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**ELECTRON CYCLOTRON HEATING IN NSTX**

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**Abstract.** Heating and current drive by electron cyclotron waves in high magnetic field tokamaks is commonly done by coupling power from the low-field side to the O-mode. However, for tokamaks with  $\omega_{pe}/\omega_{ce} > 1$ , such as the spherical tokamak NSTX, the O-mode is cutoff throughout most of the plasma. An alternative method for accessing the cyclotron layer is via the fast X-mode and its mode conversion to an electron-Bernstein wave (EBW)[1]. We show that for a given plasma density and magnetic field profile, an appropriate choice of the frequency allows one to form a triplet (cutoff-resonance-cutoff) X to EBW mode-conversion scenario. This is similar to the low-frequency, ion-ion hybrid resonance scenario for which 100% mode conversion was shown to be possible[2]. The mode-conversion efficiency for DIII-D and NSTX is calculated.

We report on our initial studies of a new means for supplying the ECRF power into the bulk of a spherical tokamak plasma. In this method, the ECRF power is coupled into the plasma by exciting the X-mode. At the upper-hybrid resonance (UHR) located in the plasma, the X-mode undergoes mode conversion to EBW which can then propagate towards the core of the plasma and damp at the electron cyclotron resonance, or its harmonics, by Doppler-shifted electron cyclotron damping. Simulations of a related mode conversion scheme (O-X-B) have shown that substantial mode conversion can be achieved for a suitable choice of ECRF frequencies and parallel wavelength.[3] The mode conversion of the X-mode to the EBW occurs in a region of the plasma where one encounters a cutoff-resonance followed by a cutoff. This is the so-called “triplet” mode-conversion scenario, which has been encountered in the ion cyclotron range of frequencies (ICRF), and for which we have provided a complete analytical description.[2] We use a similar analysis for the mode conversion of the X-mode to EBW. In the following we summarize our analysis and illustrate the mode conversion and EBW damping for tokamak parameters of DIII-D and NSTX. A similar approach to this mode conversion process is alluded to in [4] but details are not given there.

Assuming an equilibrium magnetic field  $\vec{B} = B_0\hat{z}$  in the toroidal direction only, and considering a slab geometry model for the radial (x-direction) propagation of ECRF waves in the equatorial plane, the poloidal (y-direction) component of the wave electric field is given by

$$\frac{d^2 E}{dx^2} + \frac{\omega^2}{c^2} \frac{K_R K_L}{K_\perp} E = 0. \quad (1)$$

This equation describes the propagation of the X-mode through a resonance, ( $K_\perp = 0$ ), and two cutoffs, ( $K_R = 0$  and  $K_L = 0$ ). This wave equation can be solved approximately as we have shown before.[2] We find that for an incident X-mode from the low B-field side, the fraction of power resonantly absorbed at the UHR (hence, mode converted to the EBW) is given by

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

where

$$\eta = \frac{\omega_{ce}(x_{UHR})}{\sqrt{2cb}}, \quad (3)$$

and

$$b = \frac{1}{n_e(x_{UHR})} \left| \frac{dn_e(x)}{dx} \right|_{x=x_{UHR}}. \quad (4)$$

$\theta$  is the phase of  $\Gamma(-i\eta/2)$ ,  $\phi$  is essentially the phase of the wave reflected from the high-field side left-hand cutoff relative to the incident wave, and  $x_{UHR}$  is the position of the UHR. For substantial mode conversion ( $C > 1/2$ ) one requires typically  $0.1 < \eta < 0.5$ .

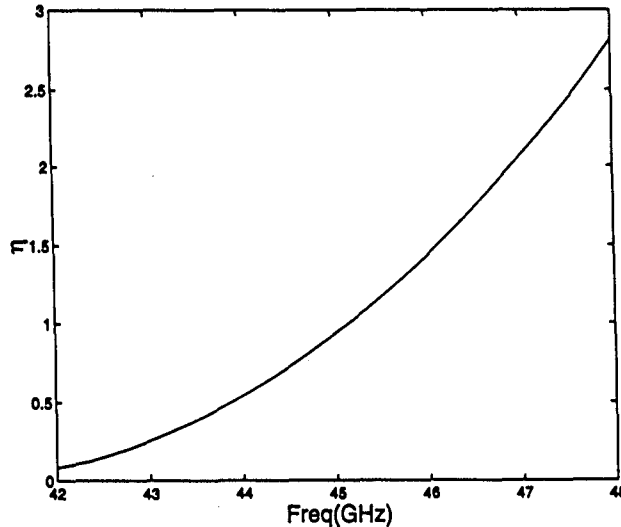
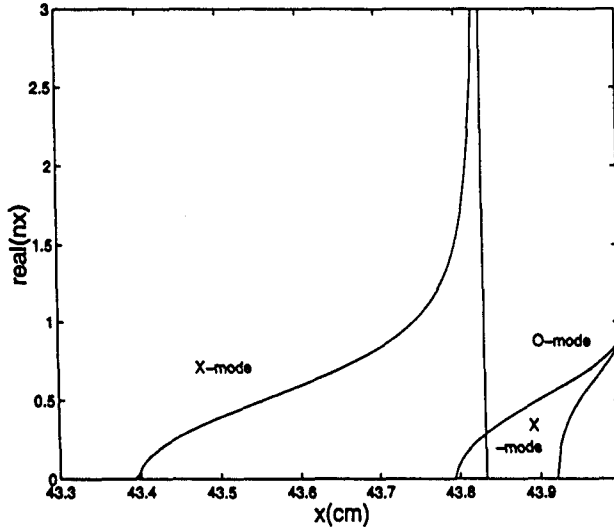


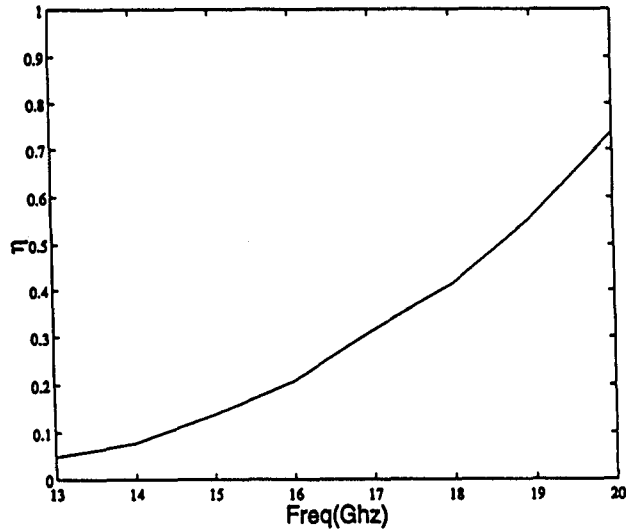
Figure 1. Plot of the mode conversion parameter  $\eta$  as a function of the frequency of the RF wave for DIII-D. The parameters are: minor radius  $a = 0.7\text{m}$ , major radius  $R = 1.7\text{m}$ ,  $B_0 = 2\text{T}$ ,  $n_e = n_{edge} + (n_0 - n_{edge})(1 - (x/a)^2)^{1/2}$ , where  $n_{edge} = 1.6 \times 10^{18}\text{m}^{-3}$  and  $n_0 = 8 \times 10^{19}\text{m}^{-3}$ .

We have applied the above analysis to the parameters for General Atomic's DIII-D tokamak.[5] IN Figure 1 we plot  $\eta$  given in (3) as a function of the frequency of the excited wave. To achieve the desired range of  $\eta$  necessary for substantial power mode conversion, for DIII-D requires sources in the frequency range of  $42 \text{ GHz} < f < 44\text{GHz}$ . In this frequency range, the triplet occurs near the plasma edge. This is due to the fact that, for a significant amount of power to be mode converted, it is necessary for the distance between the first cutoff and the resonance (effectively  $\eta$ ) to be small. As a result, as seen from (3) and (4), the density gradient near the resonance must be very steep, and, in general, the density is steepest near the edge of the plasma.

Since EBW's and electron heating are due to finite electron temperatures of the plasma, we need to consider a Vlasov description to account for the propagation and damping of EBWs. Using our code which numerically solves the hot plasma dispersion relationship, we have studied the propagation and damping of EBW's for DIII-D tokamak parameters. We find that the coupling of the X-mode to the EBW near the UHR is as predicted by the cold plasma model. The mechanism by which the EBW power is delivered to the electrons is through Doppler-shifted cyclotron damping. The EBW propagates into the bulk of the plasma and damps rapidly near the region where  $\omega = \omega_{ce}$ . Since this effect is only present when  $k_{\parallel} \neq 0$ , it is important to determine the dependence of the mode-conversion on  $k_{\parallel}$ . Previous analysis has shown that large  $|k_{\parallel}|$  may change the nature of the dispersion relation significantly.[6]



**Figure 2.** Plot of the cold plasma local dispersion relationship for NSTX showing the triplet structure. The parameter of the plasma,  $a = 0.44\text{m}$ ,  $R = 0.8\text{m}$ ,  $n_e = n_{edge} + (n_0 - n_{edge})(1 - (x/a)^2)^{1/2}$ , where  $n_{edge} = 6 \times 10^{17}\text{m}^{-3}$  and  $n_0 = 3 \times 10^{19}\text{m}^{-3}$ , and ECRF frequency of  $17.3\text{GHz}$ . In the region shown,  $B_t \approx .22\text{T}$ ,  $B_p \approx -.08\text{T}$ .



**Figure 3.** Plot of the mode conversion coefficient  $\eta$  as a function of the ECRF frequency.(see figure 2)

We have also initiated a study of ECRF heating and current drive in NSTX. Unlike conventional tokamaks, the ratio of the magnitude of  $B_p$  to  $B_t$  can be of order 1. This leads to a complicated coupling between the wave electric fields  $E_y$  and  $E_z$ , and the wave equation is no longer of the form (1). However, near the edge of the plasma where the mode conversion takes place,  $B_p$  is small compared to  $B_t$ , and equations (1)-(4) are still valid. Figure 2 shows the dispersion relation with the triplet structure for NSTX and figure 3 shows  $\eta$  as a function of the ECRF frequency.[7] For substantial power to be mode converted to EBWs, we require wave frequencies in the range  $14.5\text{GHz} < f_i < 18.5\text{GHz}$ . We are currently studying the effect of nonzero toroidal and poloidal wavenumbers on the mode conversion process in NSTX.

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