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Coupling to and Emission of Electron Bernstein Waves in NSTX High-Beta Plasmas

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ABSTRACT

The high β operating regime of spherical tokamaks (ST), such as in NSTX and MAST, make them attractive fusion devices. To attain the high β's there is a need to heat and to drive currents in ST plasmas. While ST plasmas are overdense to conventional electron cyclotron (EC) waves, electron Bernstein waves (EBW) offer an attractive possibility both for heating and for driving plasma currents. In this paper we consider techniques for the excitation of EBWs on NSTX and MAST-type plasmas. For the proposed scenarios on exciting EBWs in NSTX and MAST, electron heating observed near the EC resonance can only be attributed to EBWs.

INTRODUCTION

In NSTX and MAST, $f_{pe}/f_{ce} >> 1$ over most of the plasma cross section so that the ordinary O-mode and/or the extraordinary X-mode are not suitable for heating the plasma. (f_{pe} and f_{ce} are the electron plasma and cyclotron frequencies, respectively). However, the EBW, which has no density limits, propagates for frequencies above f_{ce}, and damps effectively on electrons near the Doppler-shifted electron cyclotron resonance or its harmonics. The excitation of EBWs in STs can be either indirect or direct. Direct coupling to EBWs is possible using a slow wave structure which generates, essentially, a radial electric field. The slow wave structure needs to be placed inside the plasma beyond the slow X-mode cutoff (for NSTX, only a few millimeters inside the plasma edge). The indirect coupling is through mode conversion of the slow X-mode to EBW at the upper hybrid resonance (UHR). In this paper we present results for indirect coupling to EBWs.

There are two techniques for indirect excitation of EBWs. The first technique (X-B) is to launch the fast X-mode from the outboard side [1-3]. The fast X-mode tunnels through the upper hybrid resonance (UHR) and couples to the slow X-mode, which, in turn, mode converts to EBWs at the UHR. The second technique (O-X-B) involves the launching of an O-mode, from the outboard side, at such an angle (relative to the magnetic field) that the O-mode cutoff is spatially located at the same point as the left-hand cutoff of the slow X-mode [4]. Then the O-mode power is coupled to the slow X-mode, which in turn mode converts to EBWs at the UHR.

From our ray tracing calculations we find that the damping of EBWs on electrons is highly localized and occurs near the Doppler-shifted electron cyclotron resonance or its harmonics. The spatial location of the damping can be controlled by an appropriate placement of the launcher in the poloidal plane. The $n_{\|}$'s along the EBW rays can undergo significant upshifts so that near damping $|n_{\|}|$ can be greater than 1. This leads to significant Doppler-broadening of the resonance and the EBWs can damp far from the actual location of the resonance. For current drive this could have important consequences. The localized, strong absorption of EBWs also makes their emission from the electron cyclotron resonance, or its harmonics, as a useful means for diagnosing the electron temperature profile [5]. For this we need to know the fraction of the EBW power that is mode converted to the externally observed X- or O-modes. This "inverse" mode conversion process is also being studied using the techniques developed for mode conversion to EBWs.

THEORETICAL MODELLING OF MODE CONVERSION

From an analytical analysis of wave propagation in an inhomogeneous, cold plasma [1-3], we find that the mode conversion efficiency is dependent on an effective tunneling parameter η given by:

$$\eta \approx \frac{\omega_{ce} L_n}{c\alpha} \left[\sqrt{1+\alpha^2} - 1 \right]^{1/2} \tag{1}$$

where all the quantities on the right-hand side are evaluated at the location of the UHR, $\omega_{ce} = 2\pi f_{ce}$, L_n is the density scalelength, $\alpha = f_{pe}/f_{ce}$, and c is the speed of light. For $\alpha \sim 1$:

$$\eta \approx \frac{1}{2} \left[\frac{\omega_{ce} L_n}{c} \right] \approx 293.5 \, |B L_n|_{UHR} \tag{2}$$

where B is the local magnetic field in Tesla and L_n is in meters.

For maximum X-B mode conversion, we find that the X-mode should be propagating essentially across the magnetic field (i.e., $n_\parallel \ll 1$ where $n_\parallel$ is the wave index parallel to the magnetic field). Then, for a given plasma configuration, the maximum power mode conversion efficiency (at $n_\parallel \approx 0$) is:

$$C_{\max} = 4 e^{-\pi\eta} (1 - e^{-\pi\eta}) \tag{3}$$

For $C_{\max} \gtrsim 0.5$, we require that $0.05 \lesssim \eta \lesssim 0.6$.

The O-X-B mode conversion is most efficient when the O-mode cutoff coincides with slow X-mode cutoff. This occurs at a critical $n_\parallel$:

$$(n_\parallel)_{\text{crit}} = 1/\sqrt{1+\alpha} \tag{4}$$

In addition, we find that, in order to avoid coupling appreciable power to the outgoing fast X-mode, we also require $\eta > 1$. From these conditions, we find that the X-B and the O-X-B mode conversion processes optimize in different regions of frequency and $n_\parallel$ space.

FULL-WAVE EQUATIONS FOR MODE CONVERSION AND EMISSION

We have developed a numerical code that solves for the mode conversion coefficient in an inhomogeneous slab plasma with a sheared magnetic field. Since the code allows for arbitrary $k_\parallel$, the X-mode and the O-mode can no longer be distinctly identified. The code uses an approximate kinetic (Maxwellian) plasma model in which the EBW can be clearly identified. This is a sixth order ordinary differential equation and the mode conversion coefficient is determined from the actual power flowing in EBW. This code can also be used to determine the emission of EBWs from an electron cyclotron resonanace or its harmonics. These EBWs would mode convert to the X-mode and/or O-mode radiation at the UHR and be detected in the vacuum region of a plasma device. Such emission studies have been proposed as a diagnostic for measuring electron temperatures [5]. Below we outline the approximate kinetic, full-wave model. The details of this model is described elsewhere [1,2].

We consider a stationary, neutral, electron-ion plasma equilibrium in an inhomogeneous, sheared magnetic field:

$$\vec{B}_0(x) = \hat{y} B_0(x) \sin\Psi(x) + \hat{z} B_0(x) \cos\Psi(x) \tag{5}$$

where Ψ is the angle between $\vec{B}_0$ and the z-axis in a cartesian (x, y, z) coordinate system, and x, y, and z are the radial, poloidal, and toroidal components, respectively. The equilibrium plasma density is assumed to vary with x: $n_0 = n_0(x)$. For the high frequencies in the range of electron cyclotron frequencies we can neglect the dynamics of the ions.

From Maxwell's equations and upon expanding the kinetic (Vlasov) permittivity tensor to second order in the electron Larmor radius for representing the electrostatic EBW, the set of equations describing the propagation of the X mode, the O-mode, and the EBW is:

$$\frac{d\vec{F}_K}{d\xi} = i \overleftrightarrow{A}_K \cdot \vec{F}_K \tag{6}$$

where the field vector $\vec{F}_K$ is chosen such that its transpose (row) is

$$\vec{F}_K^T = [E_x \; E_y \; E_z \; (i\tilde{\chi}E'_x) \; cB_z \; (-cB_y)] \tag{7}$$

$E'_x = (dE_x/d\xi)$, $\xi = \omega x/c$, ω is the angular frequency of the wave,

$$\overleftrightarrow{A}_K = \begin{bmatrix} 0 & 0 & 0 & -\tilde{\chi}^{-1} & 0 & 0 \\ n_y & 0 & 0 & 0 & 1 & 0 \\ n_z & 0 & 0 & 0 & 0 & 1 \\ K_{xx} & \chi_{xy} & \chi_{xz} & 0 & n_y & n_z \\ -\chi_{xy} & K_{yy} - n_z^2 & \chi_{yz} + n_y n_z & 0 & 0 & 0 \\ -\chi_{xz} & \chi_{yz} + n_y n_z & K_{zz} - n_y^2 & 0 & 0 & 0 \end{bmatrix} \tag{8}$$

$$\overleftrightarrow{\chi} = \frac{-\gamma^2}{(1-\beta^2)} \begin{pmatrix} 1 & -i\beta_c & i\beta_s \\ i\beta_c & 1-\beta_s^2 & -\beta_s\beta_c \\ -i\beta_s & -\beta_s\beta_c & 1-\beta_c^2 \end{pmatrix}, \qquad \overleftrightarrow{K} = \overleftrightarrow{I} + \overleftrightarrow{\chi} = \begin{pmatrix} K_{xx} & \chi_{xy} & \chi_{xz} \\ -\chi_{xy} & K_{yy} & \chi_{yz} \\ -\chi_{xz} & \chi_{yz} & K_{zz} \end{pmatrix} \tag{9}$$

$\gamma^2 = \omega_{pe}^2(x)/\omega^2$, $\beta = \omega_{ce}(x)/\omega$, $\beta_c = \beta \cos\Psi(x)$, $\beta_s = \beta \sin\Psi(x)$, $\overleftrightarrow{I}$ is the second-rank identity tensor,

$$\tilde{\chi} \;=\; \frac{-3\omega_{pe}^2\omega^2}{(\omega^2 - \omega_{ce}^2)(\omega^2 - 4\omega_{ce}^2)} \left(\frac{v_{Te}}{c}\right)^2 . \tag{10}$$

$v_{Te} = \sqrt{(\kappa T_e/m_e)}$ is the electron thermal velocity, and n_y and n_z are the poloidal and toroidal wave indexes, respectively.

We have developed a comprehensive numerical package for solving the kinetic, full-wave equation (6) to study the coupling of EBWs to the X- and O-modes. With the appropriate boundary conditions, this code can be used to study mode conversion to EBWs from vacuum launched X- and O-modes, or to study the emission of EBWs. Below, we give results of our studies on mode conversion to EBWs.

NUMERICAL RESULTS ON MODE CONVERSION TO EBWs

We have studied, analytically and numerically, mode conversion to EBWs from the X- and O-modes in NSTX-type and MAST-type equilibria. Since there already exist sources at 60 GHz on MAST, we determined the optimum density profiles for efficient mode conversion in MAST.

In NSTX-type high-β equilibria [1,2], for an edge magnetic field of $0.28\,T$ and a density profile of the form $(1 - r^2/a^2)^{1/2}$ where $a = 0.44\,\text{m}$ is the minor radius, the edge density is $6\times10^{17}\,\mathrm{m}^{-3}$, and the peak density is $3\times10^{19}\,\mathrm{m}^{-3}$, we obtain the following results. The X-B mode conversion efficiency is greater than 50% in the frequency range $13 \lesssim f \lesssim 18$ GHz for $n_{\|} \approx 0$, with an efficiency of 100% for $f = 15$ GHz. For $f = 15$ GHz, the efficiency is greater than 50% for $0 \lesssim n_{\|} \lesssim 0.35$. The O-X-B mode conversion efficiency is 100% for $f = 28$ GHz and $(n_{\|})_{\rm crit} \approx 0.48$. The range of $n_{\|}$'s for which the efficiency is greater than 50% is $0.4 \lesssim n_{\|} \lesssim 0.6$.

For MAST-type parameters with an edge magnetic field of $0.37\,T$, an edge density of $4\times10^{19}\,\mathrm{m}^{-3}$, and a fixed source frequency of 60 GHz, we find that, for $n_{\|} = 0$, the X-B conversion efficiency of 100% is possible if $L_n \approx 1.7\times10^{-3}\,\mathrm{m}$ at the UHR. This corresponds to a density profile of the form $(1 - r^2/a^2)^{0.25}$. For optimizing the O-X-B mode conversion, a scale length of $L_n \approx 6\times10^{-2}\,\mathrm{m}$ at the UHR for a $(n_{\|})_{\rm crit} \approx 0.4$ is required.

Thus, both analytically and numerically, it is apparent that the X-B and the O-X-B mode conversion processes optimize in different regimes of frequency and parallel wavenumber space. This allows for a certain amount of flexibility when considering the launching of EBWs in different ST equilibria.

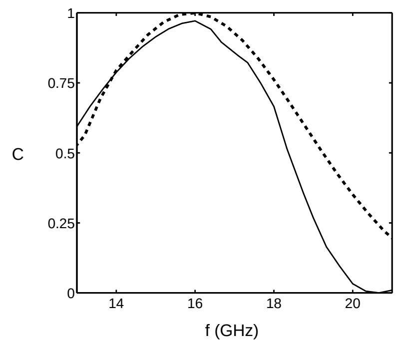

Figure 1: Power mode conversion coefficient as a function of frequency for NSTX-type parameters. The solid line is the result from the kinetic description of the EBW while the dashed line is from the analytic expression in Eqs. (1,3). Both results are for $n_y = n_z = 0$.

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