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I - 33194

DR-0379-4

UCID-17530-88
REVISION 7

The Computational Physics Program
of the National MFE Computer Center

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January 1988

Lawrence
Livermore
National
Laboratory

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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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Printed in the United States of America
Available from
National Technical Information Service
U. S. Department of Commerce
5205 Port Royal Road
Springfield, VA 22161

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I. INTRODUCTION

DE88 005236

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. Another major objective of the group is to develop efficient algorithms and programming techniques for current and future generations of supercomputers. 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. Moreover, many of the group's computer codes employ state-of-the-art algorithms that use and test the prototypical hardware and software features of the new machines; these codes have played a major role in perfecting the software supplied by NMFECC.

The group currently consists of six Ph.D. physicist/mathematicians - D.V. Anderson, G.D. Kerbel, A.E. Koniges, M.G. McCoy, A.A. Mirin and D.E. Shumaker. In addition, students (currently numbering 3) in the Department of Applied Science (U.C. Davis) are engaged in fusion research under the guidance of senior group members.

The computational physics group is involved in several areas of fusion research. One main area is the application of Fokker-Planck/quasilinear codes to tokamaks. Another major area is the investigation of resistive magnetohydrodynamics in three dimensions, with applications to compact toroids. A third major area is the investigation of kinetic instabilities using a 3-D particle code. This work is often coupled with the task of numerically generating equilibria which model experimental devices. Ways to apply statistical closure approximations to study tokamak-edge plasma turbulence are being examined. In addition to these computational physics studies, the group has developed a number of linear systems solvers for general classes of physics problems and has been making a major effort at ascertaining how to efficiently utilize multiprocessor computers.

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:

RF heating and current drive in tokamaks	GA, PPPL, AMPC, LLNL
Fokker-Planck/transport analyses of tokamaks	PPPL, LLNL
Tokamak equilibrium and stability	U.C. Davis
Resistive stability of RFP	LANL
Compact torus transport/equilibrium/stability	LANL
MHD evolution of Spheromak and FRC	LANL, LLNL
Tandem mirror equilibria	MIT
Turbulence models in plasma physics	PPPL, GA, UCSD

MASTER

Iterative matrix solvers

U. Texas

Direct matrix solvers/3-D equilibrium
and stability calculations

Ecole Polytechnique
Federale de Lausanne

A summary of our program follows.

II. COMPUTATIONAL STUDIES

A. EQUILIBRIA AND STABILITY

1. TIME INDEPENDENT MODELS

In simple 1-D configurations the calculation of plasma equilibrium profiles is rather trivial. For more realistic two and three dimensional plasmas, the determination of the equilibrium magnetic fields and the plasma pressure is a complicated nonlinear problem involving the solution of elliptic partial differential equations. One of the goals of this work is to obtain configurations like those seen in experiments; accordingly some of our calculations use boundaries and external coil sets which accurately represent the devices under study. A secondary goal is to compute equilibria of sufficient accuracy so that the results can be used by stability codes with some confidence. In this connection high order finite element or finite difference representations have been used. These equilibria are also used to explore single particle effects in equilibrium magnetic fields.

Most of our codes solve Ampere's law given some nonlinear dependence of the currents on the fields. Other codes use a dynamic evolutionary approach with artificial damping to obtain steady flow equilibria. Still others merely numerically evaluate known analytical equilibrium profiles. Several of these codes are briefly described in Table 1.

Our research has been in the following areas:

*A code was developed to solve the 2D MHD equilibrium problem for compact toroids. The algorithm is applicable to elongated plasmas. Finite elements are used to solve the Grad-Shafranov equation. The region in which the equilibrium is computed may contain a separatrix, and plasma may be present both inside and outside of the separatrix. The equilibrium is determined from adiabatic quantities, magnetic fluxes and entropy; hence, the solver is suitable for insertion in a transport code. This code has been documented and made available to the fusion community.

*A 2D kinetic equilibrium code for compact toroids has recently been developed. The distribution functions depend on the Hamiltonian and the canonical angular momentum; the electrostatic potential is obtained from quasineutrality. The code can also compute zero-electron-temperature equilibria; in this case the electrostatic potential is an input quantity. The numerical techniques are similar to those of the MHD equilibrium code described above.

• Tandem mirror equilibrium calculations have been undertaken in 3D, with the goal of making the simulations as realistic as possible. A multispecies plasma is modeled in a multi-region configuration to account for the various types of trapped and passing components known to exist in these devices. Ambipolar effects are included. High beta and finite curvature effects are modeled without making low beta or long-thin approximations. A finite element representation is used on a rectangular grid. The effect of sheath formation has been shown to be in agreement with other theory and experiments. Some species, such as sloshing ions, are poorly represented by ad hoc pressure functions, so these are being supplemented by models using correct moments of microscopic distribution functions. Comparison with models using the paraxial approximation have been carried out. It appears that the long-thin approximation is not valid for most realistic mirror configurations.

• A code which computes the vacuum magnetic field inside a toroidal vessel of arbitrary cross-section was developed and applied to HELIAC. General curvilinear coordinates conforming to the shape of the vessel are used. The magnetic scalar potential is expanded as a double Fourier series in the poloidal and toroidal angles. The resulting magnetic fields have been evaluated for their minimum-average-B and shear stability properties using the field line tracing code TUBE. The aim has been to find optimum vessel configurations by calculating the resulting surface currents and later discretizing these skin currents with closed current loops.

Our time-independent equilibria and stability publications are summarized in Appendix A1.

2. 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 tractable, 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 instabilities tend to grow more slowly than ideal MHD instabilities, thereby requiring longer running times. 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. 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 2). Moreover, most of these codes use an implicit time discretization, so that there is no restrictive non-physical upper bound on the size of the timestep.

Our MHD research has been in the following areas:

- Linear studies of resistive interchange modes in the reversed field pinch were carried out using a two-fluid code. These simulations included Hall terms and tensor thermal conductivities and viscosities. It was shown that Hall and electron thermal conduction effects together (but neither alone) would provide stabilization.

- A 3D nonlinear, resistive, initial-value, compressible code has been used to model a cylindrical reversed field pinch. In one application, this code, along with four other 3D codes (developed at other institutions), has simulated an identical problem to try to ascertain the effects of compressibility in RFP dynamics. The study showed that compressibility could be instrumental in determining field reversal maintenance.

- Our nonlinear 3D code is being applied to the behavior of resistive modes in a spheromak. Whether or not a general equilibrium relaxes to a force free state, and if it does, how long it takes and how the relaxation is affected by MHD modes, has been under investigation. The effects of Hall terms are included. Applications have been primarily to the decaying spheromak.

- The nonlinear 3D code described above has been modified to include implicit differencing. For the purposes of economizing computer time, a multitasked semi-implicit technique has been implemented. Hall terms are also treated semi-implicitly. Implicit simulations of the spheromak have been carried out, with a factor of 30 savings in computer time.

- A study of the stability of long, thin theta-pinch equilibria to the $n = 1$ tilt mode was undertaken. Earlier numerical work predicting a fast growing tilt instability was in contradiction to the long quiescent times of the experiments. The hypothesis that the computations were based on incorrect models of the theta pinch equilibrium is now refuted. Usage of a resistive MHD stability code has shown that stretching of the closed elliptical flux surfaces (making them more racetrack as in the experiments) is destabilizing. The stability of these devices to this mode is due to effects beyond the MHD model. In particular, kinetic effects must be taken into consideration.

Our time-dependent MHD publications are summarized in Appendix A2.

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 have been applied to tokamaks, compact toroids and tandem mirrors. A list of our transport codes and their applications appears in Table 3.

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

- Fokker-Planck/transport studies of tokamaks
- Anomalous electron transport in tokamaks
- Transport in compact toroids
- Radial transport in tandem mirrors

A brief summary follows.

•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 last decade FPT has been applied to a number of experiments. Most recently it has been used to model TFTR and ITER. The TFTR simulations have concentrated on ascertaining the beam-beam, beam-target and thermonuclear fusion rates;

excellent agreement with the "supershot" results is obtained. The ITER simulations have concentrated on evaluating the effectiveness of neutral beam current drive; efficiencies comparable to those of rf schemes are obtained.

•Anomalous Electron Transport in Tokamaks

Over the years, 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 and has as 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 has been applied to the Doublat experiments at GA Technologies, Inc.

•Transport in Compact Toroids

The compact torus experiments (field reversed theta pinch and spheromaks) differ from the tokamak in that the plasma extends to the axis of rotational symmetry. Interest in the compact torus is due to the fact that it is likely to attain high beta and the fact that there is an engineering advantage of not having any structure through the center of the torus.

A transport code, CIT, has been written to describe the evolution of the plasma and magnetic field in a compact torus. This code differs from the tokamak transport codes in that the plasma extends to the axis of rotational symmetry and the 2-D equilibrium calculation contains a separatrix. The system evolves by alternating between the solution of four 1-D transport equations and the calculation of a 2-D equilibrium. The independent variable is the poloidal magnetic flux. Classical diffusion, Pfirsch-Schluter diffusion, radiation, Joule heating, lower hybrid drift diffusion and open field line loss are modeled.

The code has been used to model the FRX and the CSS experiments. In the former case good agreement with the experiment is obtained provided the collision frequencies are appropriately enhanced; discrepancies along the open field lines, however, point to the need for 2D modeling in that region.

•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, was 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 has been used to study the Tandem Mirror Experiment and to help design larger tandem mirror devices.

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 devices where there is neutral beam injection, rf heating or a large d.c. electric field, the ion distribution functions will be characterized by an energetic component (in addition to the Maxwellian background). These are 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 4.

Progress has been made in the following areas:

- We developed a user-oriented package, FPPAC, which computes the coefficients of the uniform-field nonlinear 2D velocity-space Fokker-Planck collision operator and time-integrates the corresponding finite difference equations. The user may specify additional physics terms and rather arbitrary boundary conditions. FPPAC has been made available to the MFE community.

•A nonlinear multispecies Fokker-Planck code (CQL) which bounce-averages the differential operators of Coulomb collisions, quasilinear resonant diffusion induced by wave-particle interaction and an Ohmic electric field has been recently developed. A zero banana width is assumed. CQL is designed primarily to simulate toroidal devices, although it can be utilized for mirror applications. The relativistic collisional coefficients incorporate an arbitrary number of terms in the Legendre expansion of the distribution functions. The rf operator incorporates mass shift, spectral and collisional resonance broadening and models waves at the electron cyclotron, ion cyclotron and lower hybrid frequencies. CQL has recently been put in package form and released to the MFE community.

•To obtain a global view of tokamak operation, the two dimensional (v, θ) code CQL described above has been incorporated into a three dimensional driver, CQL3D, which allows the calculation to proceed at several radial mesh points simultaneously. Due to the bounce averaging, the resulting picture is, in most cases, actually four dimensional, if one considers the poloidal perspective. The 3D version is well suited to implementation in a multitasking environment since the distribution functions at the various radial meshpoints are advanced independently. A wave damping calculation to compute electric fields and other relevant wave parameters as a function of position (radial and poloidal) provides linkage between the radial meshpoints. CQL3D is intended for use primarily on the Cray-2.

•A number of studies have been undertaken with the CQL family. In collaboration with G.A., fusion reactivity enhancement by ICRF has been examined; at high Q the enhancement factor ranges from 1.3 to 2.0. A more recent application of the code examines the relative merits of inside vs. outside launch schemes for ECH current drive, with particular attention to relativistic effects. The CQL study advises an outside launch, which is contrary to what is currently being done in D3D. Present efforts include (1) a coupling of CQL3D to the GA transport code ONETWO; this will allow global simulation of tokamak performance; (2) coordination between the full wave propagation calculations for ICRH and ray optics calculations for ECRH and the consequent quasilinear development of the underlying distributions; (3) the use of CQL to evaluate linear growth rates for beam-driven instabilities; and (4) relaxation of the zero-banana-width restriction to allow the calculation of non-Maxwellian corrections to neoclassical transport coefficients.

•Tandem Mirror Applications

A study of electrostatically trapped electrons in a tandem mirror thermal barrier has recently been completed. This has required solving Fokker-Planck equations for trapped electrons in the presence of passing electrons and under the influence of electron cyclotron resonant heating.

Calculations of fusion performance in D-D tandem mirrors have also been completed. Fokker-Planck equations for deuterons and the four reaction products have been solved. Radiation losses, recycling and drift pumping for ash removal have been included. Some p-based calculations have also been carried out.

A 2D nonlinear multispecies code has been used to assess trapping rates of passing ions in tandem mirror end cells. A scaling law valid over a wide range of mirror ratio, trapping parameter and potential-to-temperature ratio has been developed.

Our Fokker-Planck publications are summarized in Appendix C.

D. PARTICLE AND VLASOV MODELS

•Three-Dimensional Particle Code

A 3-D quasi-neutral hybrid particle-in-cell code has been developed for the Cray-2. Unlike earlier particle codes that required disk memory and scalar interpolation, tedious coding of buffered disk memory and the corresponding waste of CPU time have been eliminated and new algorithms which allow every phase of the calculation to be vectorized and multitasked have been developed. The interpolation between the grid and the particles has been coded in terms of indirect indices and executes in vector mode via the hardware gather and scatter instructions. An optimized particle sorting scheme consistent with vectorization was developed. A multigrid technique is used to compute the fields in the vacuum region. Studies of Field Reversed Configurations have been undertaken. As a benchmark, the rotational instability of the rigid rotor was modeled and found to agree with a 2D particle code; for this purpose a special treatment of the low density regions had to be incorporated. The code has recently been applied to a study of the nonlinear evolution of the tilt mode instability in a FRC. It is shown that in the large gyroradius limit kinetic effects stabilize the mode. The growth rates are in fair agreement with linear calculations using a kinetic model.

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

•A single particle orbit following code allows us to make detailed studies of the confinement properties of equilibrium fields in two and three dimensions. Studies of adiabaticity as well as resonant orbital effects were made. Experimentalists have used the code to design ion probe diagnostics.

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

Publications in this area are listed in Appendix D.

E. EFFICIENT NUMERICAL ALGORITHMS AND PROGRAMMING TECHNIQUES

•Solution of Sparse Implicit Systems

A general study of Preconditioned Conjugate Gradient Methods for solving sparse linear systems is being carried out. This technique has been shown to be considerably faster than other traditional linear solvers such as SOR and ADI. Solvers applicable to both scalar and vector 2D and 3D operators have been written and made available to the MFE community. These solvers incorporate (as an option) the biconjugate gradient (BCG) method. BCG tends to converge faster than ordinary CG and is more amenable to multitasking. A multitasked form of the BCG solvers is available. The use of vectorized indirect indexing has made it possible to produce packages applicable to various mesh stencils and sparsity patterns with a minimum of effort. In this connection a fully implicit Maxwell's equation solver in which the various field components are closely coupled has been built and tested. Our sparse matrix solvers, which are listed in Table 5, have been/are being published to provide adequate documentation and allow easy access by other users.

•Solution of Block-Banded Systems

In some applications the structure of the resulting matrix system is block tridiagonal with dense blocks. This kind of structure arises from the use of spectral representations in one or more of the coordinate directions. We have developed a new code, PAMS, that solves this type of system. PAMS has been designed to exploit the three forms of parallelism available on the Cray-2 - multitasking, vectorization and functional unit overlap. Speeds in excess of 1 Gflop have been measured, thus making PAMS one of the fastest codes available on the Cray-2. PAMS has also been used as a benchmark for vector supercomputers. It has been tested on the Cray-X/MP, Cray-2, Fujitsu VP-200, NEC SX-2 and the CDC-205.

•Multitasking

The CRAY-XMP and CRAY-2 computers possess more than one CPU and hence have the capability of parallel computation. Computer codes that require large fractions of the central memory or that need fast real time performance can benefit if they are written such that parallel computation is feasible. This mode of calculation is referred to as multitasking in the CRAY environment. The computational physics group is investigating the efficient utilization of the CRAY-2 in this direction. Some of our multitasking applications have been discussed in the above section on sparse matrix solvers. A brief summary of our other multitasking applications follows.

•The VEPEC code, which computes 3D tandem mirror plasma equilibria (see Table 1), has been used as a test bed for studying multitasking in the CTSS environment. The idea here has been to ascertain the extent to which existing codes can be converted to multitasking without too much rewriting. The efficient multitasking of a vectorized 3D ADI solver appropriate for certain nonlinear problems has been demonstrated. This shows the perhaps unexpected value of multitasking even for tightly coupled implicit systems. Another important issue is the cost of the overhead required to implement multitasking--this is closely related to the granularity of the tasks. A further objective has been to provide feedback as to the design of the operating system, where in fact VEPEC experience led to a new system scheduler that gives greatly improved multitasking performance.

•Our multitasked simulation code (SIMU) uses the concept of ensemble averaging to solve a prototypical three-wave interaction problem. The use of ensemble averaging, as opposed to time-averaging, turns the problem into an ideal candidate for multitasking. Since realizations of the dynamical equation can be grouped into arbitrary-sized packets, the multitasking nature of the code can be adapted for machines with arbitrary numbers of processors - from four to four thousand. In order to run SIMU and guarantee reproducible results independent of the multitasking, we require a means of producing strings of random numbers for each process. This problem is very important in all Monte-Carlo calculations run on multiprocessor computers. We have devised a method for producing independent strings based on hopping through a random number sequence at large intervals and picking up a seed for each process. This method is particularly useful for our application and shows promise for use in general Monte Carlo codes.

•Another important issue is the degree of multiprocessing efficiency one should expect to get under CTSS, which is an intense time-sharing environment. In this regard we have used our 3-D MHD code TEMCO to study multitasking performance as a function of task size and code field length. This has led to a theoretical model designed to predict the multiprocessing performance under CTSS. This model shows, for example, that (assuming the time to get an additional processor is 6 ms) a multitasking job must have a field length of at least 10 Mwds if an overlap factor of 3.5 is to be attained. We have found in general that the CTSS scheduler allows good overlap provided the code is large and the task string (i.e. the set of tasks which are available to run consecutively on a processor) is of medium-to-large granularity.

Our multitasking codes are summarized in Table 6.

Publications in efficient numerical algorithms and programming techniques are summarized in Appendix E.

F. OTHER AREAS

We have undertaken some projects in other areas, as follows:

•Plasma Turbulence Modeling

An investigation aimed at demonstrating the viability of applying Markovian approximations to density-gradient-driven or drift-wave turbulence has been completed. In this study, a numerical simulation of the statistical dynamics of a one-field drift-wave equation was performed. By numerically determining the time-lag correlation and infinitesimal response functions, the fluctuation-dissipation relation was shown to be qualitatively valid for certain drift-wave systems in steady state. Many statistical closure approximations assume this relation to be valid. This study goes on to show that fluid turbulence models may provide a good steady-state description of plasma turbulence provided that they are carefully extended and applied to the plasma equations.

We are examining ways to apply statistical closure approximations to more realistic plasma equations. For our first major problem, we have chosen a collisional drift-wave model in two dimensions. We are in the process of deriving the appropriate physics equations and applying a relevant turbulence model. The resulting equations will require numerical solution.

•Convergent Neutral Beams

A study was 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 probabilities were carried out for both geometries.

Publications in these areas are summarized in Appendix F. Miscellaneous publications are listed in Appendix G.

TABLE 1. MFECC TIME INDEPENDENT CODES

CODE	CONTACT	CHARACTERISTICS AND APPLICATIONS
CYLEQ	D.V. ANDERSON	2D (R,Z), Bicubic Splines, Finite Element, Tensor Pressure; Tandem Mirrors, Compact Toroids
VEPEC	D.V. ANDERSON	3D (X,Y,Z), Tricubic Splines, Finite Element, Vector Potential, Tensor Pressure, Ambipolar Effects, Vlasov Species Tandem Mirrors
ABCXYZ, TPSIC	D.V. ANDERSON	Auxiliary codes for VEPEC
HILLSV	D.V. ANDERSON	Auxiliary code for CYLEQ
EIV	D.E. SHUMAKER	2D, Flux Coordinates, Finite Elements, Open and Closed Field Lines; Compact Toroids
EQV	D.E. SHUMAKER	2D, Kinetic Equilibria, Flux Coordinates, Finite Elements, Open and Closed Field Lines; Compact Toroids
VAFIS	A.I. SHESTAKOV*	3D, Double Fourier Series, General Coordinates; Stellarators, HELIAC
TUBE	A.A. MIRIN	Field Line Tracing Code; General Magnetic Fields

*Currently in CP-Division (LLNL)

TABLE 2. MFECC TIME DEPENDENT MHD CODES

CODE	CONTACT	CHARACTERISTICS AND APPLICATIONS
TEMCO	A.A. MIRIN	3D (R, ϕ ,Z), Nonlinear, Semi-Implicit, Resistive, Fourier Expansion in ϕ , Viscous, Hall terms; Compact Toroids, RFP
RIPPLE VI	A.I. SHESTAKOV*	2D (R,Z), Linear, Nonaxisymmetric Perturbations, Implicit, Resistive; Compact Toroids
ALIMO	A.I. SHESTAKOV*	2D (R,Z), Linear, Axisymmetric Perturbations, Implicit, Resistive; Compact Toroids
RIPPLE V	A.I. SHESTAKOV*	1D (y), Linear, Implicit, Equilibrium Flow
RIPPLE IV	A.I. SHESTAKOV*	1D (r), Linear, Implicit, Resistive; Tokamaks, RFP
ODRIC	A.A. MIRIN	1D (r), Linear, Implicit, Resistive, Compressible, Tensor Viscosity, Tensor Thermal Conductivity, Hall terms, Two-Fluid; Tokamaks, RFP
STABCRIT	D.V. ANDERSON	2D (R,Z), Ballooning Modes, Energy Principle

*Currently in CP-Division (LLNL)

TABLE 3. 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, θ); Tokamaks
CTT	D.E. SHUMAKER	1D (Poloidal Flux)/2D Equilibrium; Compact Toroids
TRANSPORT	A.A. MIRIN	1D (R); Tokamaks
LDL	M.G. McCOY	2D (R,V); Electron Transport; Tokamaks

TABLE 4. MFECC FOKKER-PLANCK CODES

CODE	CONTACT	CHARACTERISTICS AND APPLICATIONS
HYBRID II	A.A. MIRIN	2D (V, θ) , Nonlinear, Multispecies Ions; Mirrors and Tokamaks
TDMFP	A.A. MIRIN	2D (V, θ) , Nonlinear, Multispecies Ions and Electrons; Mirrors
TDMSZ	A.A. MIRIN	3D (V, θ, Z) , Nonlinear, Multispecies Ions and Electrons
FPPAC	M.G. McCOY A.A. MIRIN	2D (V, θ) , Nonlinear, Multispecies Ions; General Package
ISOTIONS	A.A. MIRIN	1D (V) , Nonlinear, Multispecies Ions and Electrons; Mirrors and Tokamaks
CQL	M.G. McCOY G.D. KERBEL	2D (V, θ) , Nonlinear, Bounce Average, Multispecies Ions, Quasilinear rf, Relativistic; Tokamaks
CQL3D	M.G. McCOY	3D (r, V, θ) , Nonlinear, Bounce Average, Multispecies Ions and Electrons, RF with Wave Damping, Relativistic; Tokamaks

TABLE 5. MFECC ITERATIVE MATRIX SOLVERS

CODE	CONTACT	PURPOSE
ICCG2	D.V. ANDERSON	2D Symmetric, Scalar
ICCG3	D.V. ANDERSON	3D Symmetric, Scalar
ILUCG2	D.V. ANDERSON	2D Asymmetric, Scalar
ILUCG3	D.V. ANDERSON	3D Asymmetric, Scalar
ILUBCG2	A.E. KONIGES	2D Asymmetric, Scalar
CPDES2	D.V. ANDERSON	2D Asymmetric, Vector
CPDES3	D.V. ANDERSON	3D Asymmetric, Vector
MTBCG2	A.E. KONIGES	2D Asymmetric, Scalar
MTCS2	A.E. KONIGES	2D Asymmetric, Vector
MTCS3	A.E. KONIGES	3D Asymmetric, Vector

TABLE 6. MFECG MULTITASKING CODES

CODE	CONTACT	PURPOSE
VEPEC	D.V. ANDERSON	Plasma Equilibria
MTBCG2 MTCS2 MTCS3	A.E. KONIGES	Iterative Matrix Solvers
QN3D	D.E. SHUMAKER	Particle Code
SIMU	A.E. KONIGES	Turbulence
PAMS	D.V. ANDERSON	Direct Matrix Solver
TEMCO	A.A. MIRIN	MHD Evolution/Stability

Appendix A1 - Time Independent Equilibria and Stability References

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