RAY TRACING AND ABSORPTION OF ELECTRON CYCLOTRON WAVES IN THE L-2 STELLARATOR*

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ABSTRACT

The absorption of electron cyclotron waves in L-2 stellarator plasmas has been investigated by adapting the RAYS geometrical optics code developed at Oak Ridge National Laboratory to the parameters of L-2. Two heating schemes were considered: (1) low-field launching of the ordinary wave at the fundamental resonance and (2) low-field launching of the extraordinary wave at the second harmonic. Significant power absorption (up to 100%) of the extraordinary mode at the second harmonic resonance was obtained. A multipass absorption model was used to estimate the contribution to plasma heating of the power that remains after the first pass which is subsequently reflected from the vessel walls. Finally, results obtained with the RAYS code and with a code developed at the Institute of Automation and Electrometry were compared and found to be in good agreement.

INTRODUCTION

During the last few years, electron cyclotron resonance heating (ECRH) experiments have been carried out in the L-2 stellarator. To predict the absorption efficiency and to provide optimum heating, it is necessary to simulate the propagation and absorption of the electron cyclotron waves in the plasma. A ray tracing code for L-2 stellarator plasmas was developed for this purpose at the Institute of Automation and Electrometry (IAE) and used for calculations at the General Physics Institute (GPI).^{1, 2} The absorption efficiencies obtained with the IAE code and those inferred from a diamagnetic measurement were found to be in disagreement.³ This disagreement could result from approximations assumed in the computational model. Because the IAE code included several simplifications (near-perpendicular wave propagation, a 'rotating ellipse' model of the flux surfaces), a comparison of the results obtained with this code and with the RAYS code developed independently at Oak Ridge National Laboratory (ORNL) was suggested. The theoretical background of the RAYS code is described in Refs. 4 and 5.

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MASTER

MAGNETIC FIELD GEOMETRY AND WAVE LAUNCHING

Correct calculation of the magnetic field is very important in obtaining valid results in tracing the rays as well as in determining the power deposition profile. We start by comparing the different methods used to obtain contours of constant B . The magnetic field is calculated with the Biot-Savart law in the RAYS code and with a concept developed at GPI⁶ in the IAE code.

Figure 1 shows contours of constant B and flux surfaces obtained with RAYS approximating the helical windings in L-2 with a single filament. Approximating the finite width of the helical windings with a finite strap was also done and did not make a significant difference in the region of interest. The magnetic field geometry calculated by the GPI code is represented in Fig. 2. After careful inspection of the contours of constant B calculated by the two different methods, we conclude that they are essentially the same.

A second difference in the two codes is their methods for determining the flux surfaces. In the RAYS code the flux surfaces are computed self-consistently with the Biot-Savart magnetic calculation; the IAE code uses the so-called 'rotating ellipse' model in which the flux surfaces are elliptical in a plane of constant toroidal angle and rotate about the minor axis with the helical windings. For plasmas with current or finite beta the centers of the ellipses are shifted outward along the major radius coordinate, but the last closed flux surface, or separatrix, does not move relative to the vacuum. Therefore, the outward shift and variable eccentricities of the ellipses need to be taken into account.

Fig. 1. Mod- B and flux contours obtained with the RAYS code for the L-2 stellarator. The axis of the incident microwave beam lies in this plane, and the single-filament model was used to represent the helical windings.

Fig. 2. Mod- B and flux contours obtained with the GPI code.

RAY TRACING CALCULATIONS

Figure 3 shows the ray trajectories of an ordinary-mode (O-mode) beam for $N_e(0) = 1.26 \times 10^{13} \text{ cm}^{-3}$ ($\omega_{pe}/\omega = 0.85$). In this figure, the fundamental resonance lies at the magnetic axis ($\omega_{ce}(0)/\omega = 1$), the central electron temperature is 400 eV, and the profile is of standard width. Figure 4 represents the single-pass absorption versus the central electron temperature for the case with $N_e(0) = 1.26 \times 10^{13} \text{ cm}^{-3}$. At $T_e(0) = 400 \text{ eV}$ the absorption efficiency increases from 0.2 to 0.53 for the various width density profiles. The single-pass absorption increases with increasing electron temperature, but it does not achieve 100% even at $T_e(0) = 2 \text{ keV}$. Therefore, we suggest that multipass absorption may take place for this heating scheme. We plot the calculated single-pass absorption efficiency as a function of central density in Fig. 5. The single-pass absorption increases with increasing plasma density until the efficiency drops to zero owing to the ray refraction. The maximum single-pass absorption efficiency occurs at $N_e(0) = (1 - 1.3) \times 10^{13} \text{ cm}^{-3}$ when the fundamental resonance lies near the magnetic axis.

The single-pass absorption of the X-mode at the second harmonic resonance is represented as a function of the magnetic field in Fig. 6. With this heating scheme, it is possible to achieve higher plasma densities than with O-mode heating; because of this higher density, the X-mode at the second harmonic resonance has more efficient single-pass absorption (about two to five times as strong as that for the fundamental resonance). To obtain the maximum absorption, it is necessary to operate at a central plasma density of about $2 \times 10^{13} \text{ cm}^{-3}$. The absorption depends also on the N_e and T_e profiles.

Fig. 3. Poloidal projections of O-mode rays, with $N_e(0) = 1.26 \times 10^{13} \text{ cm}^{-3}$ and with the standard-width profile of N_e .

Fig. 4. Single-pass absorption efficiency of the O-wave vs $T_e(0)$ at $N_e(0) = 1.26 \times 10^{13} \text{ cm}^{-3}$.

DISCLAIMER

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Fig. 5. Single-pass absorption efficiency of the O-wave vs $N_e(0)$ at $T_e(0) = 400$ eV.

Fig. 6. Single-pass absorption of the X-wave as a function of the central magnetic field level.

SUMMARY AND CONCLUSIONS

Using a three-dimensional ray tracing code developed at ORNL, a study has been made to ascertain the features of absorption of cyclotron waves in the L-2 stellarator. We have given great attention to simulation of the L-2 magnetic field. The magnetic field structures obtained by the GPI and ORNL codes have been compared and found to be similar. The main purpose of the calculations has been to determine the single-pass absorption and to obtain a heating profile for a simulated antenna beam with fixed polarization. The calculations were performed as a function of the on-axis magnetic field, the central and line-average densities, the central temperature, and the N_e and T_e profiles. We find that appreciable wave absorption occurs for magnetic fields in a narrow range about the fundamental resonance and the second cyclotron harmonic. We have compared the results of calculations made with the RAYS code and with the IAE code. We find that for both heating schemes the single-pass absorption efficiencies are the same and have identical dependences on the on-axis magnetic field and the plasma parameters (N_e , T_e). Thus, the two codes provide similar descriptions of the absorption of cyclotron waves in the L-2 stellarator.

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