MODE-CONVERTED ELECTRON BERNSTEIN WAVES FOR HEATING AND CURRENT DRIVE IN NSTX

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Abstract

The power coupled to electron Bernstein waves in a triplet mode conversion resonator from a fast X-mode at the plasma edge in NSTX is shown to be $> 80\%$ for $f_{ce} < f < 2f_{ce}$. The EBW damping in the plasma is strong and localized and, thus, should be useful for heating, current drive, or profile control.

1. INTRODUCTION

The excitation and localized damping of electron Bernstein waves (EBW) in toroidally confined plasmas presents the possibility of efficient means for plasma heating, current drive, and current profile control with external power in the electron cyclotron range of frequencies (ECRF). Such use of EBW is particularly interesting for high-β plasmas at low magnetic fields (e.g., MAST, NSTX) in which the usual heating by O-mode excitation and propagation into the plasma can only be assured for frequencies at very high harmonics of the electron cyclotron frequency where damping is rather weak. A new aspect for wave coupling and propagation in these high-β plasmas is that their equilibria entail poloidal magnetic fields that are not negligible compared to toroidal fields as is the case in most low-β tokamaks.

In principle, excitation of EBW's is possible by mode conversion from externally launched electromagnectic power in O-mode, X-mode, or mixed O/X-mode polarizations [1-6]. For high-β, spherical-type tokamaks (NSTX, in particular) we have recently proposed a scenario for fast-X to EBW mode conversion that shows promise of high mode-conversion efficiency over a broad range of frequencies in the vicinities of the fundamental and second harmonic of the electron cyclotron frequency [7,8]. For the low magnetic field of such high-β plasmas this falls in a frequency regime in which high-power cw sources are readily available. Furthermore, for these frequencies and moderate $n_{\parallel}$ we find effective and localized damping of the generated EBW's in the vicinity of the Doppler-shifted electron cyclotron resonance. This type of fast-X to EBW mode conversion (which has been independently considered in [5] but not dealt with in detail) is based upon setting up at the plasma edge a mode conversion resonator, with the mode conversion to a propagating EBW as an effective "dissipation" in this resonator. In this paper we present the results of fast-X to EBW mode conversion for NSTX, compare it to the O-X-EBW mode conversion process, and illustrate the propagation and damping of the EBW's.

2. THE TRIPLET MODE CONVERSION RESONATOR IN ECRF

Figure 1 shows the spatial distribution of various critical frequencies in propagation across the toroidal and poloidal magnetic fields, calculated along the major radius of the equatorial plane for an NSTX equilibrium [9]. As can be appreciated from the simplest cold plasma dispersion [7] and Figure 1, at low electron cyclotron harmonics a fast X-mode launched from the outboard will encounter a right (R) cutoff in close proximity to the upper-hybrid resonance (UHR), followed by a slow X-mode which connects back to the UHR (and kinetically, to the EBW) and continues to the left (L) cutoff. This combination of R-cutoff/UHR followed by the L-cutoff forms a triplet resonator containing the mode conversion "dissipation", which, in a cold plasma description is resonant absorption at the UHR, and in a kinetic description is energy flow in the EBW. Such a triplet mode conversion resonator can achieve 100% mode conversion from X to EBW. The critical parameters for achieving this follow from a simplified (neglecting variations in magnetic fields and $n_{\parallel}$) cold-plasma full-wave analysis expanded in the vicinity of the UHR, and solution of the associated differential equation for the X-mode electric field.
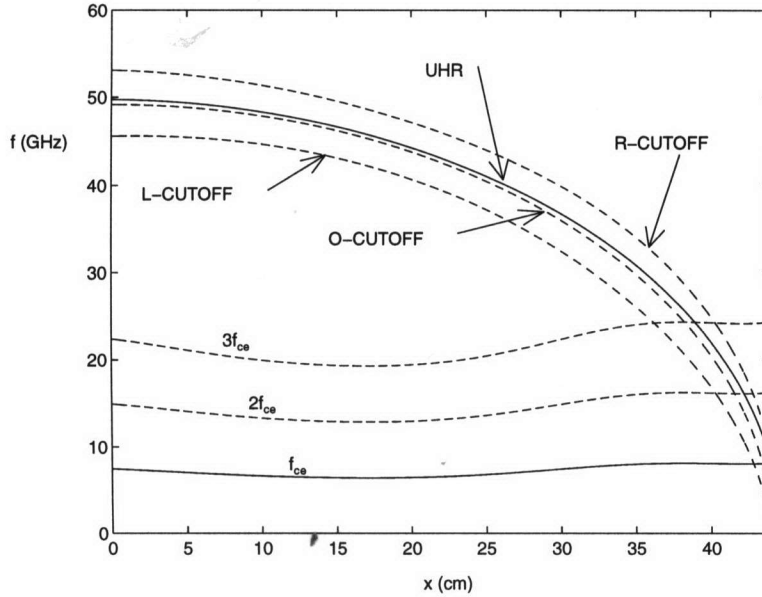
Figure 1: Location of critical frequencies as a function of minor radius along the equatorial plane, as calculated for NSTX parameters [9].

The results, which can be carried over from our previous analysis of a triplet resonator mode conversion from fast Alfvén waves to ion-Bernstein waves [10], give a power mode conversion coefficient

$$C = 4e^{-\pi\eta}(1 - e^{-\pi\eta})\sin^2\left(\frac{\phi}{2} + \theta\right) \tag{1}$$

where the Budden-parameter η is found to be [7]

$$\eta = \frac{\omega_{ce}(x = x_{UH})}{\sqrt{2}\,c}\,L_n\;; \quad L_n = \left|\frac{d}{dx}\ln n_0(x)\right|^{-1}_{x=x_{UH}} \tag{2}$$

θ = phase of the gamma function $\Gamma(-i\eta/2)$, and ϕ is the phase difference between the slow X-mode propagating toward the L-cutoff and the reflected component propagating toward the UHR. Equation (1) shows that 100% mode conversion ($C = 1$) is possible for $\eta = 0.22$, and $(\theta + \phi/2) = \pi/2$. To acheive near optimal mode conversion for NSTX one finds from (1), (2) and Figure 1 the need for setting up the triplet mode conversion in the density gradient near the plasma edge, and in the frequency range near $2f_{ce}$.

A full-wave cold plasma slab code, for arbitrary n_z and n_y, similar to what was used in [4] but including the full description of both toroidal and poloidal magnetic field variations, gives the mode conversion as a function of frequency, for both $n_z = 0$ and $n_z = 0.1$, as shown in Figure 2. We observe that high mode conversion efficiencies ($> 80\%$) are obtained over a broad range of frequencies of about 4 GHz around the peak in $C \approx 0.97$ at $f = 16$ GHz. Furthermore, introducing a change in the edge-density by 5% shifts the peak by about 1 GHz, but does not change its peak value or shape. We thus conclude that this X-EBW triplet mode conversion for NSTX is both very efficient and quite robust. The optimal parameters based upon (1) and (2) are essentially verified by the full-wave code results.

We have also generated and run an approximate full-wave kinetic code that removes the cold plasma resonance absorption at the UHR and describes the mode conversion as energy flow (electromagnetic and kinetic) onto the EBW [8]. The results are also shown in Figure 2 and are observed to be close to those based upon the full-wave cold-plasma description; however, the kinetic code gives the correct energy flow description, particularly in the transition of the upper-hybrid frequency from below to above the second electron cyclotron harmonic.
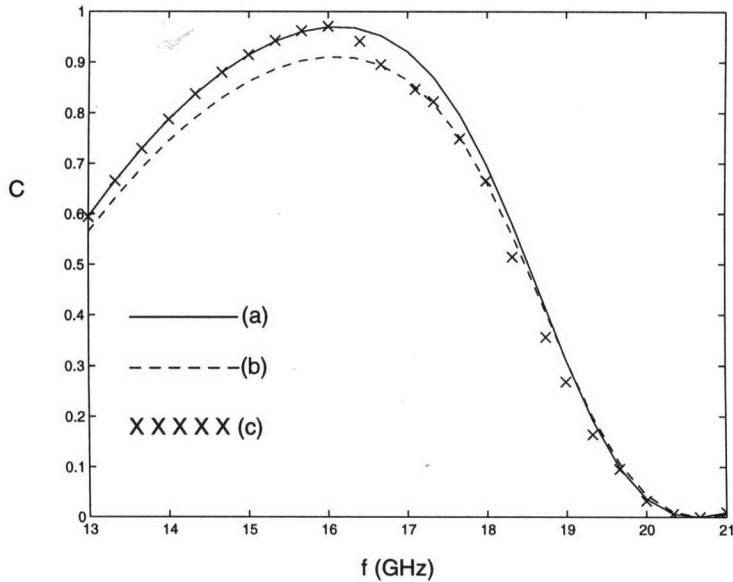
Figure 2: Mode conversion of fast X-mode to EBW as a function of frequency in a plasma with NSTX parameters [9] from full-wave calculations [8] using (a) a cold-plasma model with $n_z = 0$, (b) a cold-plasma model with $n_z = 0.1$, and (c) an approximate kinetic model with $n_z = 0$.

3. COMPARISIONS OF O-X-B AND X-B MODE CONVERSION

As in Ref. [4], we can also integrate the cold-plasma equations to derive a mode-conversion coefficient for O-X-B mode conversion. Figure 3 shows the resonant absorption mode conversion of an O-mode launched into a plasma with the same NSTX parameters as in Section 2. In each case, we observe that the mode conversion fraction peaks at the optimal value of n_z, $n_{z,opt}^2 = \omega_{ce}/(\omega + \omega_{ce})$ [1]. The peak in mode conversion increases with frequency, but significant mode conversion is then achieved only over a narrow range in n_z. We remark that although it is possible to obtain full mode conversion from the O-mode to the slow X-mode (albeit at a substantial $n_{z,opt}$) the subsequent conversion of this slow X-mode to EBW is at most $(1 - T)$, where T is the Budden tunneling factor $T = \exp(-\pi\eta)$, with η given by (2). Thus high mode conversion for O-X-B requires $T \ll 1$. At high frequencies (28GHz) the confluence of the O-mode and L cutoffs at $n_{z,opt}$ is farther into the plasma where density gradients are weaker and T is negligible; however, as n_z deviates from $n_{z,opt}$, the separation between the O and L cutoffs increases rapidly, drastically reducing O-mode to slow X-mode conversion. For the low frequency case (14GHz), we see that even at $n_{z,opt}$ only $\approx 40\%$ mode conversion is possible, since the confluence point is closer to the edge where the higher density gradients mean T is not negligible, and our calculations show that most of the reflected power leaves the plasma on the fast X-mode. Hence we conclude that at 14GHz, the tunneling of the X-mode is more advantageous to the triplet mode conversion of the fast X-mode to the EBW, as shown in Section 2.

4. PROPAGATION AND DAMPING OF THE MODE-CONVERTED EBW

Beyond mode conversion, the location of the damping of the EBW must be determined by ray tracing. The poloidal magnetic field leads to changes in the poloidal mode numbers of the EBW and, subsequently, a change in $k_\parallel$ [11]. With these changes it is possible for EBWs to Landau damp on electrons in a region which is not near the electron cyclotron resonance or its harmonic. Using a non-relativistic, hot Maxwellian plasma ray tracing code [11] we have carried out preliminary studies of the propagation of mode-converted EBWs launched at the equatorial plane in plasmas similar to high-β scenarios of NSTX. We find that the EBW propagate away from the mode-conversion region towards the center of the plasma and damp near the Doppler-shifted electron cyclotron resonance. In the poloidal plane the EBWs remain close to the equatorial plane and even though there are significant changes in $k_\parallel$ along the EBWs, there is no electron Landau damping prior to the encounter with the position of the Doppler-shifted cyclotron resonance.
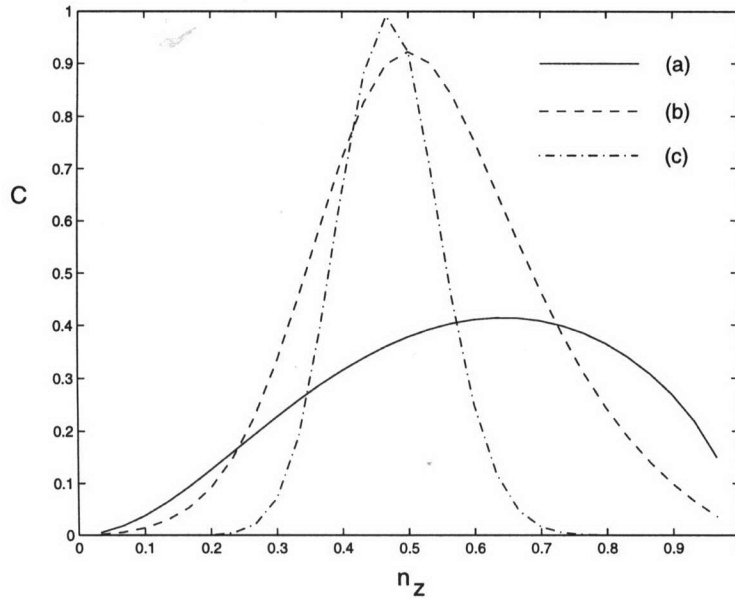
Figure 3: Mode conversion of O-mode to EBW (O-X-B conversion) as a function of n_z at (a) $f = 14\text{GHz}$, (b) $f = 21\text{GHz}$, and (c) $f = 28\text{GHz}$, in a plasma with NSTX parameters [9] from cold-plasma full-wave calculations.

5. ACKNOWLEDGEMENTS

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    NSTX: $R = 1.05\text{m}$; $a = 0.44\text{m}$; $n_{e0} = n_E + (n_0 - n_E)(1 - x^2/a^2)^{1/2}$; $n_0 = 3 \times 10^{19}/\text{m}^3$;
    B_T and B_p fit to profiles. $T_{e0} = T_E + (T_0 - T_E)(1 - x^2/a^2)^2$; $T_0 = 3\text{keV}$; $(n_E, T_E) = 0.02(n_0, T_0)$.
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