

PSFC/JA-01-35

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December 2001

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To appear in *Proceedings of the 14th Topical Conference on Radio Frequency Power in Plasmas*, Oxnard, California, May 7–9, 2001.

Emission of Electron Bernstein Waves¹

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INTRODUCTION

We have previously shown that the high- β NSTX-type plasmas can be heated by waves in the electron cyclotron range of frequencies by mode converting the X mode or the O mode to electron Bernstein waves (EBW) at the upper hybrid resonance [1]. From ray tracing analysis we have also shown that EBWs are locally and strongly absorbed at the Doppler shifted electron cyclotron resonance or its harmonics. For spherical tokamak plasmas, the location of the EBW energy deposition is significantly different for excitations on or away from the equatorial plane [1,2]. The strong and localized absorption implies that thermal emission of EBWs can occur for frequencies corresponding to the local electron cyclotron frequency. We have developed a kinetic model for mode conversion of the X mode and the O mode to EBWs. Using this model we evaluate, analytically and numerically, properties of the X mode and the O mode that would be observed in the vacuum region from mode conversion of EBWs at the upper hybrid resonance (UHR). The mode conversion studies have shown that the optimum regime, in frequency and parallel wavelength space, for conversion of the X mode to EBWs is different from that of the O mode conversion to EBWs. In particular, X-mode couples efficiently to EBWs for longer parallel wavelengths and smaller frequencies than the O-mode. Our results show that the emission of EBWs provide a good indication of the possible scenarios for conversion to EBWs for heating and driving currents in overdense plasmas.

The excitation and emission of EBWs has been studied on the Wendelstein 7-AS [3]. More recently, experiments on CDX-U and NSTX [4] and MST [5] have observed emission of EBWs via the mode conversion process and studied its dependence on the edge properties of the plasma.

In this paper we formulate the kinetic description of the mode conversion process which includes the propagating EBWs. From numerical solutions of this model we find that the conversion efficiency of EBWs to the X and O modes is the same as the conversion efficiency of the X mode to EBWs and of the O mode to EBWs. Consequently, one can design an EBW excitation experiment based completely on the observed characteristics of the emitted X and O modes.

¹) Work supported by DoE Grants DE-FG02-91ER-54109 and DE-FG02-99ER-54521.

APPROXIMATE KINETIC DESCRIPTION OF THE MODE CONVERSION

Our previous studies have shown that efficient coupling between EBWs and the X or O modes occurs when the UHR is in the steep density gradient regions near the edge of the plasma. For this region we use the slab geometry model where the x axis is the direction of inhomogeneity and corresponds to the radial direction, the y axis is along the poloidal direction, and the z axis is along the toroidal direction. The equilibrium magnetic field is assumed to be sheared with the form

$$\vec{B}_0(x) \equiv B_y(x)\hat{y} + B_z(x)\hat{z} = B_0(x) \sin \Psi(x)\hat{y} + B_0(x) \cos \Psi(x)\hat{z} \quad (1)$$

where Ψ is the angle between \vec{B}_0 and the z -axis. The variation of the fields in the y and z directions is assumed to be of the form $\exp(ik_y y + ik_z z)$ where k_y and k_z are the appropriate components of the wave vectors. The time dependence is assumed to be of the form $\exp(i\omega t)$ where ω is the wave angular frequency. Assuming that the EBWs are electrostatic, we find that the approximate full wave description of the propagation of the X mode, O mode, and the EBWs is given by [1]

$$\frac{d\vec{F}}{d\xi} = i \overset{\leftrightarrow}{A}_K \cdot \vec{F} \quad (2)$$

where $\xi = \omega x/c$ is the normalized spatial variable,

$$\vec{F}^T = [E_x \ E_y \ E_z \ (i\tilde{\chi}E'_x) \ cB_z \ (-cB_y)] \quad (3)$$

is the transpose of the field vector \vec{F} , $E'_x = (dE_x/d\xi)$,

$$\overset{\leftrightarrow}{A} = \begin{bmatrix} 0 & 0 & 0 & -\chi_1^{-1} & 0 & 0 \\ n_y & 0 & 0 & 0 & 1 & 0 \\ n_z & 0 & 0 & 0 & 0 & 1 \\ K_{xx} & \chi_{xy} & \chi_{xz} & 0 & n_y & n_z \\ -\chi_{xy} & K_{yy} - n_z^2 & \chi_{yz} + n_y n_z & 0 & 0 & 0 \\ -\chi_{xz} & \chi_{yz} + n_y n_z & K_{zz} - n_y^2 & 0 & 0 & 0 \end{bmatrix} \quad (4)$$

$$\overset{\leftrightarrow}{K} = \overset{\leftrightarrow}{I} + \overset{\leftrightarrow}{\chi} \quad (5)$$

$$\overset{\leftrightarrow}{\chi} = \frac{-\omega_p^2}{\omega^2 - \omega_c^2} \begin{pmatrix} 1 & -i\omega_{cz} & i\omega_{cy} \\ i\omega_{cz} & 1 - \omega_{cy}^2 & -\omega_{cy}\omega_{cz} \\ -i\omega_{cy} & -\omega_{cy}\omega_{cz} & 1 - \omega_{cz}^2 \end{pmatrix} \quad (6)$$

where $\omega_p(x)$ is the electron plasma angular frequency, $\omega_{cy}(x) = eB_y(x)/m_e$, $\omega_{cz}(x) = eB_z(x)/m_e$ are the electron cyclotron angular frequencies for the poloidal and toroidal fields, respectively, $\omega_c = \sqrt{\omega_{cy}^2 + \omega_{cz}^2}$,

$$\chi_1 = \left(\frac{v_T}{\omega_c}\right)^2 \left(\frac{\omega_p^2}{\omega^2 - \omega_c^2} - \frac{\omega^2}{\omega^2 - 4\omega_c^2}\right) \quad (7)$$

and $v_T = \sqrt{T(x)/m}$ is the electron thermal velocity for corresponding to the temperature $T(x)$.

EXCITATION AND EMISSION OF ELECTRON BERNSTEIN WAVES

For NSTX-type parameters discussed in [1], and for a wave frequency of 14 GHz, Fig. 1a shows the mode conversion efficiency C_{XB} for the excitation of EBWs when a X mode is launched from outside the plasma. Figure 1b shows the mode conversion efficiency C_{OB} when, for the same parameters when an O mode is launched from the outside.

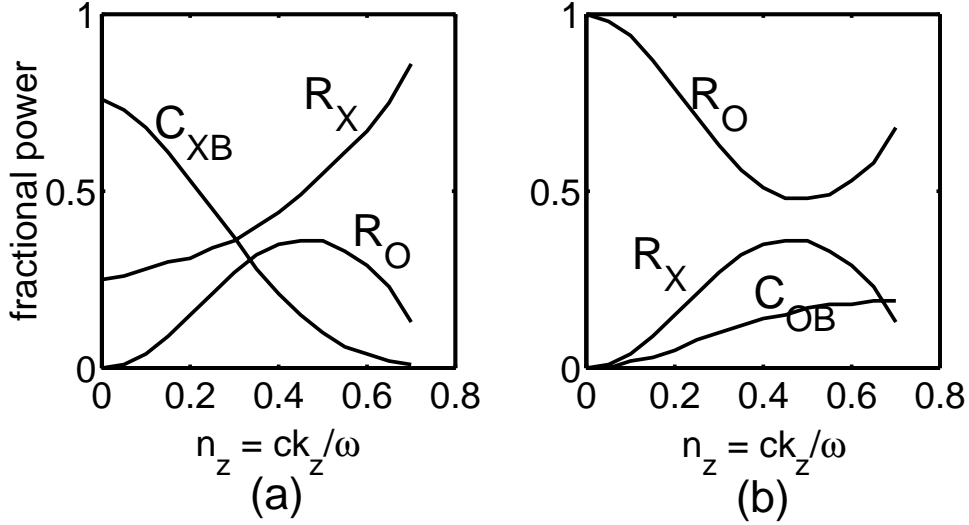


FIGURE 1. The fraction of the input power, as a function of k_z for $k_y = 0$, that is reflected out on the X mode R_X , on the O mode R_O , and mode converted to Bernstein waves: (a) for incoming X mode the conversion coefficient is C_{XB} ; (b) for incoming O mode the conversion coefficient is C_{OB} .

When EBWs are emitted from inside the plasma, they propagate out to the edge where they can couple to the X and O modes near the UHR. Some of the EBW power reaching the UHR will get reflected back into the plasma. For the same parameters as discussed above, Fig. 2 shows the fraction of the emitted EBW power, as a function of k_z , that is converted to the X mode E_X , to the O mode E_O , and reflected back into the plasma R_B . Upon comparing the results from Figs. 1a and 1b with those given in Fig. 2 we note the following relationships

$$E_X = C_{XB} \quad \text{and} \quad E_O = C_{OB} \quad (8)$$

Thus, the fraction of the EBW emitted power that is mode converted to the X mode and the O mode is the same as the power that is mode converted from the X mode to the EBW and, separately, from the O mode to EBW. Since $E_X + E_O \leq 1$, it follows that if the plasma conditions are such that the X-B conversion process is optimized then the O-B conversion process is not effective, and vice-versa. We have

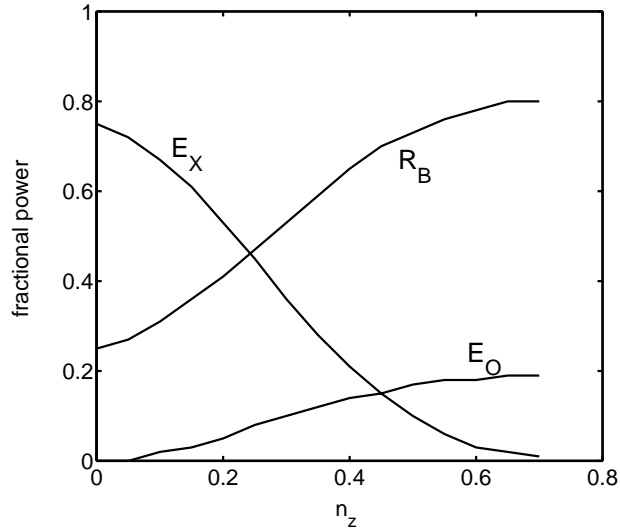


FIGURE 2. The fraction of the outgoing EBW power, as a function of k_z for $k_y = 0$, that is converted to the X mode E_X and on the O mode E_O . R_B is the fraction of the emitted EBW power that is reflected back into the plasma at the upper hybrid resonance.

noted this effect before when studying the mode conversion excitation of EBWs [1]. It was found that the X-B and the O-B conversion processes were optimized in, essentially, mutually exclusive region of the parameter space spanned by (ω, k_{\parallel}) (where k_{\parallel} is the component of \vec{k} parallel to \vec{B}_0). Consequently, from the relationship in (8) we can conclude that the experimental design for the excitation of EBWs can be completely based on the EBW emission characteristics of the plasma.

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