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UCRL- 92397
PREPRINT
CONF-8505130--4

ELECTRON AND ION CYCLOTRON HEATING CALCULATIONS IN THE TANDEM-MIRROR MODELING CODE LABORATORY

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This paper was prepared for submittal to the Sixth Topical Conference on Radio Frequency Plasma Heating Meeting Proceedings, May 13-15, 1985, Pine Mountain, Georgia.

May 8, 1985

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1. Introduction

To better understand and predict tandem-mirror experiments, we are building a comprehensive Mirror Equilibrium Radial Transport and Heating (MERTH) code. In this paper we first describe our method for developing the code. Then we report our plans for the installation of physics packages for electron- and ion-cyclotron heating of the plasma.

2. Development of the MERTH Code

A new method of code development allows us to avoid a number of problems:

- The code-development environment on supercomputers changes frequently.
- Supercomputers loaded with large applications jobs cannot respond quickly to code developer's text-editing and file-manipulation commands.

A strategy for large-code development, useful for other codes as well as for MERTH, has been chosen:

- We use FORTRAN, restricting ourselves to standard features, so our code can be converted easily to any conceivable supercomputer.
- Our text-editing and file-manipulation work is done within the stable and productive programming environment of a UNIX system.
- The code architecture provides a powerful user/developer interface that is independent of the physics packages. The interface allows selection from a menu of packages so the user can do a variety of tandem-mirror design or analysis problems.
- The physics packages, each of which is developed by a different physicist, are well isolated from each other to reduce conflicts, but communicate by subroutine calls where necessary.

We are developing MERTH on a VAX/780 and will run the code on Cray-1 and Cray-2 supercomputers at NMFECC.

3. Geometry of the Magnetic Field and Plasma

MERTH eases the design of rf-heating experiments by providing a good description of the geometry of the magnetic field and plasma:

- We perform spline fits to the vacuum magnetic field, i. e., the field due to realistic coils in the absence of plasma.[1]
- Plasma diamagnetism reduces the vacuum field to the actual, equilibrium magnetic field, as described by the paraxial (or long, thin) approximation.
- The plasma pressure is computed from density and temperature profiles obtained either from analytic models or from spline fits to profiles calculated by a radial-transport package. This package is coupled back to the rf-heating packages, because they return power-absorption profiles for radial-transport calculations.

4. Electron-Cyclotron Heating

Our physics package for electron-cyclotron heating is based on the ray-tracing code developed by Audenaerde[2] and Ziolkowski.[3] That code traces a bundle of rays through the plasma, calculates the absorption along each ray, and computes the radial power-absorption profile.

We allow the following options for specification of a bundle of rays:

- The rays are all launched from the same point and have initial directions distributed within all or part of a cone.
- The rays have launch points distributed over all or part of the interior of an ellipse and the initial directions describe focusing or defocusing of the ray bundle.
- For cases not treated by the previous options, an arbitrary launch point and direction can be specified for each ray in the bundle.

For comparison with experimental diagnostics of the *transmission* of ECH power, our code outputs the power flux to a specified surface.

Important improvements in the ECH package aim to remove the assumption that the electron distribution is an isotropic, relativistic Maxwellian. Neither isotropy nor a Maxwellian energy distribution is expected or observed in a plasma for which rf diffusion dominates collisional diffusion. We are choosing model anisotropic distributions and installing an option for an anisotropic absorption calculation. Negative absorption (instability) may occur.

A difficult, but perhaps necessary, improvement is replacement of the cold-plasma approximation used in tracing rays. In the density and energy range of interest ($\omega_{pe}^2/\omega^2 \approx 0.1$ and 50 keV $< T_e <$ 500 keV), the cold-plasma approximation might lead to as large as a factor-of-two error in the absorption rate along a ray.[4] Errors would then result in the power-absorption profile.

5. Ion-Cyclotron Heating

Our physics package for ion-cyclotron heating is based on the ANTENA code developed by McVey,[5] and improvements use the bounce-averaged Fokker-Planck code of Kerbel and McCoy.[6] We solve the Maxwell equations for the wave fields that penetrate into and propagate along a cylindrical plasma. Then we compute the radial power-absorption profile.

We estimate the wave field excited by one or more antennas in the approximation used by McVey. He modeled the plasma as if it were in a region of straight, axially uniform magnetic field **B**. He treated radially stratified density and temperature profiles as an approximation for diffuse profiles.

McVey calculated the power absorption from the waves for Maxwellian ions in the straight **B**. We improve the power-absorption calculation by including

- axially varying **B** and therefore ω_{ci}
- mirror-confined ion orbits
- non-Maxwellian ion distributions.

We calculate the axial localization of the power absorption.

We describe the amplitude and polarization of the wave field by the squares of the Fourier coefficients of the electric-field components. The Fourier coefficients express the wave amplitude for a given parallel wave number $k_{\parallel}$, wave frequency ω, and azimuthal mode number m. From $k_{\parallel}$, ω, and m, the cold-plasma dispersion relation gives the perpendicular wave numbers $k_{\perp}$ for the slow and fast modes. For the electric-field components, we use the basis of left- and right-circular polarization, E_+ and E_-, and the parallel component $E_{\parallel}$.

The quantities $k_\parallel$, ω, $k_\perp$, $|E_+|^2$, $|E_-|^2$, and $|E_\parallel|^2$ serve as inputs to calculations implemented by Kerbel and McCoy:[6]

- The spatial distribution of the power absorbed by a plasma of one or more species is calculated. We compute radial, and optionally, axial profiles.
- The steady-state ion distribution in the presence of the wave fields and Coulomb collisions is calculated. This information allows us to choose model ion distributions for use with the fluid-model radial-transport package.

Acknowledgments

This collaborative work involved many people, including T. Christensen, P. F. Dubois, S. K. Ho, G. D. Kerbel, B. D. McVey, A. W. Molvik, W. M. Nevins, B. W. Stallard, S. Tamor, and R. W. Ziolkowski. Work performed by Lawrence Livermore National Laboratory for the U. S. Department of Energy under contract W-7405-Eng-48.

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