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SECOND HARMONIC ELECTRON CYCLOTRON HEATING CALCULATIONS FOR THE ATF TORSATRON*

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ABSTRACT

The heating of the Advanced Toroidal Facility now under construction at Oak Ridge National Laboratory has been investigated using ray tracing techniques. The effect of electron cyclotron waves at the second harmonic resonance is studied using the RAYS geometrical optics code assuming anticipated steady state parameters. A comparison is made of the heating efficiency using two launching schemes: a linearly polarized antenna providing a narrow beam and a TE_{02} waveguide. The first pass ray tracing calculations are incorporated in a wall reflection/power balance model which includes the effects of wall reflected rays and wall losses. It is shown that the power absorbed in the plasma after multiple reflections is preferentially absorbed near the center of the plasma. A significant fraction of the incident power is predicted to ultimately be deposited in the plasma, rather than lost to walls and ports.

I. INTRODUCTION

The ray tracing code RAYS[1,2,3] has been used to investigate electron cyclotron heating (ECH) in the Advanced Toroidal Facility (ATF). Steady state parameters anticipated for ATF operation are used in all the calculations ($f_{\rm gyro} = 53.2{\rm GH_z}, n_e = 8\times10^{12}{\rm cm}^{-3}, T_e = 750{\rm eV}, B_0 = 1{\rm T}$); the separate problem of plasma breakdown and startup is not addressed in this paper. During the design of the ECH launching system for ATF, several options were considered including a TE_{02} waveguide (circular polarization, broad null on-axis) and a carefully designed antenna giving rise to a narrow, linearly polarized beam. The absorption rate of a given ray is small unless the density and the magnetic scale length in the resonance region are large; the magnetic geometry of ATF therefore dictates that the rays should pass through resonance near the saddle point in the field (see Figs. 1 and 2). Thus the broad beam, superposition of X- and O-mode waves emanating from the TE_{02} waveguide is a cause for concern about whether significant ECH power will be centrally deposited in the plasma. To complete the picture, an elementary treatment of the power that is not absorbed in the first pass through the plasma is provided.

II. X-MODE NARROW BEAM ANTENNA VERSUS TE_{02} WAVEGUIDE

A RAYS calculation has been done assuming a 3° beam (full width) with the linearly polarizing antenna oriented so as to give pure X-mode at the center. The position of the resonance at the central saddle point region, with the beam

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passing through the region, results in 100% single pass absorption within 7 cm of the magnetic axis.

Figures 3A, 3B, and 3C show a run simulating the TE_{02} waveguide. This mode has circular polarization with the first peak at 11% off the waveguide axis. The circular polarization means that the portion of the beam which lies in the toroidal direction (i.e., up and down the torus) will be predominantly X-mode, whereas the orthogonal part of the beam is O-mode, since the magnetic field is essentially toroidal. To simulate this in the RAYS code, we launch a cone of rays with half angle of 11° and pure X-mode polarization. Figure 3C shows that 21% of the beam is absorbed on the first pass through the plasma at approximately 10 cm off axis. The remaining power impinges on the wall and is the subject of discussion in the next section.

III. WALL REFLECTIONS/POWER BALANCE MODEL

The power in the beam that is not absorbed in the plasma during the first pass strikes the wall and is partially lost due to the metallic wall and through holes for diagnostic ports. The rest of the beam is depolarized and scattered back into the plasma. The fate of this scattered power is treated statistically in Ref. 3 as emanating isotropically from a homogeneously radiating wall surface. Figure 4 shows the resulting histograph of one such run for the case of second harmonic, X-mode. Due to the complicated interaction of longer magnetic scale lengths near the center with preferential absorption at perpendicular incidence, it turns out that the X-mode reflected power suffers 8% absorption per bounce within 10 cm of the axis. Since approximately one half of the wall scattered power is O-mode (which is very weakly absorbed), the net power absorbed in the plasma is one half of the X-mode absorption, or 4% per bounce.

The power remaining in the waves after the i^{th} transit through the plasma, γ_i, can be expressed as

$$\gamma_1 = 1 - F_1^P \tag{1}$$

$$= \gamma_{i-1}\left[\left(1 - F_i^P\right)\left(1 - F_i^W\right)\right] \;;\; i \geq 2 \tag{2}$$

where F_i^P is the fraction of remaining power absorbed in the plasma during the i^{th} pass of the waves through the plasma; F_i^W is the fraction of remaining power lost to walls and diagnostic ports at the i^{th} wall reflection; and the initial power, γ_0, is taken to be unity. Using the statistical assumption described above, we take F_i^P constant for $i > 1$ and F_i^W constant for all i. We now recognize Eq. 2 to be a geometric series which can be summed to give the total power deposited in the plasma, P_∞^P, and total power lost to the wall, P_∞^W:

$$\gamma_i = \left(1 - F_1^P\right)\left[\left(1 - F^W\right)\left(1 - F^P\right)\right]^{i-1} \tag{3}$$

$$P_\infty^P = F_1^P + \frac{F^P\left(1 - F^W\right)\left(1 - F_1^P\right)}{1 - \left(1 - F^W\right)\left(1 - F^P\right)} \tag{4}$$

$$P_\infty^W = 1 - P_\infty^P \tag{5}$$

where the subscripts have been dropped from F^P and F^W. Taking into account the surface resistivity of the stainless steel walls and the area of the diagnostic ports, the fractional wall loss at each reflection is found to be 2.45%.[4] Using the wall reflection calculation described above, $F^P = 4\%$, we obtain

$$P_\infty^P = .385F_1^P + .614 \tag{6}$$

$$P_\infty^W = .385\left(1 - F_1^P\right) \tag{7}$$

This means the power deposited in the plasma can range from 61% to 100%, depending on the efficiency of the wave launcher in achieving first pass absorption; the remaining power (38% or less) is lost to the walls. For the case of the TE_{02} waveguide described in Sec. II, $F_1^P = 21\%$. Thus the power going into the plasma and walls is 69% and 31%, respectively.

CONCLUSIONS

Second harmonic ECH gives 100% central heat deposition when a narrow beam polarized to give X-mode is used with the steady state parameters envisioned for ATF. For the case of the TE_{02} waveguide (circularly polarized with on-axis null), first pass absorption drops to 21%. A power balance expression has been derived for the power fraction deposited in the walls and plasma after multiple reflections. For the TE_{02} waveguide, this expression says that 69% of the original power ends up in the plasma and 31% in the walls.

REFERENCES

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FIGURE CAPTIONS

FIG. 1. Mod-B and toroidal flux contours in the $\phi = 0°$ plane with the outline of the ATF vacuum vessel superimposed. The value of $|\mathbf{B}|$ on each contour is indicated, normalized to unity at the magnetic axis. The flux contours (dashed lines) parameterize the density and temperature and were determined by following field lines.

FIG. 2. Mod-B and toroidal flux contours in the equatorial plane ($Z = 0$).

FIG. 3. Ray trajectories in the R—Z plane (plot 3a) and $\phi - Z$ plane (plot 3b) for the TE_{02} waveguide. The dotted curve represents ray propogation outside the plasma while the asterisks indicate location of second harmonic ECH absorption. In 3c the power absorption histograph for this run is displayed with the density profile superimposed (dashed line).

FIG. 4. Power absorption histograph for ensemble of wall reflected rays. A large number of second harmonic rays are launched from the wall to simulate the vacuum chamber as a homogeneous, isotropic radiator of power back into the plasma.

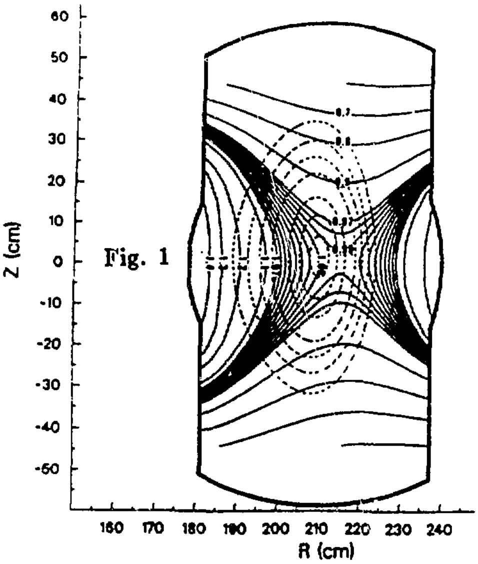

Fig. 1

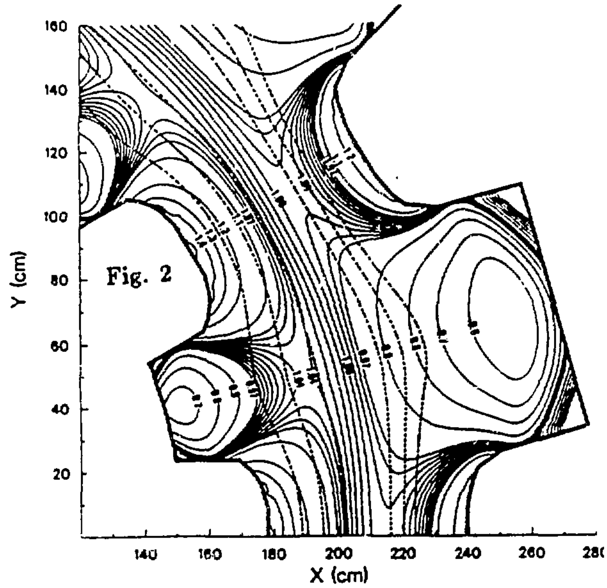

Fig. 2

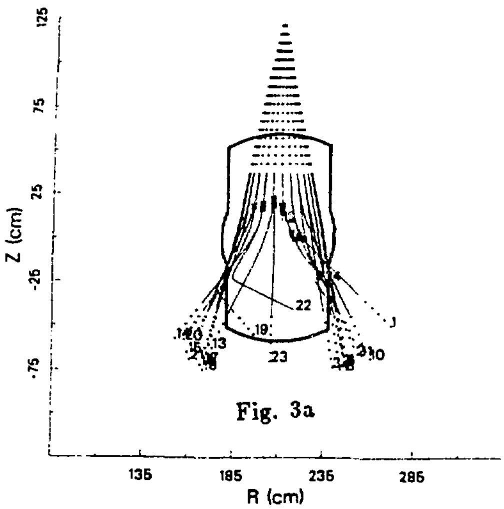

Fig. 3a

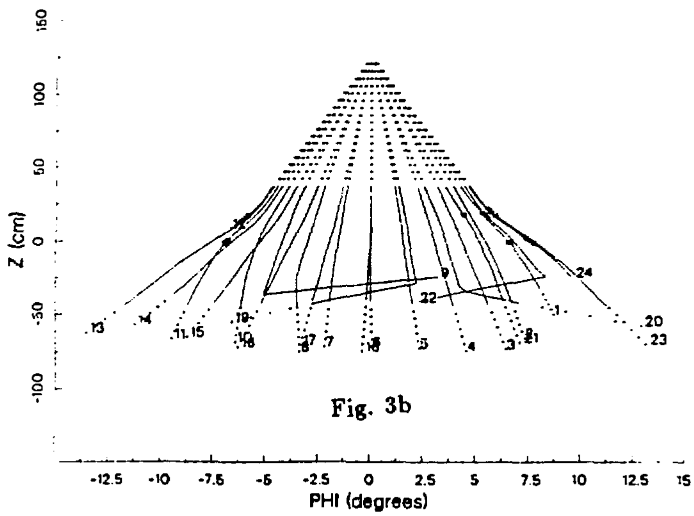

Fig. 3b

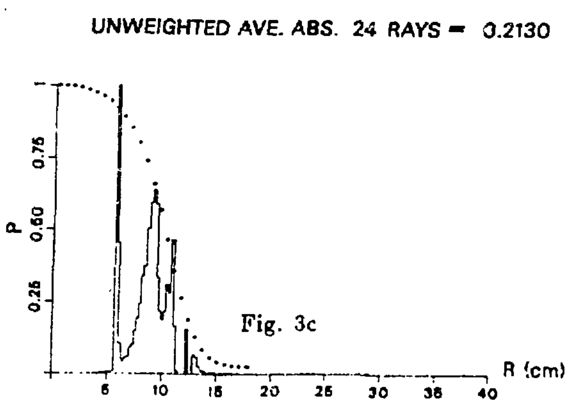

Fig. 3c

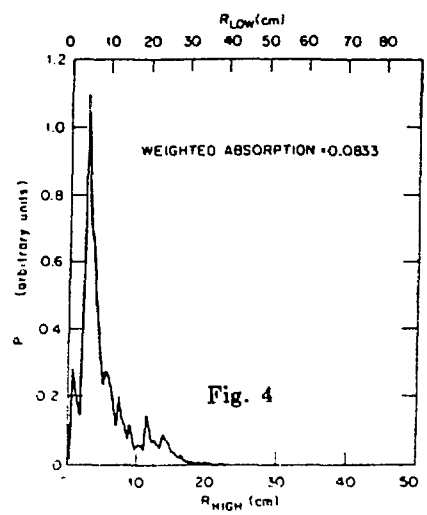

Fig. 4