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January 16, 1980

Mr. Harold Miller
Assistant Manager for Acquisitions
and Assistance
Chicago Operations Office
U. S. Department of Energy
9800 South Cass Avenue
Argonne, Illinois 60439

Dear Mr. Miller:

Enclosed are two sets of the six figures which were part of
the report for the period March 1979 to October 1979 for

Progress in Application of Hybrid Numerical Simulation Methods
to Magnetic Confinement Systems

Contract No. EG-77-S-02-4259

The two copies of the report were mailed today, but the figures
do not have the full explanation needed for Nos. 3, 4, 5, and 6.

Sincerely yours,

R. L. Morse by k.l.

Richard L. Morse
Principal Investigator

RLM:kl

Enclosures

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Fig. 1

Fig. 2

H - C - DT

Fig. 3

H - C - DT

Fig. 4

H - C - DT

Fig. 5

DT - C - H

Fig. 6

PROGRESS IN APPLICATION OF HYBRID NUMERICAL
SIMULATION METHODS TO MAGNETIC
CONFINEMENT SYSTEMS

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Prepared for
U. S. Department of Energy
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REPORT FOR THE PERIOD
March 1979 to October 1979

ABSTRACT

During the past contract period hybrid codes developed to simulate high density, high- β plasmas have been applied primarily to heating, ignition, and burn of linear reactor systems and to current profile steepening and related stability changes in tokamaks. Some code development has also been done to incorporate Monte Carlo α transport and to make it possible to treat rotation and rotational instability in compact tori and linear systems. Also, analytic expressions for temperature profiles and heat loss caused by thermal conduction in compact tori have been obtained.

I. Introduction

The University of Arizona group has concentrated its efforts on the development and application of hybrid numerical simulation codes for treatment of the full time and length scales of magnetically confined plasmas. Numerical methods for such simulations must in most cases be combinations of particle and energy transport models and MHD, which have the effect of merging several different time and length scales. These methods have been quite effective in increasing our understanding of confinement and heating in collisional linear systems and of resistive tearing mode phenomena in tokamaks. This work is also supporting and training two graduate assistants.

The group presently consists of Ted Cochran, Richard Morse, and two graduate assistants, Pat McKenty and Gerald Sowers, who are doing doctoral research. The group will soon add another faculty member to fill a position which the University has provided. The local plasma physics

community also contains Robert Carlile and Morris Farr in the Engineering College and a number of people in the various planetary and astrophysics institutes on campus.

II. Activities and Accomplishments

During the six-month contract period from 1 March to 30 September 1979, the primary emphasis has been on the application of previously developed hybrid simulation codes to heating, thermonuclear burn, and confinement in open linear systems. In addition, some analytic work has been done on thermal conduction energy loss scaling from compact tori and, because of equivalence of geometries, through divertors. Only those items are described below on which there has been significant progress since the submission of the proposal for the six-month continuation from March 1979 through October 1979. For a more complete view of the group's recent work, it is suggested that the activities and accomplishments section of the previous proposal also be seen. The accomplishments listed in the two reports constitute what we believe to be significant progress in all areas to which we have made commitments as well as some new initiatives where we have seen opportunities to contribute.

1. Comparison of Numerical Simulation of Axial Heating and Analytic 2nd Order Perturbation Treatment

The previous report described our theoretical development of an axial collisional heating technique for linear systems which could be used on open linear systems or elongated compact tori. Our studies of this technique were carried out by numerical simulation with the $1\frac{1}{2}$ -D MHD and heat flow code, PINECONE, and by an analytic second-order perturbation method. In the limit of small relative amplitude of the external pumping field, these methods should give identical results. Figures 1 and 2

show comparative plots of heating rates as a function of frequency calculated by the two methods for two different values of the dimensionless parameter λK (λ is the particle mean free path, and K is the axial wave number of the external pumping B_z field). These calculations show moderately good agreement, considering that this problem tests every process in the code, but the discrepancy is a little too large to be dismissed. The most noticeable difference between the two curves in each figure is the relative shift of the resonance peak of the heating rate which occurs where the pump phase velocity equals the axial Alfvén velocity. We have established that this shift is not caused by some small higher-order nonlinearity by doing the PINECONE runs at two different small pump amplitudes. The present suspicion, which is suggested by differences between Figs. 1 and 2, is that the shift is caused by some numerical truncation error which effectively causes a small dissipation and is telling us that simulations of the processes involved in this heating technique are sensitive to some parameter of the numerical treatment such as zone size.

2. Semi-Analytic Model of Stationary Linear Systems with Burn and Radiation Loss

It seemed reasonable to expect that the coupled hydrodynamics and heat flow equations for linear systems have stationary solutions if the radiation losses balance the energy production by fusion burn. In these solutions there would be axial as well as radial pressure balance. Of course, the solution could only be stationary on a time scale short compared to the fuel depletion time. We have obtained such solutions by using the same tabular radiation emission rates that we use in PINECONE and local deposition of reaction products, and by integrating the

resulting equations numerically from the cold end. Figures 3, 4, and 5 show temperature, density, and heat flux from such a solution for a case with mixed material end plugs of first hydrogen and then carbon and D-T fuel. From the temperature and heat flux profiles it can be seen that the relatively thin layer of carbon provides a large part of both the thermal insulation and the radiation loss. The midplane is seen to be at about 1.2 km. While such stationary solutions do not give information about ignition or ablation of the insulating layer from the plug, they do tell us quite a bit about system lengths and peak temperatures and burn rates.

3. Numerical Simulation of Ignition and Burn in Linear Systems

The previous report described the $1\frac{1}{2}$ -D (Z dependence plus one zone radial treatment) Lagrangian MHD and heat flow code, PINECONE, which was developed under this contract for simulating linear systems. The code uses tabular coronal equilibrium radiation loss rates and Monte Carlo α -particle transport, which has recently been added to provide a better treatment of burn processes. Accurate treatment of alpha transport is particularly important near ignition time when reaction rates are very sensitive to the details of reaction energy deposition.

Studies of ignition and burn in reactor length linear systems with end plugs are now being done with PINECONE. The purpose of these studies is to obtain reliable quantitative estimates of the length, which is usually the major obstacle, and other parameters that a successful linear reactor must have. Figure 6 shows the temperature, density, and pressure profiles from a typical case at a time a little before the temperature peaks and fuel depletion begins to quench the burn. This case has the

same parameters as the stationary case shown above, including the layered (H,C) plug. It can be seen that the stationary solution is a moderately good approximation to the dynamic solution at this time when the system is not changing rapidly. This work is being continued in order to find optimum system parameters.

4. Thermal Conduction Losses from Compact Tori.

In view of the increasing interest in compact tori, it seemed that it would be useful to know the energy loss rates and temperature profiles that should be produced by thermal conduction. An analytic calculation has been done in which ion thermal conduction perpendicular to field lines and electron conduction parallel combine to give quasi-stationary radial and axial temperature profiles and heat loss to the end walls.

Two qualitatively different regimes are identified, one in which the temperature on the separatrix, T_s , is much less than the peak temperature near the B field null, T_o , and one in which T_s is less than, but not much less than T_o . In the $T_s \ll T_o$ case, the heat loss is essentially determined simply by calculating radial ion conduction to the separatrix where $T_s \approx 0$. In the other case, where T_s and T_o are comparable, the determination of heat loss is a little more complicated.

In the $T_s \ll T_o$ limit, the separatrix temperature is given by

$$T_s \approx T_o \left(\frac{8}{3} \frac{\Delta r_s}{r_s} \right)^{2/5}$$

where r_s is the separatrix radius and Δr_s , the thickness of a thermal sheath outside of the separatrix, is given by

$$\Delta r_s \approx \left(\frac{35}{4} \frac{K_{io}}{K_{eo}} l_1 l_2 \right)^{1/2}$$

Here the K 's are ion and electron conductivities, and l_1 and l_2 are the half length of the toroid and the distance to the end wall respectively. The transition from the cold to the hot separatrix regime occurs when the thickness of the thermal sheath, Δr_s , becomes of the order of r_s so that $T_s \rightarrow T_0$. These analytic results should not be too difficult to check experimentally. If confirmed, they would be useful in predicting the scaling up to larger machines.

5. MHD Simulation of Current Profile Modification in Tokamaks

A preliminary investigation was made of the internal $m=1$ ideal MHD kink mode in tokamak equilibria sequences where impurity influxes near the walls might be important. In this model, the current becomes increasingly more peaked at the center with successive equilibria. Each sequence is constructed under the constraint that the total current across the column is held fixed. The first results have shown that only modest increases in the linear growth rate of 50% or less are obtained in going from a broad profile to a peaked profile. The reason seems to be that although the central q value decreases with increasing central current, the volume contained within the $q=1$ surface must also decrease if the total current is to remain fixed. Thus, the available magnetic energy which can drive this mode is a slowly varying quantity.

The large increase in unstable MHD activity which can occur in tokamaks when current channel shrinkage is observed cannot be explained by this model. It seems more likely that other effects not included in this model, primarily resistivity, are important.

Fig. 1

Fig. 2

$$H = C - DT$$

Fig. 3

Fig. 4

Fig. 5

Fig. 6