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MASTER

The Computational Physics Program of the National MFE Computer Center

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I. INTRODUCTION

Since June 1974, the MFE Computer Center has been engaged in a significant computational physics effort. The principal objective of the Computational Physics Group is to develop advanced numerical models for the investigation of plasma phenomena and the simulation of present and future magnetic confinement devices. In addition, the group interacts with the systems programming staff to improve services; it fills the roles of internal critic and advisor by representing a user viewpoint.

The group currently consists of six Ph.D. physicist/mathematicians - D.V. Anderson, M.G. McCoy, A.A. Mirin, D.D. Schnack, A.I. Shestakov and D.E. Shumaker. In addition, students in the Department of Applied Science (U.C. Davis) are engaged in fusion research under the guidance of senior group members. This year we have also had a participating guest, Yuan Li, from Rutgers Univesity.

The computational physics group is involved in several areas of fusion research. One main area is the application of multidimensional Fokker-Planck, transport and combined Fokker-Planck/transport codes to both toroidal and mirror devices. Another major area is the investigation of linear and nonlinear resistive magnetohydrodynamics in two and three dimensions, with applications to all types of fusion devices. In addition to these computational physics studies, investigations of more efficient numerical algorithms are being carried out.

One of the principal objectives of the computational physics group is to provide support for experimental and theoretical work within the MFE community. At present, this support falls into the following areas:

Spheromak formation and stability	PPPL
Stability and evolution of RFP and stability of FRTP	LASL, LLL
Tearing mode stability of reversed field plasmas	LLL
Resistive stability of Doublet III	GA
Field reversed mirror transport	LLL

Fokker-Planck/transport calculations of PLT	PPPL
Fokker-Planck and transport analyses of Tandem Mirror systems	LLL
RF current drive and electron heat transport in tokamaks	GA

A summary of our program follows.

II. COMPUTATIONAL STUDIES

A. TIME DEPENDENT MAGNETOHYDRODYNAMICS

A principal technique for determining macroscopic plasma behavior is through the solution of the time dependent MHD equations. Of particular interest is the nonlinear evolution and saturation of fluid instabilities. Accurate simulation of such phenomena requires the solution of the full set of MHD equations, which comprises a coupled system of eight nonlinear partial differential equations. This is a formidable task for any computer system. In order to make these computations tractible, approximations have often been made, including reduction in dimensionality, linearization, restriction to a particular geometry and the assumptions of infinite conductivity and/or low "beta" ("beta" is the ratio of plasma pressure to magnetic pressure). The infinite conductivity assumption (called ideal MHD) greatly simplifies the numerics, since the MHD equations are then hyperbolic rather than parabolic. Moreover resistive MHD modes tend to grow more slowly, thereby requiring a much longer run time. The low beta assumption allows an ordering in which the problem is reduced to the solution of two scalar equations.

At the MFECC, the emphasis has been on constructing resistive MHD codes which are applicable to all plasmas, independent of beta. Both linear and nonlinear codes have been written which solve the full set of resistive, "finite-beta" MHD equations in two and three dimensions (see Table 1). Moreover, these codes use an implicit time discretization, so that there is no restrictive non-physical upper bound on the size of the timestep. Additionally, the nonlinear models are cast in general orthogonal curvilinear coordinates, making them applicable to a variety of geometries. These features make our MHD codes unique to the MFE community.

TABLE 1. MFECC MHD CODES

CODE	CONTACT	CHARACTERISTICS AND APPLICATIONS
MHD2D	D.D. SCHNACK	2D (x1, x2), Curvilinear Coordinates, Nonlinear, Implicit, Resistive; RFP, FRTP
IMP	C.H. FINAN*	3D (x1, x2, x3), Curvilinear Coordinates, Nonlinear, Implicit, Resistive; RFP, Tokamaks
RIPPLE VI	A.I. SHESTAKOV	2D (R,Z), Linear, Nonaxisymmetric Perturbations, Implicit, Resistive; FRTP, Tokamaks
ALIMO	A.I. SHESTAKOV	2D (R,Z), Linear, Axisymmetric Perturbations, Implicit, Resistive; FRTP, Tokamaks
RIPPLE V	A.I. SHESTAKOV	1D (r), Linear, Implicit, Equilibrium Flow
RIPPLE IV	D.D. SCHNACK	1D (r), Linear, Implicit, Resistive; Tokamaks, RFP
RESTAB	D.D. SCHNACK	1D (r), Linear, Implicit, Resistive, Compressible, Viscous, Thermal Conductivity; Tokamaks, RFP

*Former D.A.S. student; currently in A Division at LLNL.

Our MHD research is in the following areas:

o We are applying our linear and nonlinear two dimensional codes to the behavior of resistive modes in field reversed and toroidal configurations. These calculations are applicable to Tokamaks (D III "Big Dee"), the Field Reversed Theta Pinch, the Spheromak and the Field Reversed Mirror. We are also studying the formation phase of these plasmas.

o We have been modeling the evolution and saturation of magnetic islands in both Cartesian (sheet pinch) and cylindrical (diffuse) geometries. We are currently studying the nonlinear evolution of the resistive interchange instability (or "g-mode") in the Reversed Field Z-Pinch.

o Our three dimensional code has been effective in the study of the formation of the reversed field state in a square cross-sectional Z-pinch. Similar calculations are also being carried out in two dimensions. The object of this study is to find the final nonaxisymmetric "ohmic" states of the pinch and to determine which parameters lead to the reversed field state.

Our MHD publications are summarized in Appendix A.

B. PLASMA TRANSPORT

Transport codes are used to evaluate macroscopic plasma parameters (e.g. density, temperature) on a timescale comparable to the lifetime of the plasma. They differ from other fluid codes in that the fast timescale physics is integrated out of the problem.

At the MFECC, transport codes are being applied to Tandem Mirrors, Tokamaks and Field Reversed Mirrors. A list of our transport codes and their applications appears in Table 2.

Over the past year we have made a great deal of progress in the following areas:

o Radial transport in tandem mirrors
o Fokker-Planck/transport studies of tokamaks
o Radial transport in field reversed mirrors
o Anomalous electron transport in tokamaks

A brief summary follows.

TABLE 2. MFECC TRANSPORT CODES

CODE	CONTACT	CHARACTERISTICS AND APPLICATIONS
TMT	A.A. MIRIN	1D (R); Tandem Mirrors
FPT	A.A. MIRIN	Combined Fokker-Planck/Transport, 1D (R) plus 2D (V,Ø); Tokamaks
FRT	D.E. SHUMAKER	1D (Poloidal Flux); Field Reversed Mirrors
TAT	D.E. SHUMAKER	1D (Toroidal Flux); Tokamaks
TRANSPORT	A.A. MIRIN	1D (R); Tokamaks
LDL	M.G. McCOY	2D (R,V); Electron Transport; Tokamaks

o Radial Transport in Tandem Mirrors

A tandem mirror machine consists of a long, solenoidal cell with minimum-B mirrors (plugs) at either end which act to electrostatically confine the central cell ions. The rate at which charged particles and heat diffuse in radius is of crucial importance. Of special significance is the expected enhanced transport of ions due to resonance between their azimuthal drift and axial bounce motions, which results from the presence of a non-axisymmetric magnetic field in the transition regions between the end plugs and the solenoid. A radial transport code, TMT, has been written in order to investigate this and other related phenomena. This multispecies code computes radial profiles of densities and temperatures in both the central solenoid and the end plugs along with a self-consistent electric field. Classical and neoclassical effects on transport are taken into account. This code is being used to study the Tandem Mirror Experiment (TMX) and to help design larger tandem mirror devices.

o Fokker-Planck/Transport Studies of Neutral Beam-Heated Tokamaks

Neutral beam-heated tokamaks are characterized by the presence of one or more energetic ion species which are quite non-Maxwellian along with a warm Maxwellian bulk plasma. For scenarios in which there is a large energetic ion population, it is very important to represent these energetic species by means of velocity space distribution functions and to follow their evolution in time by integrating the Fokker-Planck equations. It is essential to utilize the full nonlinear Fokker-Planck operator to assure that the slowing down and scattering of these energetic species is computed accurately and realistically.

Our Fokker-Planck/transport code (FPT), in addition to solving radial transport equations for the bulk plasma densities and temperatures, solves nonlinear Fokker-Planck equations in 2D velocity space for the energetic ion distribution functions. The FPT code is unique in that it is the only tokamak transport code which does not either linearize the Fokker-Planck operator or ignore it altogether. Also, neutral beam deposition and neutral transport are computed using appended Monte Carlo codes developed at Princeton.

During the past year, FPT has been applied principally to the Princeton Large Torus (PLT) and the Tokamak Fusion Test Reactor (TFTR).

o Radial Transport in Field Reversed Mirrors

The field reversed mirror differs from other mirror machines in that a current is induced in the plasma which produces a magnetic field structure having a reversed field. That is, the magnetic field in the center of the device is in the opposite direction from the applied field. The magnetic field structure has a toroidal region in which the magnetic field lines are confined. The confinement of the field lines gives better plasma confinement and a near Maxwellian plasma.

A transport code, FRT, has been written to describe the evolution of the toroidal region of the plasma. The code solves fluid equations on the slow diffusion time scale for ions and electrons. These equations advance the ion density, electron entropy, ion entropy, and toroidal magnetic flux. The code alternates between the solution of the four 1-D transport equations and the 2-D equilibrium equation. The 1-D transport equations are derived by integrating the equations of Braginskii over each flux surface. The equilibrium equation is the Grad-Shafranov equation. This code will be used to model the field-reversed experiment at LLNL, Beta II.

o Anomalous Electron Transport in Tokamaks

Recently, there has been considerable interest in the effects of anomalous electron transport due in part to magnetic surface destruction. Since this heat loss represents a major problem in toroidal confinement, there has been a need for a program which would simulate this loss and allow for credible estimates of the effects of electron transport on lower hybrid heating, D.C. conductivity and soft x-ray spectra.

The computer program (LDL) which has consequently been developed is 2-D with independent variables velocity magnitude and radial position. It combines a velocity and radially dependent heat source and a 1-D Fokker-Planck treatment of electron collisions with a loss operator simulating diffusion in velocity-radius. This program is in its initial stages of application to the Doublet experiments at General Atomic Corporation.

Our transport publications are summarized in Appendix B.

C. FOKKER-PLANCK

The Fokker-Planck equation is needed to treat plasmas in which the charged particle velocity space distribution functions are non-maxwellian. In a magnetic mirror device, charged particles will tend to leak out the ends of the device, resulting in a "loss cone" in velocity space. In tokamaks or mirrors where there is neutral beam injection, the ion distribution functions will be characterized by an energetic component (in addition to the maxwellian background). These are two situations which require the use of Fokker-Planck codes.

The MFECC has led the nation in the development and implementation of multispecies Fokker-Planck codes employing the complete nonlinear two-dimensional Fokker-Planck operator. Since our codes have been generalized to deal with toroidal and open-ended configurations, many physical effects have been incorporated in them and a variety of physical problems have been studied. A summary of our Fokker-Planck codes appears in Table 3.

TABLE 3. MFECC FOKKER-PLANCK CODES

CODE	CONTACT	CHARACTERISTICS AND APPLICATIONS
HYBRID II	A.A. MIRIN	2D (V,Ø), Nonlinear, Multispecies Ions; Mirrors and Tokamaks
TDMFP	A.A. MIRIN	2D (V,Ø), Nonlinear, Multispecies Ions and Electrons; Mirrors
FPRF	M.G. McCOY	2D (V,Ø), Nonlinear, Multispecies Ions and Electrons, RF Current Drive; Tokamaks
TDMSZ	A.A. MIRIN	3D (V,Ø,Z), Nonlinear, Multispecies Ions and Electrons
FPPAC	M.G. McCOY	2D (V,Ø), Nonlinear, Multispecies Ions; General Package
ISOTIONS	A.A. MIRIN	1D (V), Nonlinear, Multispecies Ions and Electrons; Mirrors and Tokamaks

One of our main achievements this year has been the development of a user-oriented package, FPPAC, which computes the coefficients of the complete nonlinear 2D velocity-space Fokker-Planck collision operator and time-integrates the corresponding finite difference equations. This package runs from 10 to 14 times as fast on the CRAY-1 as on the CDC 7600. The tremendous gain in speed is due not only to the vectorization efficiency of the CFT compiler, but also to the the fact that on the CRAY, one does not have to constantly move data between small and large core. FPPAC has been made available to the MFE community.

Our Fokker-Planck publications are summarized in Appendix C.

D. OTHER AREAS

Although most of our research has dealt with time dependent MHD, transport, and Fokker-Planck equations, we have undertaken some projects in other areas -- in particular plasma equilbria, Vlasov and particle simulations, convergent neutral beam studies and general numerical methods.

A self-consistent guiding center particle model coupled with a fluid equlibrium code has been used to study ion beam motion in a toroidal geometry. Applications include the study of collisionless beam behavior including strong counterstreaming beams and the steady state modeling of a CIT reactor, in which steady state beam currents and energy reinjection rates are computed.

A general study of the Incomplete Cholesky Conjugate Gradient Method (ICCG) for solving sparse linear systems has been carried out. This technique has been shown to be considerably faster than other traditional linear solvers such as SOR and ADI. An ICCG solver applicable to general nine point two-dimensional difference operators has been written, and it is available to the MFE community.

A study has been made involving the creation of a very dense plasma by injecting convergent neutral beams into spherical or cylindrical chambers. Calculations of particle distribution functions, densities, ionization rate parameters and ionization probabilties have been carried out for both geometries.

A one-dimensional Vlasov finite difference code for ions and electrons has been written to study the formation of a plasma sheath and to compute steady state distribution functions along with a plasma potential.

A code has been developed to solve nonlinear elliptic equations on domains of very general shape. Its main application has been to solve the equilibrium fluid equations proposed for TORMAC.

Publications in these areas are summarized in Appendices D, E and F.

III. Future Goals

The above projects are considered to be quite relevant to the National MFE effort, and we plan on continuing them. We expect that our Field Reversed Mirror and Tandem Mirror Transport Codes will be of great value to the Livermore MFE program, and that the Electron Transport Code will be a great aid in understanding anomalous heat loss in tokamaks. We also anticipate that our 2D linear MHD codes will provide much needed insight into the properties of resistive instabilities and their effects on magnetic fusion devices. In fact we have just begun to develop a 3D finite-beta nonlinear MHD code which utilizes a Fourier expansion in the toroidal direction.

Appendix A - MHD References

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