tokamak heating experiments utilizing externally applied power in the lower-hybrid range of frequencies. However, these are detected at the plasma wall and hence can not necessarily be assumed to occur in the plasma where the heating occurs. In the recent past we have undertaken a detailed study of the nonlinear (heating) aspects of the quasimode parametric excitation in an inhomogeneous plasma. This parametric excitation is a prominent one since it is nonresonant and it has a low threshold. In the past it was thought that the lower-frequency sideband (also a lower-hybrid wave) is mainly excited by scattering of the pump (the applied lower-hybrid wave) off the electrons.[21] We have recnetly shown that for the parmeters of Alcator A (but also in fact for any tokamak-type plasma) the dominant scattering is off the ions by doppler-shifted ion-cyclotron harmonic resonance of the low-frequency fields. This may explain the ion-cyclotron-harmonic structure which one observes on the sideband signal and at low frequencies.[17,23] Furthermore, nonlinearly, the quasimode excitation may be strong near the edge of the plasma. In that case the pump depletes mainly to the sideband which propagates further into the plasma but in a different direction and has a wave conversion point that is further out in the density gradient. Ion heating can then occur near wave conversion of the sideband by either linear ion-cyclotron harmonic damping or induced stochastic ion motion, as before. A small fraction of the pump power (ω_{LF}/ω_s, where LF $\equiv$ low frequency, and s $\equiv$ sideband) goes directly to the ions via the low-frequency fields of the quasi-mode.

<u>Group Velocity Rays in Toroidal Geometry</u>.

This project has been continued and completed. The results have been written up in the Ph.D. thesis of J. L. Kulp, June 1978.[24] As a result of this work we now have a sophisticated (symbolic and numeric) computer program and display for following rf energy propagation in a toroidal plasma, including all of the linear effects due to plasma and magnetic field inhomogneity, and toroidal geometry. The most important new result is the discovery that the applied $n_{||} = (ck_{||}/\omega)$ can be reduced by as much as 30-50% when $\omega \sim \omega_{LH}$ and $(\omega_{pe}/\Omega_e) \gtrsim 1$. This can have important consequences, especially in electron heating which is sensitive to $k_{||}$.

Nonresonant Current Generation for Steady State Tokamak Operation.

Continuing our past work in this area, we have recently undertaken to evaluate the current drive in a plasma which is directly associated with a traveling wave. A first evaluation shows this to be appreciable for lower-hybrid waves. A more complete quasi-linear model, including the finite extent of the fields, is now being developed.

In this connection we are also continuing our study of the high-frequency Alfvén wave excitation in the LHRF.

FUTURE ACCOMPLISHMENTS (FY '80 and FY '81)

We are currently strengthening our interactions with the experiments in RF heating at MIT. Recent results on lower-hybrid heating in Alcator A, upcoming experiments in lower-hybrid heating and current drive on Versator II, and future experiments in lower-hybrid heating on Alcator C--all of these can profit from our developed expertise in this area over the past few years. In addition we plan to evolve theoretical studies in other RF heating schemes, specifically ICR and ECR, relevant to possible future experiments on Alcator and Versator. These we would expect to become "mature" during FY '81. In the following we outline recently initiated projects that should lead to significant results in FY '80 and early FY '81.

Simulation on Nonlinear Coupling.

We have recently undertaken to carry out a simulation of the coupling region in the vicinity of a two-waveguide array. The first attempt will be a particle simulation in the electrostatic fields of the waveguide array near the plasma edge. This should provide us with a view of the stochastic heating we expect in this region, as well as the effects of strong ponderomotive forces, as discussed in the previous section. We expect that this simulation will provide us with insight on the appropriate boundary conditions for describing nonlinear propagation for lower-hybrid waves, a problem that has not been solved satisfactorily, so far. In addition we should be able to see if our proposed model for nonlinear coupling that is relatively insensitive to waveguide phasing is correct, and if so whether traveling wave excitations are still possible at high powers. The latter result is of prime importance to proposed experiments of rf-current drive for achieving steady-state operation of tokamaks.

Ion-Heating Phenomena.

We plan to continue studying various mechanisms to explain the observed ion-heating with lower-hybrid waves. Ion-heating, tail and bulk energies, and in various regions of the plasma profile, is the most common experimental observation in using lower-hybrid waves. Yet detailed models that can be used in scaling of these observations are still lacking. We plan to extend our previous studies of: (a) Stochastic heating, (b) Ion-cyclotron harmonic-damping, and (c) Parametric excitations. In the past these have been studied independently. Experimental parameters show that all three are usually effective, and their interaction is not understood.

Electron Heating and Runaways.

We plan to initiate a study that looks into the coupling of an applied rf spectrum intended to heat electrons with the applied toroidal electric field which drives the current. Recent experiments on Alcator A and especially Doublet II-A indicate that there is an appreciable enhancement of the tail of the electron velocity distribution function when rf power is applied. The proposed study is clearly also of importance to attempts at generating an rf driven current in a plasma. Basically, the study will involve describing the evolution of the electron distribution function in the presence of the simultaneous actions of a drift field, quasilinear diffusion due to rf fields, and collisions. In this connection, it may be useful to supplement this study with the use of some of the available Fokker-Planck codes that have been successful in the runaway problem.

Interaction with Experiments.

We are currently progressing with developing an understanding of the experimental results in Alcator A lower-hybrid heating. This includes models to explain the observed spectrum with CO_2-laser scattering, and the observed ion-heating in a narrow range of plasma densities.

We plan to interact with the experiments on lower-hybrid heating and current generation in Versator II which should yield significant results in FY '80.

During FY '81 our interaction will be strongest with the lower hybrid heating experiments in Alcator C.

Also during these periods of FY '80 - FY '81, possible attempts at heating Alcator A with power in the ICRF, and Versator II with power in the ECRF will initiate relevant support studies within our group.

FACILITY REQUIREMENTS

The theoretical studies of this group are strongly tied to and dependent upon symbolic and numeric computational facilities, and especially their interactive nature. Continued support for these facilities, some of which are unique and were developed by us, and for one additional computational physicist is requested and will be necessary for carrying out the proposed program.

RELATIONSHIP TO OTHER PROJECTS

Studies on supplementary plasma heating of tokamaks with external power in the lower-hybrid range of frequencies are also pursued at the Princeton Plasma Physics Laboratory and at General Atomic Company. The contact with these groups is very good so that the work is sufficiently non-overlapping and complementary in all aspects. Some of the theoretical aspects on nonlinear propagation and heating are also studied by the theory group at the Lawrence Berkeley Laboratory with whom we also have excellent contact. The aim of our studies is to be relevant to current and planned heating experiments nationally and internationally in general, and to MIT experiments on Alcator and Versator in particular.

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SUBTASK #3

COMPUTATIONAL SERVICES AND TECHNOLOGY

Ronald Davidson, Principal Investigator

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COMPUTATIONAL SERVICES AND TECHNOLOGY

19 DETAIL ATTACHMENTS

Purpose

This activity provides computation-related services to the M.I.T. Plasma Fusion Center community. It is primarily oriented towards aiding users in accessing the National Magnetic Fusion Energy Computer Center, including the implementation and maintainence of local facilities for connecting to the NMFECC via existing M.I.T. network ports. In addition, the computational group provides a centralized administration of M.I.T.'s time allocation at the NMFECC and distributes documentation for users. Because of the importance of computing in both experimental and theoretical programs, it is imperative that researchers in the DOE-supported fusion effort at the Plasma Fusion Center have convenient and efficient assess to the NMFECC. The continued strengthening of Plasma Fusion Center computational services is an essential ingredient in our major effort to increase local theory support and effective interface with the Alcator experimental program, as well as with Versator and Constance.

Relationship to other projects:

In the past, the various principal investigators at MIT have used a variety of computational facilities to carry out calculations related to ALCATOR, TOREX, RF heating, confinement, turbulence, transport, etc., including the MIT IPC (Information Processing Center) IBM 370/168, MIT MULTICS time-sharing system, MC (MACSYMA Consortium) PDP-10, the NMFECC machines, and various other off-campus machines. With the mandate of the APP Division to limit computational expenditures to the National Center (NMFECC), there is a strong motivation to coordinate the use of this facility among OFE supported personnel at MIT. Such coordination includes administering MIT's allocation of computer time at the NMFECC, disseminiating information and documentation about the center, implementing and maintaining centralized access and support facilities (networks, terminals, printers, etc.), and reducing the effective overhead of the individual investigators with major computational activities.

The importance of this centralization effort rises partly from the increased size of the fusion program at MIT and partly from the need to make maximally effective use of existing local hardware in accessing the NMFECC.

The PFC computational facility is being implemented relatively inexpensively because of the unique resources available at MIT. These include a close working relationship with the AI (Artificial Intelligence) Laboratory which developed the (local) CHAOS computer network. The AI Laboratory provided leadership in demonstrating advanced display technology on which the current on-campus terminal display system is based, and made available to us (on a limited basis) high quality graphics and document hardcopy via their XGP device and implemented numerous sophisticated hardware and software development facilities which we have relied on in the past. Further, the LCS (Laboratory for Computer Science) hosts the MACSYMA Consortium which is a unique and valuable computational facility, partially supported by DOE, which provides ARPA network access as an important by-product of its main service, the MACSYMA system.

Results Expected in FY 79:

It is expected that the administrative aspects of coordinating computational work of the PFC will be well underway during FY 79. During this time, previously proposed plans will be carried out for the implementation of a hardware configuration necessary to allow Plasma Fusion Center users to effectively access the NMFECC (currently no such capability exists at the PFC). It is assumed that the bulk of the computational load of the PFC (particularly for large scale calculations) is to be carried out at the NMFECC in Livermore. Some symbolic and smaller scale numeric computations requiring a large degree of interactiveness will continue to be done locally using the MACSYMA system on MC.

What then are the components needed to facilitate the use of these machines? The basic equipment required for remote computer use includes terminals and hardcopy devices. For a program the size of that at MIT (on the order of 100 scientists at various levels), a capacity for a moderate volume of hardcopy is essential (i.e. more than is possible by a hardcopy terminal). This in turn, implies a requirement for reliable high speed access to the NMFECC computers (usually by a network). The terminals should be high speed graphics displays because: (1) most physicists need graphical analysis of data; (2) such displays can now be obtained very economically when centralized; (3) the MC machine has a large amount of software which can make highly productive use of such displays; (4) the terminal, being the least expensive component of the machine-terminal-person system, should not be a bottleneck to interactiveness. Graphics hardcopy is also an essential facility. Since both national (ARPA) and local-MIT (CHAOS) networks exist and can be used to access the NMFECC at high data rates, it is highly attractive to use these resources, as has been demonstrated with an existing display terminal system used by several on-campus plasma physics groups.

The next important capability is to have a means for local file storage and editing. This capability is productive for several reasons: (1) it helps keep network traffic from getting out of hand due to redundant file transfers for hardcopy; (2) it reduces the interactive load on the central facility (NMFECC), freeing it for the computational tasks at which it is most efficient (running numerical codes); (3) it allows faster and less tedious editing of programs and data by local users because of the lack of network delays. Another related facility would be the ability to do local interactive (small scale) computations.

In brief, a near-term facility will include the following features: a small processor capable of handling file management and editing needs of a small number of users (8); a network connection for this processor to the local computer network (CHAOS) which runs at an 8 M bit rate; a Calcomp T-300A disk for file storage; a graphics/document quality hardcopy device; a bit-map TV display system highly integrated into the processor by memory mapping; distributed console access (TV monitors and keyboards located in offices, moveable on carts); high quality (existing) editing, display, hardcopy, and network software. It is assumed that established technology is to be used to implement such a system, and there is no intention to embark on original hardware design efforts. In general, attempts will be made to propose hardware for which system software already exists to support the interaction with MIT hardware environment.

By the end of FY 79 it is expected that the basic system will have been acquired. A systems programmer will be employed for the development of additional software required to interface this system with the external network environment.

Future Accomplishments (FY 80, FY 81)

The main goals of the computational support effort during FY 80 and FY 81 will be to improve the reliability and quality of access to NMFECC facilities. This includes the acquisition of a high-quality hardcopy device, and the improvement of system software to make network connections more convenient. Development of on-line documentation and other user aids is part of this overall objective. In addition, the computational services group will continue to provide user aids and the administation of computer time resources.

These goals will be pursued by the establishment of several sub-task efforts administration, documentation, systems programming, hardware installation, and hardcopy device acquisition.

Administation of Computer Resources

This sub-task involves the distribution and allocation of the MIT computer time resources at the NMFECC. Use of the NMFECC by MIT personnel is monitored on a weekly basis. Records of computer use will be kept, and requests for additional time allocations made when special needs arise. New accounts will be processed and user group meetings organized to disseminate information and to facilitate discussions of user problems and experiences with NMFECC personnel on problems relating to the ARPA net access and other software problems.

Documentation

This effort is directed to maintain documentation on the local terminal system and the means of access via local MIT network connections to the NMFECC facilities. In addition, local copies of much of the documentation produced by the NMFECC will be maintained for ease of reference by users. A mailing list of all interested parties at MIT will be compiled for distributing NMFECC publications and other information relating to the accomplishment of computations at NMFECC.

System Programming

Many improvements on the local systems are desirable in order to increase the reliability of accessing the NMFECC and to make the use of these facilities easier and less time-consuming. This includes debugging and improving the local network software, adding additional terminal support, and the implementation of new software to support hardcopy devices, etc. Although most of the system software for the system being acquired is already available, there are some needs specific to the Plasma Fusion Center users which have to be met, including some on-line documentation system, maintainence of existing document production facilities, and the improvement of some FORTRAN-specific editing capabilities.

Hardware Installation

In FY 80, the computational support group will be completing the connection to the local MIT network of both the Plasma Fusion Center terminal system and the ALCATOR control computer. The completion of the installation of the PFC terminal system will occur in FY 80, particularly the wiring of terminals to user's offices and the construction of a patch panel or switch for the terminals. The repair and maintainence of new and existing hardware is an important recurring function of this effort.

Hardcopy Facility

The initial terminal system at the Plasma Fusion Center does not include a provision for hardcopy facilities. During FY 79, the PFC personnel will be relying on the XGP printer at the AI Laboratory and the Gould printer accessible on campus. Since both of these facilities are about 1/4 mile away from the PFC, this situation is highly undesirable. Thus, a central activity for FY 80 will be the acquisition of comparable capability to be installed at PFX headquarters. A survey of the available graphic printers will be made and the most cost-effective device meeting our requirements will be purchased. There are several possiblities such as the recently announced Wang printer, ink-jet printers by Hitachi, Sharp, or IBM, or a new product being developed by III, Inc.

Several of the MIT fusion theorists are currently making highly effective use of software and hardware (e.g. TEX and the XGP) for technical document production, saving a great deal of time in generating copy for reports or publication. With the increased emphasis on strengthening computational support for local PFC experimental programs, there is a strong need to provide this facility in a highly cost-effective manner, by sharing this printing function with other computational needs. Thus, in addition to the usual requirements for program listings and graphics, such a printer should be capable of reasonable quality document production.

FY 81 Goals

In FY 81, the computation support group will continue the administrative functions mentioned previously. It is expected that the documentation and software improvement efforts will continue to be needed as system changes are made in response to new requirements and changes at the NMFECC. Software development for the hardcopy facilities very likely continue into FY 81.

By FY 81, it is anticipated that the PFC user community will have increased substantially in size and that the PFC computational facilities will also be used by the major experimental programs. Thus, there will be a need for expanding the number of terminals and the quantity of local file storage at the PFC. The additional load will necessitate an increase in the processor memory, so that performance will not be substantially reduced. The installation and support of this additional equipment will be a primary activity of this effort in FY 81.

SUBTASK #4

NONLINEAR AND TURBULENT PHENOMENA

Thomas H. Dupree, Principal Investigator

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PURPOSE

The fluctuations in a plasma can be roughly divided into two categories: namely fluctuations which are mainly linear, wave-like, go faster than the thermal speed of the particles and interact only weakly with the particles; and fluctuations which move at particle speeds and interact strongly with particles. This research is concerned with the latter type of fluctuations, which are highly nonlinear because of their strong interaction with particles. These fluctuations are intimately connected with transport properties and, in fact, all collisionless transport mechanisms, such as anomalous particle or heat loss across field lines or collisionless heating must involve such fluctuations. We are studying these fluctuations in both a coherent and an incoherent or turbulent regime. In the coherent regime the fluctuations are primarily BGK modes. As the number of such modes is increased, the modes collide and interact with each other and the evolution becomes chaotic and turbulent. We are attempting to understand the basic mechanisms of this phenomena and to develop tractable theories to permit practical calculations.

It turns out that the phenomena explored here is quite general and analagous problems occur in other areas of physics and plasma physics. In particular, we are applying these techniques to MHD problems involving stochastic magnetic field lines. The motion and interaction of BGK modes is analagous to the development and interaction of magnetic islands. Likewise the transition from coherent island structure to ergotic field lines is analagous to the problem of particle orbits. In addition to the development of theoretical and analytical techniques, we are utilizing computer simulations of simple problems as a guide to the development of the theory and as a means of testing the validity of the theory.

PUBLICATIONS

1. T.H. Dupree, Role of Clumps in Drift Wave Turbulence, Phys. Fluids, 21, 783 (1978).

2. T.H. Dupree and D. J. Tetreault, Renormalized Dielectric Function for Collisionless Drift Wave Turbulence, Phys. Fluids, 21, 425 (1978).

TECHNICAL PROGRESS

During FY79, we have developed a theory describing the manner in which random phase space fluctuations organize themselves into semi coherent BGK like modes. By utilizing arguments involving the mode entropy, energy and momentum, one can predict the time evolution of a collection of such interacting modes. In a simple one-dimensional problem, these modes take the form of phase space holes. Holes interact only if they collide at very small velocities, i.e., the holes overlap in phase space. In simple cases, when two holes collide, they coalesce and produce a new hole with smaller energy and larger entropy. The theory predicts that such fluctuations decay rather slowly, going as $t^{-\alpha}$ with $\alpha \lesssim 1$. The theory also predicts the amplitude of the fluctuations as well as their characteristic width in velocity space. It also predicts that as the fluctuations decay, a long range order develops in the spatial dimension. All of these predictions have been verified in a preliminary way by computer simulations. We are now undertaking more extensive simulations for a more detailed verification. In particular, we are cooperating with the UCLA group in using their array processor to study a three-dimensional version of the problem involving the decay of vorticies.

In the completely turbulent regime, we have extended the theory of clumps (the one and two point renormalized turbulence theories) to the case of finite gyro radius. This problem deals with the cyclotron motion of clumps and involves a variety of interesting phenomenon including cyclotron heating, anomalous viscosity and enhanced cyclotron radiation.

FUTURE ACCOMPLISHMENTS FY80

In addition to continuing much of the present research, we intend to make a major effort in applying the methods discussed earlier to the problem of MHD equilibria, stability and turbulence. The instabilities and non-linear phenomenon associated with the resonances at the rational surfaces are analagous mathematically to those encountered in the simple wave-particle case. As mentioned earlier, the development, evolution and interaction of magnetic islands is analagous to the behavior of BGK modes. The criterion of island overlap for the onset of ergodic magnetic field structure is, of course, the same thing as the overlap of wave resonance widths in turbulence theory or the overlap of BGK holes in the coherent version of the problem. In the magnetic island case, the radial separation between islands is analogous to the velocity separation of BGK holes. As the islands overlap and interact, the magnetic field lines become ergodic in complete analogy to the random ergodic nature of particle orbits when the holes interact and coalesce. We intend to apply the one and two point renormalized turbulence theory to MHD kink modes and tearing modes. Although our work in this area is very preliminary, it would appear that one of the principal non-linear effects is the diffusion of the magnetic field line in the region of the rational surface and the tearing layer. We also hope to be able to carry out numerical simulations of these problems when an array processor currently being developed at MIT becomes available. These simulations would be specifically designed to test the validity of non linear theory as well as to suggest new analytic or theoretical approaches.

FUTURE ACCOMPLISHMENTS FY81

While it is difficult to predict very precisely the directions of research in fiscal '81, we would expect to continue the general line of research outlined earlier. We would expect, however, to concentrate our research on those areas which seem to be the most relevant to heating and confinement problems in practical confinement devices. At this time it seems likely that we will concentrate much of our effort in the area of stochastic magnetic fields and MHD phenomena.

RELATION TO OTHER PROJECTS

Renormalized turbulence theories and their application to drift waves and stochastic magnetic fields are currently being studied at Princeton and Oak Ridge as well as at M.I.T. We appear to be the first to apply such methods to purely MHD phenomena. We are also the only group applying the two point (clump) renormalized theory of these problems.

SUBTASK #5

FUSION THEORY APPLICATIONS AND COMPUTATIONS

Principal Investigators: Ronald Davidson
Jeffrey Freidberg
Kim Molvig

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A. MAGNETOHYDRODYNAMIC EQUILIBRIUM AND STABILITY PROPERTIES OF MAGNETIC CONFINEMENT SYSTEMS

A.17 ACTIVITY DESCRIPTION

The purpose of the proposed work is to determine the important MHD equilibrium and stability limits (both ideal and resistive) of magnetic confinement systems, with immediate attention focused on stellarators and torsatrons. Specifically, one needs to know whether the critical β for MHD stability will be sufficiently high so that extrapolations of reactor size and economics are favorable. Equally important, one must learn how the critical β scales with aspect ratio in order to theoretically justify current reactor designs which utilize the desirable engineering feature of moderate to large aspect ratio.

The approach to be used consists of solving the ideal and resistive MHD equilibrium and linear stability equations primarily by analytic, asymptotic techniques. The calculations will be carried out for special simple profiles as well as for general diffuse profiles, Small to moderate computation will be required for evaluation purposes.

The work proposed here is submitted in response to the results of the recent DOE alternate concept review which indicated that substantial new stellarator/torsatron theory should be carried out before a decision can be made on a corresponding proof of principle experiment.

A.19 DETAIL ATTACHMENTS

Facility Requirements

Because the proposed work will, in part, involve numerical computations it will be necessary to have access and sufficient allocation on the MFE computer network.

Publications

Listed below are a number of publications from recent years which have a relatively direct relation to the proposed task.

Equilibria of Diffuse High Beta Stellarators
J. P. Freidberg, R. Y. Dagazian, D. C. Barnes
Submitted to Phys. Fluids, Oct., 1968.

Stability of High Beta, $\ell = 3$ Stellarator
J. P. Freidberg, W. Grossmann, F. A. Haas
Phys. Fluids 19, 1599 (1976).

Stability of a Diffuse, High Beta, $\ell = 1$ System
G. Berge and J. P. Freidberg
Phys. Fluids 18, 1362 (1975).

Magnetohydrodynamic Stability of a Sharp Boundary Model of Tokamak
J. P. Freidberg and W. Grossmann
Phys. Fluids 18, 1494 (1975).

Kink Instabilities in a High Beta Tokamak
J. P. Freidberg and F. A. Haas
Phys. Fluids 16, 1909 (1973).

Stability of a Finite Beta, $\ell = 2$ Stellarator
J. P. Freidberg
Phys. Fluids 16, 1349 (1973).

Purpose

The proposed work concerns theoretical investigations of MHD equilibrium and stability limits in magnetic confinement systems. It is by now well established that such calculations play a vital role, not only in present and near term experiments, but in the extrapolation of any given configuration to a reactor. Specifically, the size of a reactor is directly related to the maximum allowable value of beta through the requirement of optimal wall loading.

There are two main objectives to the proposed calculations. The first, which applies primarily to stellarators/torsatrons, consists of developing a realistic description of MHD equilibria. The goal here is to be able to provide design information for future experiments and for reactor system studies (i.e. such information as scaling of toroidal shift with beta, helical field amplitude, vertical field; location of the separatrix; etc.).

The second objective, which applies to all configurations of interest, is to determine the most dangerous MHD modes and the corresponding values of critical beta. An important feature of these calculations is that the equilibrium must have the maximum possible degrees of freedom so that optimization can be carried out to maximize the critical beta.

Initially, most of the emphasis will be directed towards stellarators and torsatrons. However, in the near future, similar investigations will be initiated on other configurations.

A list of the basic configurations and the main problems that will be investigated is given below:

1. Stellarator/Torsatron: MHD equilibrium, Critical beta for stability.
2. Alcator C: low m number ideal and resistive ballooning stability, tearing mode evolution.
3. Tandem Mirror: Critical β for stability of the connecting region, saturation of rotational instabilities.

Background

The concept of the stellarator as a fusion reactor and the importance of MHD equilibrium and stability calculations have both been well established since the beginning of magnetic fusion research. Events of recent years have regenerated a strong interest in the application of MHD theory to stellarator/torsatron configurations.

First, on the experimental side, there have been a number of very encouraging new results, particularly from the Cleo experiment at Culham. These results indicate that stellarators appear to work about as well as tokamaks of comparable size. Most promising is the evidence that performance improves with decreasing ohmic heating current, although no stellarator has yet been able to operate with no ohmic heating current at all.

Second, the extensive tokamak reactor designs indicate that the limiting value of β is a critical parameter for determining reactor size. If critical β's on the order of 5% or greater cannot be achieved, then the corresponding reactor becomes undesirably large.

These points were brought out in the recent DOE alternate concept review. The results indicated that stellarators did indeed have potential as a fusion reactor but that considerably more theory should be carried out before the decision can be made on a proof of principle experiment. The work proposed here is a response to this recommendation.

Approach

The basic approach to calculating MHD equilibria and stability of stellarators and torsatrons will be to solve the corresponding equations analytically by asymptotic expansion techniques. The advantage of such as approach is that detailed scaling laws as well as extensive parameter studies can be carried out with relative ease. To do this, small to moderate amounts of computation will be required, although only for straight forward evaluational purposes.

Technical Progress

During FY 80 the following technical progress is expected:

1. A calculation of self consistent equilibria in an ideal toroidal stellarator using the surface current model. An ideal stellarator is one in which the ohmic heating current is zero and the harmonic content of the applied stellarator field is purely sinusoidal. The goal is to determine the equilibrium condition relating toroidal shift, plasma beta, helical field amplitude and vertical field amplitude and to see how high a plasma beta can be contained.

2. A calculation of the stability of the above equilibrium to ideal and resistive kink modes. Specifically, the goal is to determine the most unstable mode and to calculate the corresponding critical beta.

3. The development of a relatively simple numerical code to calculate realistic diffuse stellarator/torsatron stellarator equilibrium equations.

During FY 81 the following technical progress is expected:

1. A calculation of surface current equilibrium for a a generalized stellarator/torsatron. This configuration allows the possibility of:
   a) an ohmic heating current
   b) higher harmonic content in the applied helical fields (say due to wires rather than a sinusoidally distributed current)
   c) a sideband helical field, whose ℓ value differs by 1 and whose wave length is the same as the main helical field. (Such a field adds greater flexibility to the equilibrium as pointed out in high β stellarator theory)
2. A calculation of the ideal and resistive kink stability of the above equilibrium. The goal is to learn how to optimize this equilibrium to maximize the critical beta.
3. Perform parameter studies with the diffuse equilibrium code to provide guidance in the design of a proof of principle experiment and to provide input for reactor system studies.
4. Formulate the ideal MHD stability problem for the diffuse low β asymptotic equilibria calculated above.

Future Accomplishments

The theoretical studies pertaining to stellarators and torsatrons should provide important input into the decision as to whether or not to build a proof of principle experiment. If such an experiment is built, it will clearly represent further important progress in the national magnetic fusion effort.

Hopefully, the studies of MHD instabilities in tokamaks will shed some light on the understanding of transport scaling in the Alcator experiment. Such knowledge would be very helpful in plotting the future course of high field tokamaks.

It is important to understand the MHD stability limits of a tandem mirror, because extrapolations to reactors are very much more attractive if sufficiently high β's are possible.

Relationships to other projects

Despite the complications associated with calculating MHD equilibrium and stability of such complicated geometrics as the stellarator or tandem mirror, there is reasonable confidence that substantial progress can be made in several years with modest manpower levels. This confidence is a result of the extensive experience acquired in recent years from the MHD studies of tokamaks and high β stellarators at various fusion laboratories in the U.S.A. and other countries.

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B. STABILITY AND TRANSPORT PROPERTIES OF MIRROR FUSION SYSTEMS/ADVANCED FUSION CONCEPTS

B.17 ACTIVITY DESCRIPTION

It is proposed to continue investigations of the equilibrium, stability and transport properties of linear and toroidal fusion systems, with particular emphasis on microstability properties and associated nonlinear transport in field-reversed mirror and ion layer configurations, gradient-driven instabilities in the linear section of TMX, nonlocal studies of the mirror-drift-cone instability, and microinstability behavior affecting late-time transport in toroidal reversed field pinch configurations. During this period, an intense effort will be made to develop an effective theoretical interface with the Constance I and II mirror experimental programs, as well as provide strong interactive support for the Lawrence Livermore magnetic confinement program.

B.19 DETAIL ATTACHMENTS

Facility Requirements

Because the proposed work will involve numerical computations, adequate access and time allocation on the MFE computer network is required.

Publications

The following 1977-78 publications are indicative of recent progress and related to the general subject matter of this proposal.

"Effects of Finite Plasma Beta on the Lower-Hybrid-Drift Instability," R. C. Davidson, N. T. Gladd, J. Huba, and C. W. Wu, Phys. Fluids 20, 301 (1977).

"Sheath Broadening by the Lower-Hybrid-Drift Instability in Post-Implosion Theta Pinches," P.C. Liewer and R. C. Davidson, Nucl. Fusion 17, 85 (1977).

"Numerical Study of Theta-Pinch Implosion Including Two-Step Ionization," R. C. Davidson and B. H. Hui, Phys. Fluids 20, 707 (1977).

"Anomalous Transport in High-Temperature Plasmas," R. C. Davidson and N. M. Krall, Nucl. Fusion 17, 1313 (1977).

"Influence of Strong Inhomogeneities and Magnetic Shear on Microstability Properties of the Tormac Sheath," R. C. Davidson, N. T. Gladd, Y. Goren, and C. S. Liu, Phys. Fluids 20, 1876 (1977).

"Influence of Strong Inhomogeneities on High-Frequency Mirror-Drift-Cone and Convective-Loss-Cone Instabilities," R. C. Davidson and N. T. Gladd, Phys. Fluids 20, 1516 (1977).

"Influence of Magnetic Shear on the Lower-Hybrid-Drift Instability — with Application to Microstability Properties of Toroidal Reversed-Field Pinch Profiles," R. C. Davidson, N. T. Gladd and Y. Goren, Phys. Fluids 21, 992 (1978).

"Quasilinear Stabilization of Lower Hybrid-Drift Instability," Phys. Fluids 21, 1375 (1978).

"Stability Properties of a Cylindrical Rotating P-Layer Immersed in a Background Plasma," H. S. Uhm and R. C. Davidson, Phys. Fluids 22, in press (1979).

"Stability Properties of Field-Reversed Ion Layers," R. C. Davidson and H. S. Uhm, Phys. Fluids 22, in press (1979).

"Microstability Properties of Reversed-Field Pinches," R. C. Davidson and N. T. Gladd, 1978 Padova Workshop on Reversed Field Pinches.

"Kink Instabilities in Reversed-Field Pinches," J. Y. Choe and R. C. Davidson, 1978 Padova Workshop on Reversed Field Pinches.

"Nonlocal Hybrid-Linetic Stability Analysis of the Mirror Drift-Cone Instability," R. C. Davidson, H. Uhm and R. Aamodt, manuscript in preparation (1979).

Purpose

The Office of Fusion Energy has placed a major emphasis on the timely development of Magnetic Mirror configurations (such as the tandem mirror and the field-reversed mirror) and promising Advanced Fusion Concepts. The purpose of the proposed research is to investigate the equilibrium, stability and transport properties of linear and toroidal fusion systems, with particular emphasis on microstability properties and associated nonlinear transport in field-reversed mirror and ion layer configurations, gradient-driven instabilities in the linear section of TMX, nonlocal studies of the mirror-drift-cone instability, and microinstability behavior affecting late-time transport in toroidal reversed field pinch configurations. During this period, an intense effort will be made to develop an effective theoretical interface with the Constance I and II mirror experimental programs, as well as provide strong interactive support for the Lawrence Livermore magnetic confinement program.

Technical Progress

There has been considerable technical progress during the past year relating to (a) high-frequency microstability and transport properties of fusion systems with steep spatial gradients, (b) stability properties of field-reversed configurations, (c) nonlocal stability behavior associated iwth the mirror-drift-cone instability for both low- and high-frequency perturbations, and (d) MHD kink stability properties of reversed field pinch (RFP) configurations. In this section, we give a brief overview of recent progress in several of these areas.

Drift-Cyclotron Loss-Cone Instability: The drift-cyclotron loss-cone instability plays a major role in determining particle losses and transport properties of mirror-confined plasmas. Previous investigations[1] of this instability have included a study of the influence of strong inhomogeneities on stability behavior ($r_{Li}/R_p \lesssim 1$), with particular emphasis on the high-frequency regime and maximum growth properties in a parameter regime similar to 2XIIB. More recently, we have made use of a hybrid-kinetic model[2] (Vlasov ions and cold-fluid electrons) to develop a fully nonlocal theory of the mirror-drift-cone instability. The stability analysis assumes electrostatic flute perturbations about a cylindrical ion equilibrium $f_i^0 (H_\perp - \omega_i P_\theta, v_z)$, where ω_i = const. = angular velocity of mean rotation. The radial eigenvalue equation for the potential amplitude $\hat{\phi}(r)$ has been solved[2] exactly for the particular choice of f_i^0 corresponding to a sharp-boundary (rectangular) density profile. The resulting dispersion relation for the complex eigenfrequency ω has been investigated numerically for a broad range of system parameters including the important influence of large ion orbits and ion thermal effects. It is found that the instability growth rate is typically more severe for fast rotational equilibria ($\omega_i = \hat{\omega}_i^+$) with axis encircling orbits than for slow rotational equilibria ($\omega_i = \hat{\omega}_i^-$). Stability behavior is investigated for the entire range of r_{Li}/R_p allowed by the equilibrium model ($0 < 2\hat{r}_{Li}/R_p < 1$). For low values of azimuthal harmonic number ℓ, the mode structure is macroscopic and the detailed nonlocal stability properties differ significantly from the conventional local stability results for a diffuse profile. We emphasize that the present sharp-boundary calculation of the mirror-drift-cone instability represents a "worst-case" stability analysis. The nonlocal stability behavior for diffuse equilibrium profiles is currently under investigation, making use of the hybrid-kinetic eigenvalue equation[2] derived for general $f_i^0(H_1 - \omega_i P_\theta, v_z)$.

Stability of Field-Reversed Configurations: Field-reversed mirrors and ion layers have received considerable recent attention as magnetic confinement configurations for fusion plasmas. Such field-reversed configurations are likely subject to various macro- and microinstabilities. For example, recent theoretical studies[3] of the negative-mass stability properties of a weakly diamagnetic ion layer embedded in a background plasma predict instability for perturbations with frequency near harmonics of the layer rotational frequency. These studies[3] have been carried out for a low-intensity ion layer characterized by $\nu<<1$, where $\nu=N_b e^2/m_i c^2$ is Budker's parameter for the layer ions, and $N_b=2\pi\int_0^{R_c} dr\, r\, n_b^0(r)$ is the number of ions per unit axial length. A more general stability analysis is required to investigate stability properties for an intense field-reversed ion layer characterized by $\nu>>1$. In this regard, we have investigated[4] the stability properties of an intense field-reversed proton layer (P-layer) immersed in a background plasma within the framework of a hybrid model in which the layer ions are described by the Vlasov equation, and the background plasma electrons and ions are described as macroscopic, cold fluids. Moreoever, the stability analysis[4] is carried out for frequencies near multiples of the mean rotational frequency of the layer. It is assumed that the layer is thin, with radial thickness (2a) much smaller than the mean radius (R_0). Electromagnetic stability properties are calculated for flute perturbations ($\partial/\partial z=0$) about a P-layer with rectangular density profile, described by the rigid-rotor equilibrium distribution function $f_b^0=(m_i n_b/2\pi)\delta(U-\hat{T})G(v_z)$, where n_b and $\hat{T}$ are constants, m_i is the mass of the layer ions, $G(v_z)$ is the parallel velocity distribution, and U is an effective perpendicular energy variable. Stability properties are investigated including the effects of (a) the equilibrium magnetic field depression produced by the P-layer, (b) transverse magnetic perturbations ($\delta \underset{\sim}{B}\neq 0$), (c) small (but finite) transverse temperature of the layer ions, and (d) the dielectric properties of the background plasma. All of these effects are shown to have an important influence on stability behavior.[4] For example, for a dense background plamsa, the system can be easily stabilized by a sufficiently large transverse temperature of the layer ions.

Stability and Transport Properties of Toroidal Reversed Field Pinches: Both microscopic and macroscopic stability properties of reversed-field pinch configurations have been investigated with particular emphasis on parameter regimes anticipated in the Los Alamos ZT-40 experiment. For example, the influence of magnetic shear on the lower-hybrid-drift instability[5,6] has been investigated, including application to microstability properties of post-implosion reversed-field-pinch profiles.[7,8] The analysis includes the influence of magnetic shear and finite ion beta in a fully electromagnetic model that assumes $T_e/T_i \ll 1$ but otherwise incorporates the effects of transverse magnetic perturbations ($\delta \underset{\sim}{B}\neq 0$). It is found that sufficiently strong magnetic shear can completely stabilize the lower-hybrid-drift instability. The theoretical model has been used to investigate the microstability properties of post-implosion reversed-field-pinch profiles, and it is found that the lower-hybrid-drift instability persists in regions of moderate magnetic shear only if the local density gradient is sufficiently large. Moreoever, for the diffuse profiles anticipated in the Los Alamos ZT-40 experiment, the lower-hybrid-drift instability is completely stabilized.[7,8]

In addition, we have investigated[9] the ideal MHD stability properties of reversed field pinch configurations, with particular emphasis on the parameter regime anticipated in the ZT-40 experiment. In a straight cylindrical model of the RFP, it is found that the m=1 kink instability is generally characterized by four types of unstable modes, depending on the radial location (r_s) of the singular surface. These are: (a) the interchange mode, (b) the Suydam mode, (c) the Robinson mode, and (d) the external kink mode. Local analyses have been carried out to determine the relevant physical quantities that characterize each type of unstable mode, and the corresponding criteria are shown to be in good agreement with the stability results obtained numerically. The numerical results[9] show that, while the Robinson and the Suydam modes can be easily stabilized on resistive diffusion time scales by adequate profile shaping, the interchange and the external kink modes can be stabilized only for a narrow range of equilibrium profiles.

Future Accomplishments

During FY 80 and FY 81 we will continue to examine equilibrium, stability and transport properties of linear and toroidal fusion systems, with particular emphasis on microstability properties and associated nonlinear transport in field-reversed mirror and ion layer configurations, gradient-driven instabilities in the linear section of TMX, nonlocal studies of the mirror-drift-cone instability, and microinstability behavior affecting late-time transport in toroidal reversed field pinch configurations. During this period, an intense effort will be made to develop an effective theoretical interface with the Constance I and II mirror experimental programs, as well as provide strong interactive support for the Lawrence Livermore magnetic confinement program.

The research will include but not be limited to the following types of studies:

Tearing Mode Instability in Field-Reversed Configurations: As discussed earlier, we have recently developed techniques for investigating microstability properties of a field-reversed ion layer embedded in a background plasma. The analysis[4] was carried out for flute perturbations ($\partial/\partial z=0$), and incorporated the important influence of transverse magnetic perturbations as well as the (kinetic) effect of large ion orbits. It is proposed to extend this analysis to investigate tearing mode stability behavior for $k_z \neq 0$. Particular emphasis will be placed on low-frequency ($|\omega| \lesssim \omega_{ci}$) tearing mode stability properties, including a detailed investigation of the influence of axial velocity spread and background plasma density on stability properties. This analysis will provide important guidance for planning of field reversal experiments in long solenoids with desirable long-time stability properties.

Mirror-Drift-Cone Instabilities: The drift-cyclotron loss-cone instability, although the subject of many theoretical studies, continues to demand further intense investigation, particularly with regard to (a) nonlocal stability properties at low azimuthal mode numbers, (b) identification of mechanisms for stabilizing the high-frequency (short-wavelength) portion of the wave spectrum, and (c) a detailed understanding of instability sensitivity to plasma electron properties. Investigations will be carried out in each of these important problem areas. These studies will include: (a) application of the nonlocal hybrid-kinetic stability formalism developed in Ref. 2 to investigate the macroscopic mode structure and nonlocal stability properties for choices of ion distribution function $f_i^0\ (H_1 - \omega_\theta P_\theta, v_z)$ that give diffuse equilibrium profiles, and (b) investigation of nonlinear saturation mechanisms and/or dissipative effects that may suppress the short-wavelength portion of the wave spectrum. In addition, an important component of our theoretical studies relating to microinstability processes in magnetic mirrors will be directed at establishing strong local theory support for the Constance experiment. This work will include an identification of the waves excited by beam injection, and the associated influence on plasma properties and suppression of the DCLC instability.

Gradient-Driven Instabilities in TMX/Long Solenoids: Our extensive investigations of the lower-hybrid-drift instability[10,11] in linear theta-pinch configurations have indicated, at least in strong-gradient situations, the importance of this instability in producing anomalously high resistivity and associated radial transport in circumstances where the late-time behavior is not dominated by end losses. It is proposed to apply the techniques and understanding developed in the investigation of the lower-hybrid instability to study stability and transport properties associated with the drift-cyclotron instability in both the low- and high-frequency regimes. Particular emphasis will be placed on local stability studies for profiles and parameters appropriate to the linear section of TMX. Based on our experience with the lower-hybrid-drift instability,[6] it is anticipated that finite-beta electromagnetic effects (particularly for $T_e/T_i > 1$) and ∇B_0 orbit modifications will have a strong influence on stability behavior. If the instability growth rate is found to be sufficiently strong, an investigation of the nonlinear development of the instability and the associated anomalous radial transport will be initiated.

Instabilities Driven by Anomalous Resistivity: Nonideal MHD studies with small but finite classical resistivity have long predicted the importance of tearing modes localized near surfaces where $\underset{\sim}{k}\cdot\underset{\sim}{B}_0 = 0$. Since high-beta experiments are often characterized by anomalously high resistivity due to wave-particle interactions, it is proposed to ascertain the linear growth properties of the tearing-mode instability in an environment where the (microinstability produced) turbulent resistivity is larger than the classical resistivity. Particular emphasis will be placed on the toroidal reversed field pinch configuration. The basic theoretical model used in these studies will be the MHD equations, generalized to include an anisotropic anomalous collision frequency for momentum transfer,

$$\left(\frac{\partial}{\partial t} N_j m_j \underset{\sim}{V}_j\right)_{an} = e_j \langle \delta N_j \delta \underset{\sim}{E} \rangle_{an} ,$$

which allows for difference resistivity properties in the cross-field directions $\underset{\sim}{J} \times \underset{\sim}{B}$ and $\underset{\sim}{B} \times (\underset{\sim}{J} \times \underset{\sim}{B})$.

References

1. R. C. Davidson and N. T. Gladd, Phys. Fluids 20, 1516 (1977).
2. "Nonlocal Hybrid-Kinetic Stability Analysis of the Mirror Drift-Cone Instability," R. C. Davidson, H. Uhm and R. Aamodt, manuscript in preparation (1979).
3. "Stability Properties of a Cylindrical Rotating P-Layer Immersed in a Background Plasma," H. S. Uhm and R. C. Davidson, Phys. Fluids 22, in press (1979).

4. "Stability Properties of Field-Reversed Ion Layers," R. C. Davidson and H. Uhm, Phys. Fluids 22, in press (1979).
5. R. C. Davidson, Phys. Fluids 21, 1375 (1978).
6. R. C. Davidson, N. T. Gladd, J. Huba, and C. W. Wu, Phys. Fluids 20, 301 (1977).
7. R. C. Davidson, N. T. Gladd and Y. Goren, Phys. Fluids 21, 992 (1978).
8. "Microstability Properties of Reversed-Field Pinches," R. C. Davidson and N. T. Gladd, 1978 Padova Workshop on Reversed Field Pinches.
9. "Kink Instabilities in Reversed-Field Pinches," J. Y. Choe and R. C. Davidson, 1978 Padova Workshop on Reversed Field Pinches.
10. R. C. Davidson, and N. A. Krall, Nucl. Fusion 17, 1313 (1977).
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C. ANOMALOUS TRANSPORT IN TOROIDAL FUSION SYSTEMS

C.17 ACTIVITY DESCRIPTION

The purpose of the proposed work is to develop a self-consistent microturbulence theory for magnetic confinement systems, primarily toroidal (tokamak and stellerator) systems. Given macroscopic MHD stability, reactor control and economics will be determined by microturbulence (anomalous transport). Successful reactor designs will depend largely on our ability to predict and/or scale these anomalous transport processes theoretically.

Although our present understanding of the anomalous loss processes in tokamaks is minimal (the mechanism of anomalous losses is not known), several recent developments appear to be converging on the solution to this problem. They are: (a) appreciation of the importance of very small magnetic perturbations in electron transport, (b) experimental evidence (through understanding the soft X-ray anomally) from Alcator and T10 that magnetic fluctuations are the mechanism of anomalous heat loss, and (c) discovery of the resonance broadening effects due to magnetic shear, which provides an effective saturation mechanism for low frequency microturbulence, and allows the computation of self-consistent anomalous transport coefficients. Alpha particle behavior, particularly slowing down, will in all likelihood be dominated by turbulence driven by the extremely non-thermal alpha distribution function. Here the role of alpha slowing down in ignition experiments is clear and crucial. The likely possibility of lowering the ion temperature threshold for ignition due to anomalous slowing down justifies theoretical work in this direction.

The proposed work is to develop a reliable theoretical framework for the anomalous transport calculations in toroidal systems. There is optimism, based on the last six month's efforts, that this can be done in the next several years.

C.19 DETAIL ATTACHMENTS

Facility Requirements

It is desirable to have computer facilities (both time allocations and computational physicists) at MIT for the numerical solution of the eigenvalue equations of microturbulence theory. This will become increasingly necessary as more realistic models are used for the calculations. Even at the present level of complexity, numerics are needed to verify analytic speculation. We are presently relying on Oak Ridge for this part of the work.

Publications

"Theory of the Runaway Electron Tail", Kim Molvig, Miloslav S. Tekula, and Abraham Bers, Phys. Rev. Lett. 38, 1404 (1977).

"Plasma Heating with a Rotating Relativistic Electron Beam. I. Return Current Processes", Kim Molvig and Normal Rostoker, Phys. Fluids 20, 494 (1977).

"Plasma Heating with a Rotating Relativistic Electron Beam. II. Magnetosonic Wave Emission", Kim Molvig and Norman Rostoker, Phys. Fluids 20, 504 (1977)

"Observation of the Fluid-Ion Cyclotron Instability by Scattering of Pulsed CO_2 - Laser Radiation", A. Gondhalekar, Kim Molvig and M.S. Tekula, Phys. Rev. Lett. 38, 354 (1977).

"Fueling and Shielding by Gas-Plasma Blankets in Alcator", Ronald Parker, Kim Molvig and Louis Scaturro, Proceedings of the Workshop in Fusion Fueling. (Princeton, New Jersey, 1977).

"Filamentary Instabilities of Rotating Electron Beams", Kim Molvig, Gregory Benford and William C. Condit, Jr., Phys. Fluids 20, 1125, (1977).

"Surface Filamentation of a Relativistic Electron Beam in a Plasma", Kim Molvig, C. W. Roberson, and T. Tajima, Phys, Fluids 21, 975 (1978).

"Theory of Runaway Electrons: Structure of the High Energy Distribution Function", Kim Molvig, Miloslav S. Tekula, submitted for publication (1978).

"Mechanism for the ω_{pe} Radiation in Tokamaks," I. H. Hutchinson, Kim Molvig, and S. Yuen, Phys. Rev. Lett. 40, 1091 (1978).

"Evidence for Magnetic Stochasticity as the Machansim for Heat Loss in Alcator," Kim Molvig, M. S. Tekula and J. Rice, Phys. Rev. Lett. 41, 1240 (1978).

"Comments on 'Nonthermal Emission at the Plasma Frequence'," I. H. Hutchinson, and Kim Molvig, Phys. Fluids 21, in press (1979).

"Turbulent Destabilization and Saturation of the Universal Drift Mode," S. P. Hirsham and Kim Molvig, to be published in Phys. Rev. Lett. (1979).

"Finite β_e Universal Mode Turbulence and Alcator Scaling," Kim Molvig and S. P. Hirshman.

Technical Progress

1. Anomalous Electron Thermal Conductivity

(a) Soft X-ray Anomally: While anomalous electron heat loss is clearly one of the major physics problems in toroidal confinement, the process or processes responsible for it are still largely unknown. Traditionally, anomalous losses have been attributed to drift waves of various kinds, but the experimental evidence for this assumption is ambiguous at best. More recent measurements seem to rule out drift waves, for densities > 10^{14} cm^{-3}, at least in the usual quasilinear sense. However, even at fluctuation levels below those required to produce significant quasilinear transport, the inherently non-linear effect of magnetic surface destruction can lead to sizeable transport. These points were emphasized recently by Callen. There are basically two forms this magnetic surface destruction can take. In the first, the so-called "magnetic flutter" model, one has essentially coherent island structures most of the time. These grow up out of noise to an amplitude at which islands overlap. Stochasticity of the field lines ensues and presumably damps the underlying drift waves, allowing the original equilibrium to reform, wherein the process repeats itself. Alternatively one can have some quasi-steady saturated turbulence level in which "stochasticity" prevails. Either form can lead to substantial enhancements of thermal transport.

We have made a connection between these magnetic fluctuations and an anomaly in the soft X-ray spectrum that has been found persistently in Alcator. This anomaly cannot be explained by classical processes. We have shown that magnetic fluctuations give rise to an enhanced suprathermal tail in the electron distribution function which is related to the thermal flux. The tail and energy flux are both gauged by the same parameter, τ_E, the energy confinement time. By fitting the X-ray spectrum a τ^*_E can be determined. The τ^*_E so obtained agrees with the bulk energy confinement measurements both in absolute magnitude and scaling with the plasma density.

(b) Shear Induced Resonance Broadening: In a sheared magnetic field, turbulent diffusion of electrons in the vicinity of a mode rational surface can eliminate the stabilizing influence of nonresonant electrons and lead to an absolute instability at small but finite wave amplitudes. As the turbulence grows, the inverse electron Landau resonance is broadened in both velocity and configuration space, and the convective shear damping due to ions is enhanced by turbulent spatial broadening of the mode until saturation occurs.

The original work of Pearlstein and Berk indicated the existence of an absolute universal instability of a confined plasma ($\nabla p \neq 0$) in a sheared magnetic field. Recently, numerical integration of the exact differential equation describing the radial structure of the drift wave eigenmode showed the absence of an absolute instability, regardless of how weak the shear or how large the poloidal wave number. The stability of the universal mode in these improved treatments is due to the inclusion of nonresonant, nonadiabatic electrons in the region about the mode rational surface where $k_{\parallel}(r) = [m - nq(r)]/Rq \leq \omega/v_{Te}$. Here, m and n are poloidal and toroidal mode numbers, respectively, $q(r) = rB_T/RB_P$ is the safety factor, ω is the mode frequence, and $v_{Te} = (2T_e/m_e)^{1/2}$ is the electron thermal velocity. Thus, instability might be recovered by an effect altering the electron response in the region around the rational surface.

We have shown that turbulent diffusion of electrons across the rational surface, due to a combination of shear ($\partial k_{\parallel}/\partial r \equiv k'_{\parallel} \neq 0$) and random $\vec{E} \times \vec{B}$

fluctuations and/or stochastic magnetic perturbations, results in a finite amplitude-induced version of the absolute universal instability. Physically, the turbulent scattering of electrons across the rational layer leads to an effective finite value for $k_{\parallel}$ which destroys the stabilizing influence of the nonresonant electrons. At larger amplitudes, the electron growth is reduced and the ion shear damping is enhanced by spatial broadening of the mode, yielding nonlinear stabilization.

The turbulent diffusion process in a sheared magnetic field produces a resonance broadening mechanism for the electrons which is fundamentally different than the process, due to random $\vec{E} \times \vec{B}$ drifts alone, in a shearless field. With shear, stochastic radial motion combines with parallel electron streaming to induce random poloidal motion. The decorrelation frequency resulting from this random motion of electrons in a sheared field can exceed the magnitude of the *real* part of the linear eigenfrequency for low levels of turbulence.

(c) <u>Finite β_e Universal Mode Turbulence and Alcator Scaling:</u> An outline for a self-consistent theory of finite β_e universal mode turbulence has been given. Saturation results from resonance broadening of the electron response due to magnetic shear. Electron diffusion, for $\beta_e > m_e/m_i$, is due to the magnetic part of the fluctuations. The diffusion coefficient, $D = 0.1\ (T_e/(T_i + T_e)^4\ (m_e/m_{i\ e})(L_s/L_n)^2 \times v_i\rho_i{}^2/L_n$, scales inversely with density, is independent of magnetic field, and is in excellent quantitative agreement with observations on the Alcator tokamak.

One of the principal theoretical goals in tokamak research is the development of a self-consistent turbulence theory for the short wavelength fluctuations responsible for anomalous transport. We have given a heuristic outline of such a theory for the finite β_e universal instability. The treatment so far is approximate in its solution of the eigenmode equations, but can, in practice, be carried out to arbitrary accuracy. The resulting formula for the anomalous electron thermal conductivity has many similarities, including absolute magnitude and density, temperature and ion mass scalings, with experimental observations. For $\beta_e > m_e/m_i$, as is typical, the calculation constitutes an example of a self-consistent theory of stochastic magnetic fluctuations.

Until recently, most turbulence theories ignored shear in the equilibrium magnetic field. Without shear, turbulence mainly effects the ions. The basic saturation picture, as developed by Dupree, balanced linear electron growth, γ_e^L, against nonlinear (turbulent) ion damping, γ_i^{NL}, taking $\gamma_i^{NL} = k_\perp^2 D$ as the basis for the $\gamma_e^L/k_\perp^2$ estimates of the anomalous diffusion coefficient. However, recent theory has shown that $\gamma_i^{NL} \ll k_\perp^2 D$, because the ion-wave interaction is weak for low frequency modes. Consequently, for tokamak parameters, ion non-linearity is not a viable saturation mechanism.

With shear, because of their rapid mobility along the field lines, electrons are the most effected by turbulence. Here, the ions cause damping linearly, due to the shear, γ_i^S. Electron growth is modified by shear induced resonance broadening, to γ_e^{NL}. Saturation, $\gamma_e^{NL} = \gamma_i^S$ can occur at low turbulence levels, consistent with observations.

In a sense, the main point of this work has been to show that shear induced resonance broadening is applicable to the electromagnetic problem and provides an effective mechanism for the saturation of such instabilities. The specific example considered is basically a drift wave, although finite β_e does modify the shear damping in an important way, and when $\beta_e > m_e/m_i$, most of the transport is due to the magnetic part of the fluctuation.

2. Anomalous Slowing Down of Alpha Particles:

A systematic search for alpha driven instabilities has been initiated. The first step of identifying the highest growth rate modes has been essentially completed, with the study of modes in the frequency range $\omega_{ci} < \omega < \omega_{LH}$, using a proper toroidal treatment. There are bands of instability centered on the gyroharmonics with a continuum starting at mode number N such that $N\varepsilon > 1$ ($\varepsilon = a/R$ is the inverse aspect ratio). Beyond N, the growth rates go to zero as the resonance broadening due to spatial inhomogeneity eventually leads to an unmagnetized (stable) alpha response.

These are very fast modes, growing at a rate which is a sizable fraction of the ion gyrofrequency. They are driven by the inverted energy population of alphas with the consequence that the dominant weak turbulence effect is enhanced slowing down. Obviously, the effect of such modes, if not accompanied by deleterious side effects, is to change the requirements for ignition. This fact motivates our study.

Future Accomplishments (FY 80 and FY 81)

The proposed work follows naturally from the technical progress of the past year outlined above. The underlying motivation is to resolve as definitively as possible, the physics of turbulence induced anomalous transport in toroidal systems. As such, the study involves the formulation and analysis of the relevant experiments as well as the questions of turbulence theory that the anomalons transport problem raises. On the theoretical side, the study will focus on the relationship of stochasticity to turbulence theory, in the hope of justifying some of the crucial approximations (such as the random phase approximation) which at the present time are based mostly on convenience.

1. Anomalous Electron Thermal Conductivity

The experiments most relevant here are the CO_2 scattering experiment and the soft X-ray spectral measurements. Analysis of this data will continue. There is some hope that the CO_2 experiment will be more definitive on Alcator C - either by giving a detectable signal in the center of the discharge or setting meaningful limits on the density fluctuations there. This would then verify or refute the recent thinking, attributing losses to magnetic fluctuations.

Theoretically, the past year has seen a very helpful development, namely the discovery of shear induced resonance broadening. This is clearly the dominant turbulence effect for low frequency modes in tokamaks and allows the calculation of saturated states and the associated transport coefficients, self-consistently. Some of the higher order turbulence effects are not so clear, however, and the question of how to calculate them properly remains open. This problem will be the primary focus of the following year. The approach will be to study the wave dynamics directly, looking for stochastic behavior of the wave phases. This would allow a reliable derivation of weak turbulence theory and a clear delineation of its bounds of validity.

2. Anomalous Alpha Particle Transport

The main thrust of this work will be to estimate the turbulence effects of the high frequency modes described above, specifically the enhanced slowing down rates and attendant modification of ignition criteria. Much of this can be done with a direct application of quasi-linear theory (evolution to the marginally stable point), but attention will be given to the points outlined above.

SUBTASK #6

STABILITY AND TRANSPORT PROPERTIES OF LINEAR AND TOROIDAL FUSION SYSTEMS

J. E. McCune, Principal Investigator

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Stability and Transport Properties of Linear and Toroidal Fusion Systems

17. TASK DESCRIPTION

Plasma kinetic theory is applied to the study and description of (a) the dynamic and kinetic behavior of Tokamak discharges, and (b) the stability properties of high-β plasmas in a tandem-mirror environment. In (a), the focus is on determining self-consistently the various quasi-equilibria of toroidal discharges as they evolve in time. Over a wide range of collisionality a study of the dynamics of such systems, including the development of any ambipolar fields (and possible associated rotation) is carried out. The quasi-equilibria are then perturbed to test for low-frequency eigenmode stability, including toroidal effects. In (b), a stability analysis of the high-β central-cell plasma of a tandem mirror device is studied kinetically. Compared with earlier (low-β) studies we expect novel results related, for example, to ∇B-drift resonances and coupling with various Alfven waves.

19. DETAIL ATTACHMENTS

Purpose

Toroidal Discharge (Tokamak) Study. The primary purpose of this work is to achieve an understanding of the dynamical development of hot, low-collisional plasmas confined magnetically in Tokamaks. Insight into the sequential development of various processes is important in various ways: (1) optimal operation of the system; (2) eventual control of the device (especially near ignition); and (3) self-consistent determination of quasi-static equilibria. In the latter instance, the "equilibria" themselves often depend on the history of their development. There appears to be, for example, no other way to determine uniquely the (ambipolar) fields in various discharge phases than through the study of the dynamics through which they evolve. Such fields, in turn, can affect strongly both the transport and stability properties of the system. Further, as increased knowledge of the various possible states of such discharges is gained, increasingly realistic analysis of their stability can be carried out.

Tandem Mirror Stability. The purpose of this work is to study micro instabilities in a high plasma typical of the tandem-mirror control cell. New features of well-known instabilities (e.g., the low-β drift-universal mode) can be expected to arise through strong coupling with various electromagnetic modes and with certain MHD (Alven) waves. In addition, new (or stronger) wave-particle resonances can be expected, for example through magnetic-curvature and "∇B"-particle drifts.

Technical Progress

Tori: A principal tool for carrying out a dynamical study of various types of fusion (or near-fusion) plasmas (in linear or toroidal systems) is the "Inertial Drift-Kinetic Equation." This equation allows treatment of the low-collisionality plasma without a priori ordering of the "$\vec{E} \times \vec{B}$"-drift as small compared with ion thermal speeds.

In FY '78, a major step forward was taken, on completion under this program of the thesis by J. Fisher* in which the "Inertial Drift-Kinetic Equation" was derived. This work provided a means of studying toroidal plasma dynamics in the plateau- and banana-regimes, including possible significant rotation and associated inertial effects. Fisher showed that this equation, in the form developed by him, could be solved in a variety of cases. He indicated possible strong asymmetries in the perturbed (guiding-center) distribution function, possibly leading to enhanced particle- and energy-losses.

Following up on this work both Svolos and Rubenstein (FY '78 and '79) initiated dynamical studies of Tokamak plasmas at low-collisionality. Rubenstein has recently (FY '79) established important flux-friction relationships, for both ions and electrons, which provide important constraints on the relationship between possible rotation and the cross-flux (ambipolar) fields.

Work is continuing in this area. Rubenstein is concentrating on developing the dynamics (and resulting quasi-equilibria) with sufficient precision to determine transport properties, including the effects self-consistent cross-flux fields. Svolos is using the equilibria developed by him and by Fisher to initiate detailed studies of (low-frequency) microinstabilities in toroidal geometry.

*Fisher, J.L., "Finite beta and inertial effects in a toroidal discharge," PhD thesis, MIT, June (1978).

<u>Mirrors</u> In the high-β central cell plasma of the tandem mirror, the equilibrium is perhaps most usefully described using a drift-kinetic (roughly, a guiding-center) treatment. Hastings (FY '78 and early '79) has developed a general means for describing such equilibria in plasmas in a tandem-mirror enviornment. Building on this, and using a gyro-kinetic equation, Hastings has recently (FY '79) developed a general mathematical procedure for establishing the perturbations of such equilibria, including finite Larmor radius effects. At persent, the work in this area is focussed on setting up the corresponding "radial eigenmode" problem, and interpreting the results physically in various parameter regimes.

<u>Publications</u>

"Calculation of a self-consistent, low-frequency electrostatic field in the drift-kinetic approximation," Beasley, C. O., Jr., McCune, J. E., Meier, H. K., and vanRij, W. I., J. Plasma Phys. <u>20</u>, 115-126 (1978).

"Numerical study of drift-kinetic evolution of collisional plasmas in tori," Beasley, C. O., Jr., McCune, J. E., et al, J. Plasma Phys. <u>19</u>, 593 (1977).

"Inertial drift-kinetic equation," J. Fisher with J. McCune, under revision for resubmission.

<u>Future Accomplishments (FY '80)</u>

Milestone 1. (Rubenstein)

Upon completion of this work a more general treatment of neo-classical equilibria, including significant cross-flux fields, will be available. Edge-effects on plasma transport properties will be better understood.

Milestone 2. (Svolos)

A study of drift modes in "honest" toroidal geometry, including cross-flux E-fields and inertia, will help assess the vulnerability of large-scale (fusion-oriented) Tokamaks to various low-frequency modes, especially drift modes.

Milestone 3. (Hastings)

The mathematical method already developed, for solution of the gyro-kinetic equation and study of high-β plasma eigenmodes in a tandem mirror environment, will be exploited in a variety of practical cases. Increased insight into the (possibly) different stability characteristics of low-β and high-β plasmas will be made available.

Future Accomplishments (FY '81)

The "natural state" of high-temperature magnetized, "confined" plasma seems to turbulent, including stochastic fields. The possibility of treating plasma "equilibria" which a priori includes such turbulence will be explored in FY '79-'81. A "Milestone" for this period would be the achievement of a self-consistent picture of a fusion plasma, including both the equilibrium and the saturated turbulence associated with it. Turbulence "modeling," an advanced engineering technique in rapid development in fluid dynamics may also be useful in application to plasmas.

Relationship to Other Projects

The research on Tokamak discharges is closely related to Alcator, as well as to the future development of such devices as relate to a Tokamak ignition experiment. The "mirror" studies (high-β plasma stability analysis) is largely motivated by the Tandem Mirror Experiment at LLL.

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U.S. DEPARTMENT OF ENERGY

FIELD TASK PROPOSAL/AGREEMENT

1. WP BIN NUMBER	2. TASK NO.	3. REV. NO.	4. PROJECT NO.	5. DATE PREPARED (mm dd yy)	6. CONTRACTOR NUMBER

7. TASK TITLE: MACSYMA

8. WORK PACKAGE TITLE: PFC Applied Physics Division, MACSYMA Group

9. BUDGET AND REPORTING CODE	10. TASK TERM Begin: (mm dd yy) End: (mm dd yy)	11. CONTRACTOR NAME	12. CODE (see instructions)

13. CONTRACTOR TASK MANAGER (Name, FTS No.)

Ronald C. Davidson
Director, Plasma Fusion Center
617/253-8102

14. PRINCIPAL INVESTIGATORS

Joel Moses

15. WORK LOCATION (See instructions): Name of facility, City, State, ZIP Code

Massachusetts Institute of Technology Plasma Fusion Center
Cambridge, Massachusetts

16. Does this task include any management services efforts?
☐ YES
☐ NO

17. TASK DESCRIPTION (Approach, relation to work package, in 200 words or less)

This activity provides the research and development on a hardware/software system that allows researchers in the magnetic fusion community to manipulate mathematical expressions symbolically. Consultation is provided for users at the national labs, other universities, as well as at MIT. There is ongoing research on new algorithms for making this system more useful to DMFE. Hardware alternatives to the MACSYMA Consortium computer at MIT are also being developed. The computer is currently being used as a gateway to MFECC by the MIT fusion community, and it is expected that this system will become an integral part of the MFE network.

18. CONTRACTOR TASK MANAGER

Person in Charge: Ronald C. Davidson, Director, Plasma Fusion Center

Ronald C Davidson (Signature) 5/30/79 (Date)

19. DETAIL ATTACHMENTS: (See instructions)

☐ a. Facility Requirements
☐ b. Publications
☐ c. Purpose
☐ d. Background
☐ e. Approach
☐ f. Technical progress
☐ g. Future accomplishments
☐ h. Relationships to other projects
☐ i. Environmental assessment
☐ j. Explanation of milestones
☐ k. Other (specify):

19. DETAIL ATTACHMENTS

Facility Requirements

All facilities, such as DEC KL-10, DEC VAX 11/780, LISP machine have been provided via other grants in the past. We expect this practice to continue. For informational purposes, our major hardware needs in FY 80-81 will be for several super-micro personal computers, costing about $75K.

Purpose

The purpose of this work is to carry out research and development on the MACSYMA symbolic manipulation system including provisions for the use of the system by the national MFE community. Support is also provided for access to the MFECC by the MIT fusion community.

Publications (1977 - 1978)

Wang, Paul S.-H. "Preserving Sparseness in Multivariate Polynomial Factorization," Proceedings of the MACSYMA Users' Conference, NASA, Berkeley, Ca., July 1977.

White, Jon L., "Lisp: Program is Data — A Historical Perspective on MACLISP," Proceedings of the MACSYMA Users' Conference, NASA, Berkeley, Ca., July 1977.

White, Jon L., "Lisp: Data is Program — A Tutorial in LISP," Proceedings of the MACSYMA Users' Conference, NASA, Berkeley, Ca., July 1977.

Zippel, Richard E., "Univariate Power Series Expansions in MACSYMA," Proceedings of Sympsoium on Symbolic and Algebraic Computation, ACM, Yorktown Heights, N. Y., August 1976.

Zippel, Richard E., "Radical Simplification Made Easy," Proceedings of the MACSYMA Users' Conference, NASA, Berkeley, Ca., July 1977.

Zippel, Richard E., "Simplification of Radicals with Applications to Solving Polynomial Equations," unpublished S. M. thesis, MIT, Department of Electrical Engineering and Computer Science, June, 1977.

Genesereth, Michael R., "An Automated Advisor to a Complex Computer System," Ph.D. Talk, Harvard Univ., Sept., 1978.

Technical Progress

The value of the MACSYMA project to MFE can be determined, in large part, by the continued high utilization rate of our computer by the national MFE community and by the fusion community within MIT. We measure this usage by the number of logged on hours per month. These figures hit a high of 2,900 hours last May and have been over 2,000 hours for most of 1978. Roughly one half the usage is internal to MIT and one half is from the outside. As a measure of the value of this time, we multiply the monthly usage by $20. As a further comparison, the next largest group of MACSYMA users are from the US Navy labs who never use more than 600 hours in a given month. It should be noted that the non-MIT users come from every major lab (LASL, LLL, GA, PPPL, ORNL) as well as other universities (e.g. Prof. Bakshi's students at Boston College). As indicated repeatedly in the past, increased utilization of the system can be expected if it were possible to log into it from the MFENET. Progress has been made to permit MIT fusion theorists to log into MFECC via our computer, but the reverse operation is still not available. Due to internal changes in computer hookups, which are detailed below, the monthly usage figures for MIT users has decreased by over 50% since November, 1978. This is essentially a computer accounting quirk. Internal usage has, if anything, somewhat increased due in part to Lidsky's use of MFECC via our computer.

August '78 - MIT obtains access to MFECC via ARPANET connection of MACSYMA computer. This was largely accomplished through improvements in MFENET software.

September '78 - Completion of PhD thesis by Michael Genesereth on an automated advisor for MACSYMA users.

September '78 - Addition of 1 megabyte of core memory to MACSYMA system.

November '78 - Local high-speed network interface of Plasma Theory Group to MACSYMA computer.

March '79 - Addition of 4 megabytes of memory to MACSYMA system.

April '79 - First version of FORTRAN to LISP translator completed.

June '79 - Second MACSYMA Users Conference, Washington, D.C. Approximately ten papers from MIT are expected.

Future Accomplishments (FY 80 and FY 81)

The following accomplishments are anticipated in FY 80 and FY 81:

October '79 - Completion of PhD thesis by Richard Zippel on new algorithms for factorization and solution of linear equations.

October '79 - Completion of PhD thesis by Barry Trager on new algorithms for integration.

January '80 - MACSYMA on LISP machines capable of running very large problems. Beginning of integrated numeric/symbolic system.

June '80 - First version of LISP system on DEC VAX computer.

January '81 - Release version of MACSYMA on DEC VAX computer' early version of MACSYMA on super-micro computers.

June '81 - Early version of integrated numeric/symbolic system on personal super-micro computers.

Relationship to Other Projects

The MACSUMA system is, to our knowledge, the only general symbolic manipulation system being made available to the MFE community nationally.