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Electron Cyclotron Resonance Heating in Spherical Plasmas: O-X-EBW Mode Conversion in MAST

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Electron cyclotron resonance heating in spherical plasmas: O–X–EBW mode conversion in MAST

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Using a full wave solution, the O–X–EBW mode conversion is examined for density and magnetic profiles in MAST. The effects of magnetic shear and the sharp density pedestal for H-mode operation are considered with an eye to understanding both electron cyclotron emission (ECE) and electron cyclotron resonance heating (ECRH). © *2001 American Institute of Physics.*
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I. INTRODUCTION

While electron cyclotron resonance heating (ECRH) has proven to be a highly efficient heating scheme in standard tokamaks, considerable work is still needed to examine its efficiency in spherical plasmas like Mega-Ampere Spherical Tokamak (MAST) or National Spherical Torus Experiment (NSTX). It has been shown[1] that a 60 GHz linearly polarized X-mode, launched radially in at the midplane from the low-field side will penetrate into the core of a MAST plasma, provided the density $n<2.5\times10^{13}\,\mathrm{cm}^{-3}$. The power is resonantly absorbed in the second and third electron cyclotron harmonic regions. However, for overdense plasmas, this straightforward approach fails since the rf power will be reflected at the cutoff before reaching the resonant regions and being absorbed in the plasma core.

Now the electron cyclotron emission is widely used as a rf diagnostic in standard tokamaks and stellerators. However, because of the very low magnetic field and high plasma density in spherical plasmas, the topology of plasma cutoffs and resonances makes (see Fig. 1) the interpretation of conventional electron cyclotron emission (ECE) measurements more difficult.[2]

Both these complimentary problems can be resolved if one considers the linear mode conversion of an obliquely incident O mode into an X mode at the plasma resonance and which will subsequently convert to an electron Bernstein wave (EBW) at the upper hybrid resonance (UHR).

Our power estimates for absorption/emission are based on a Wentzel–Kramers–Brillouin (WKB) analysis[3,4] as well as a full wave (numerical) solution of Maxwell's equations for an inhomogeneous slab of magnetized cold plasma.[5] Currently, our warm plasma model is limited to wave frequencies between the first and second harmonics—and so is not applicable to our problem.[6] With the cold plasma field singularity at the UHR being eliminated by the introduction of weak *ad hoc* collisions, one can determine the power in the X mode that is absorbed at the UHR. In a warm plasma, the X mode is converted into an EBW at the UHR, which is then resonantly absorbed at an electron cyclotron harmonic. We give estimates for the power absorbed for incident frequencies between 18 and 60 GHz as well as restrictions on beam alignment and polarization.

II. TRANSMISSION OF O MODE THROUGH THE PLASMA RESONANCE

For the O–X–EBW mode conversion, it is crucial that the O mode propagates through the plasma resonance region at oblique incidence. Using a WKB analysis,[3,4] the transmitted O-mode power through the plasma resonance region in a weakly inhomogeneous magnetized plasma slab is given by

$$T=\exp\left\{-\frac{\pi k_{\mathrm{vac}}}{8\kappa_p}\left(\frac{2\omega}{\omega_{\mathrm{ce}}}\right)^{1/2}\left[\frac{\omega_{\mathrm{ce}}^2}{\omega^2}\left(1-\left(\frac{N_z}{N_z^{\mathrm{opt}}}\right)^2\right)^2+\frac{2\omega_{\mathrm{ce}}}{\omega}N_y^2\right]\right\}, \tag{1}$$

where $k_{\mathrm{vac}}=\omega/c$, $\kappa_p=n_{\mathrm{cnt}}^{-1}dn/dx_p$ with x_p being the position of the plasma resonance. $N_z^{\mathrm{opt}}=(\omega_{\mathrm{ce}}/(\omega+\omega_{\mathrm{ce}}))^{1/2}$, where ω_{ce} is the electron cyclotron frequency. z is the direction of the total magnetic field in the plasma resonance region, and x is the radial direction (see Fig. 2). $N_{y,z}=k_{y,z}/k_{\mathrm{vac}}$ are the normalized wave number components for the incident wave of frequency ω. For $k_{\mathrm{vac}}\gg\kappa_p$, only very narrow beams, centered around $N_y=0$, $N_z=N_z^{\mathrm{opt}}$, can penetrate into the dense plasma.

III. MAGNETIC SHEAR

The effect of magnetic shear on the O mode transmitted through the plasma resonance has been considered by Cairns *et al.*[7] in the WKB limit. The main effect is to rotate the rf

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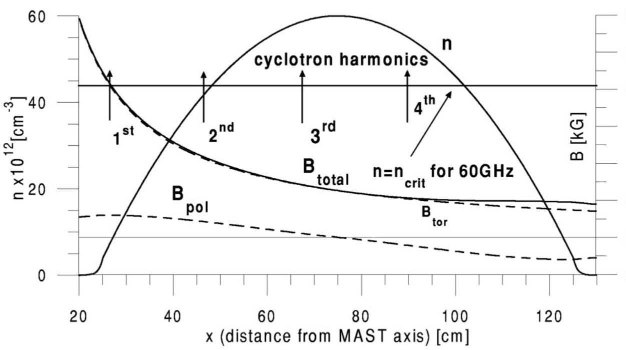

FIG. 1. The parabolic density and magnetic field profiles used in determining the effects of magnetic shear on power absorption in MAST.

power absorption in the (N_y, N_z) plane through the angle of shear. For spherical plasmas, and consequently in MAST, the effects of shear are very important on the incident angle of the optimal beam. In our full wave slab solution to Maxwell equations, the toroidal and poloidal magnetic fields are assumed to have radial dependence, with $B_{tor} \approx 1/x$ and B_{pol} being approximated by a cubic polynomial interpolation, Fig. 1 (since only preliminary data from MAST is available). Finite element solutions to the Maxwell equations are sought in the form

$$E(x, N_y, N_z) = \exp[i(N_y y + N_z x - \omega t)]$$

with appropriate boundary conditions.[5] The wave incidence geometry is shown in Fig. 2, with α being the angle of incidence, β the angle between $\boldsymbol{E}^{inc}$ and the plane of incidence, and γ the angle between $\boldsymbol{B}_{tot}$ and the plane of incidence. Thus, $N_y = \sin\alpha \sin\gamma$ and $N_z = \sin\alpha \cos\gamma$.

In our numerical computations, we consider two model profiles for MAST: (a) a simple parabolic density profile, Fig. 1, and (b) a narrow flat density profile appropriate for the formation of the H-mode transport barrier, Fig. 3. The plasma surface is located at $x = 130$ cm, with $B_{pol} = -3$ kG at the separatrix.

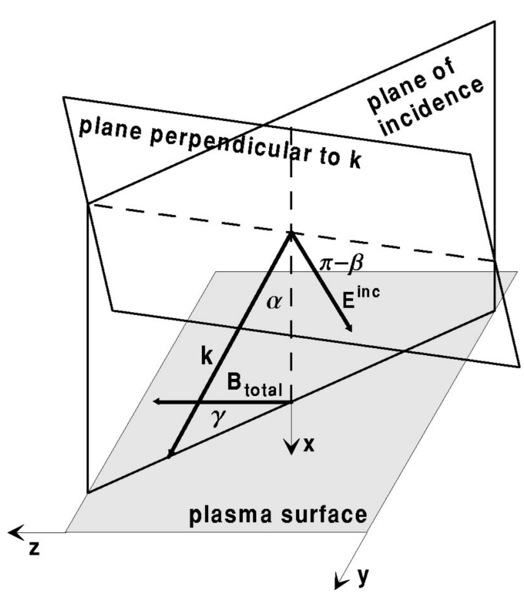

FIG. 2. The geometry of a linearly polarized electromagnetic wave incident onto a plasma.

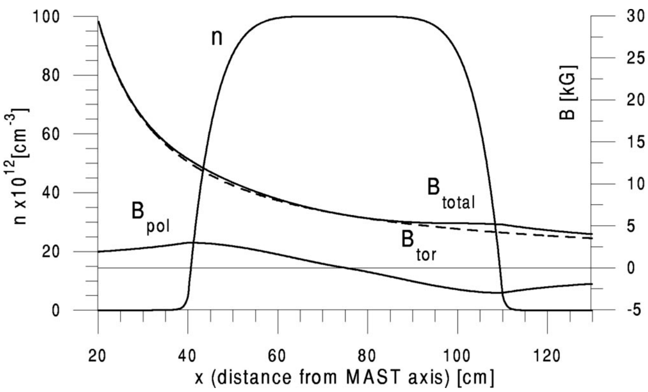

FIG. 3. The narrow flat density and magnetic field profiles corresponding to the formation of a H-mode transport barrier in MAST.

Before presenting our full wave numerical results for power absorption, we briefly review the WKB slab solution to gain deeper insight into the actual wave propagation in MAST. From Fig. 4, it is clear that the X mode is reflected at the R cutoff while the O mode penetrates through the plasma resonance for optimal launch $(\alpha = 25°)$ since then the evanescent layer between the plasma resonance and the L cutoff disappears. The O mode converts to the fast branch of the X mode which, deeper within the plasma, is the reflected back as the slow branch of the X mode. In the WKB approximation, the only effect of magnetic shear is to change the tilt of the incident wave vector, corresponding to the direction of the total magnetic field in the plasma resonance region.

The full wave solution to the power absorbed at oblique incidence of a linearly polarized wave $(f = 60$ GHz, $B_{pol} = -3$ kG at the separatrix) is shown in Fig. 5. The magnetic shear (see Fig. 1) simply induces a rotation in the absorption spectrum through an angle $\Delta\phi(x_p) = 14.6°$ from the $N_y = 0$ line. As can be seen from Fig. 5, the incident beam must be very well collimated (with an angular deviation $< \pm 2°$) for wave absorption. (More details on the propagation of the 60

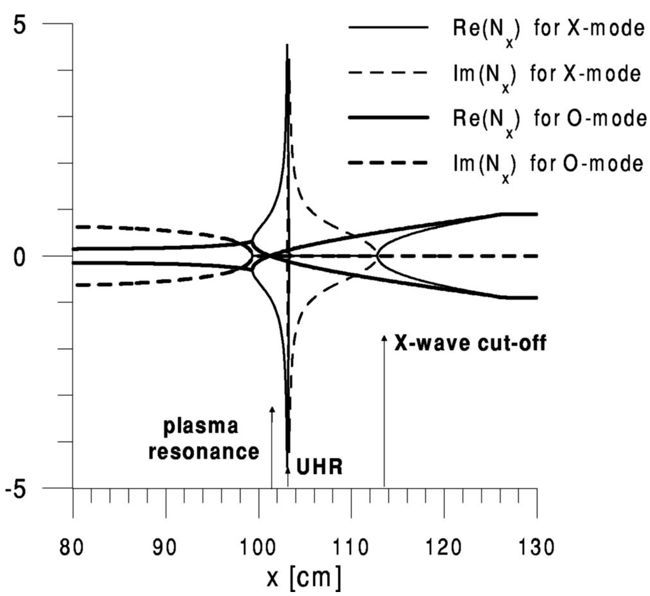

FIG. 4. WKB solution of the cold dispersion equation for optimal launch into a simple parabolic MAST density profile, Fig. 1, $N_y = 0.11$, $N_z = 0.42(\alpha = 25°)$, $f = 60$ GHz and weak collisions: $\upsilon/\omega = 10^{-4}$.

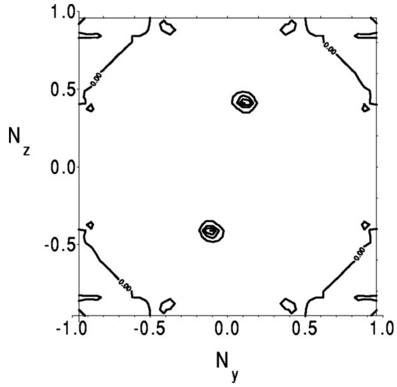

FIG. 5. Contour map in the (N_y, N_z) plane of the power absorbed in MAST for a linearly polarized wave $(\beta=0)$. Same plasma parameters as in Fig. 4.

GHz wave into MAST can be found in Ref. 8.)

When the incident wave impinges on the plasma edge, the wave is split into the X and O modes. For our parameters, the X mode is immediately reflected back out of the plasma and only the incident power in the O mode can be absorbed by the plasma. Now the relative amplitudes of the X and O modes are dependent on the polarization of the incident wave. In Ref. 8, we showed that one can achieve total absorption for an appropriately chosen obliquely incident circularly polarized wave.

Here we investigate the effect of frequency on the power absorption for the narrow flat density profiles appropriate for H-mode transport barrier operation in MAST. Consider oblique launch parameters that will allow for the complete absorption of an incident circularly polarized wave at $f=30$ GHz at the optimal incident angle. The absorbed power in the (N_y, N_z) plane is shown in Fig. 6. Note that a very broad circularly polarized beam will now mode convert efficiently into an EBW. The EBW is absorbed at the second electron cyclotron harmonic, which is located deep within the plasma.

As a preliminary to discussing ECE emission data,[2] we have investigated the wave vector directions (N_y, N_z) of the most intense absorption of O–X–EBW [corresponding to the wave vector directions for the most intense emission of the EBW–X–O conversion]. We have considered a linearly polarized wave (with $\boldsymbol{E}$ in the plane of incidence) in a MAST plasma operating in the H mode. These results are presented

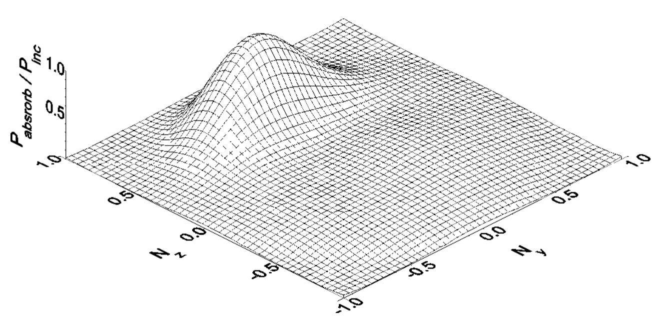

FIG. 6. The power absorption spectrum in a H-mode MAST plasma (Fig. 3) at optimal oblique incidence for a circularly polarized wave. $f=30$ GHz, $B_0=6.3$ kG, $\upsilon/\omega=10^{-4}$.

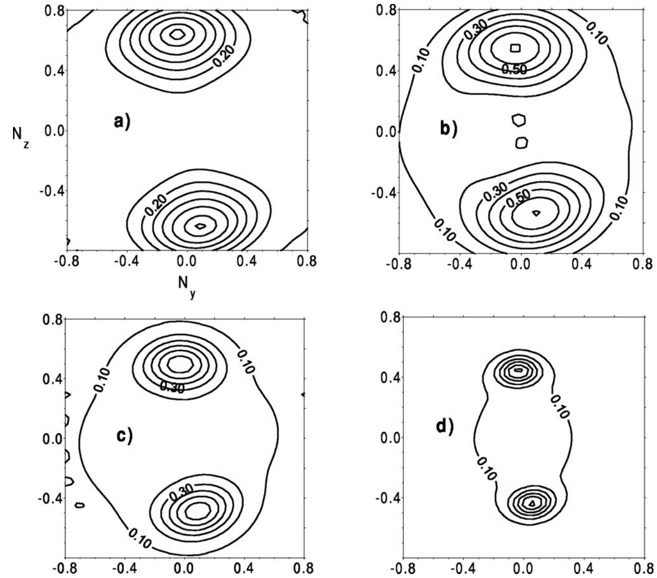

FIG. 7. Contour maps of absorbed power in MAST at various frequencies for optimal oblique incidence of linearly polarized wave for H-mode operation (see Fig. 3). (a) $f=18$ GHz, $\alpha=41°$, (b) $f=30$ GHz, $\alpha=35°$, (c) $f=40$ GHz, $\alpha=31°$, and (d) $f=50$ GHz, $\alpha=26°$.

in Fig. 7 for various frequencies, ranging from 18 to 60 GHz.

IV. CONCLUSIONS

We have shown that the O–X–EBW conversion mechanism works well even in plasmas with magnetic shear and sharp density profiles, a regime in which the WKB approximation is not valid at the lower frequencies. The major effect of magnetic shear is to rotate the plasma absorption wave number spectrum. The optimal incident angle for absorption is determined by the direction of the magnetic field at the plasma resonance—and not by that at the plasma surface. We have also confirmed that a circularly polarized wave can, at the optimal angle for which the evanescent layer between the plasma resonance and the L cutoff disappears, penetrate fully through the plasma resonance region.

It appears that the current selected frequency of 60 GHz on MAST for ECRH is too high for optimal heating. However, waves at 30 GHz are readily absorbed. We have also provided a survey of the absorption (or ECE emission) in the k space for a series of frequencies between 18 and 60 GHz.

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