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Relativistic Effects in Heating and Current Drive by Electron Bernstein Waves

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ABSTRACT

The high-β magnetically confined plasmas in spherical tori (ST), like NSTX and MAST, provide a unique opportunity for a wide variety of applications of electron Bernstein waves (EBW). These applications range from heating of the ST plasma to modifying and controlling its current profile. Using the fully relativistic dielectric tensor for a Maxwellian distribution function, this paper presents initial results illustrating the effect of relativity on the dispersion characteristics of EBWs. It is found that, even at temperatures relevant to present STs, the relativistic dispersion properties of EBWs are significantly different from their non-relativistic counterpart.

INTRODUCTION

The EBWs, excited at the edge of the ST plasmas by mode conversion of an externally launched extraordinary or ordinary mode [1, 2], propagate into the overdense plasma and damp on electrons at the Doppler-shifted electron cyclotron resonance (or its harmonics). Depending on the poloidal location of the EBW excitation, the magnitude of the parallel (to the magnetic field) wavenumber can be either less than one (for equatorial excitation) or greater than one (for excitation away from the equatorial plane) [1]. Furthermore, for EBWs $k_\perp \rho_e \gtrsim 1$ ($k_\perp \rho_e$ is the electron Larmor radius normalized to the perpendicular wavelength) so that small Larmor radius expansions are not valid. Previous studies have found relativistic effects to be important for conventional electron cyclotron waves [3].

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RELATIVISTIC DIELECTRIC TENSOR

There are two numerically useful representations for obtaining the relativistic conductivity tensor $\overline{\overline{\sigma}}$ for a relativistic Maxwellian distribution function [4]. The first form of the conductivity tensor is:

$$\overline{\overline{\sigma}} = \frac{1}{4\pi}\frac{\omega_p^2}{\omega_c}\,\frac{c^4}{v_t^4}\frac{1}{\mathrm{K}_2\left(\dfrac{c^2}{v_t^2}\right)}\;\int_0^\infty d\xi\;\;\left\{\frac{\mathrm{K}_2\left(R^{1/2}\right)}{R}\overline{\overline{T}}_1 - \frac{\mathrm{K}_3\left(R^{1/2}\right)}{R^{3/2}}\,\overline{\overline{T}}_2\right\} \tag{1}$$

where ω_p, ω_c, v_t are the rest mass electron plasma frequency, cyclotron frequency, and the thermal velocity, respectively, K_ν is the modified Bessel function of the second kind of order ν, and

$$\overline{\overline{T}}_1 = \begin{pmatrix} \cos\xi & -\sin\xi & 0 \\ \sin\xi & \cos\xi & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{2}$$

$$\overline{\overline{T}}_2 = \frac{c^2}{\omega_c^2}\begin{pmatrix} k_\perp^2\sin^2\xi & -k_\perp^2\sin\xi\,(1-\cos\xi) & k_\perp k_\parallel\xi\sin\xi \\ k_\perp^2\sin\xi\,(1-\cos\xi) & -k_\perp^2\,(1-\cos\xi)^2 & k_\perp k_\parallel\xi\,(1-\cos\xi) \\ k_\perp k_\parallel\xi\sin\xi & -k_\perp k_\parallel\xi\,(1-\cos\xi) & k_\parallel^2\xi^2 \end{pmatrix} \tag{3}$$

$$R = \left(\frac{c^2}{v_t^2} - i\xi\frac{\omega}{\omega_c}\right)^2 + 2\left(\frac{k_\perp c}{\omega_c}\right)^2(1-\cos\xi) + \frac{k_\parallel^2 c^2\xi^2}{{\omega_c}^2} \tag{4}$$

For any equilibrium distribution function $f_0(p_\perp, p_\parallel)$, the second form of the conductivity tensor is:

$$\overline{\overline{\sigma}} = -\frac{i}{2}\,\frac{\omega_p^2}{\omega_c}\left\langle\,\sum_{n=-\infty}^{\infty}\,\frac{1}{n-\overline{\omega}}\left(\frac{1}{\kappa T}\,\frac{p_\perp}{m\gamma}\right)\,\overline{\overline{\sigma}}_N\;f_0\left(p_\perp, p_\parallel\right)\,\right\rangle \tag{5}$$

where

$$\overline{\overline{\sigma}}_N = \begin{pmatrix} \frac{n^2}{\zeta^2}p_\perp\mathrm{J}_n^2 & -i\frac{n}{\zeta}p_\perp\mathrm{J}_n\mathrm{J}_n' & \frac{n}{\zeta}p_\parallel\mathrm{J}_n^2 \\ i\frac{n}{\zeta}p_\perp\mathrm{J}_n\mathrm{J}_n' & p_\perp\mathrm{J}_n'^2 & ip_\parallel\mathrm{J}_n\mathrm{J}_n' \\ \frac{n}{\zeta}p_\parallel\mathrm{J}_n^2 & -ip_\parallel\mathrm{J}_n\mathrm{J}_n' & \frac{p_\parallel^2}{p_\perp}\mathrm{J}_n^2 \end{pmatrix} \tag{6}$$

$$\zeta = \frac{k_\perp p_\perp}{m\omega_c}, \overline{\omega} = \frac{1}{\omega_c}\left(\omega\gamma - k_\parallel\frac{p_\parallel}{m}\right), \omega_c = \frac{eB_0}{m}, \langle .....\rangle = \int_0^\infty dp_\perp p_\perp\int_{-\infty}^{\infty} dp_\parallel \tag{7}$$

NUMERICAL RESULTS

We have developed two computational codes based on the two equivalent relativistic representations discussed above. For a variety of cases we find that the two codes lead to identical results. In the mode conversion region near the edge of NSTX-type plasmas [1, 2], we find that the results obtained from the relativistic description are the same as those from the non-relativistic description. Thus, the mode conversion formalism developed in [1, 2] is not modified by relativistic effects. In Fig. 1 we show the dispersion characteristics of EBWs as a function of ω/ω_c for a uniform plasma with electron temperature of 3 keV, $\omega_p/\omega_c = 36$, and $n_\| = 0.2$. We note that the relativistic effects broaden the resonance (Fig. 1b) at the second harmonic where the real part of $n_\perp$ becomes small, and narrow down the resonance at the fundamental electron cyclotron frequency where $n_\perp$ becomes large. In Fig. 2 we show the dispersion characteristics of EBWs as a function of $n_\|$ for a uniform plasma with electron temperature of 3 keV, $\omega_p/\omega_c = 36$, and $\omega/\omega_c = 1.8$. It is now evident that there are significant differences between the relativistic and non-relativistic properties of EBWs. These local differences would accumulate along a ray path in toroidal geometry, leading to a very different spatial location of the damping region for EBWs. This will be examined in the future.

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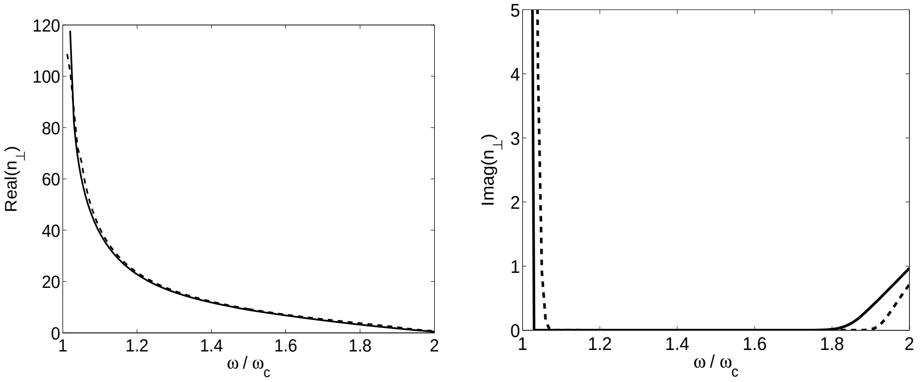
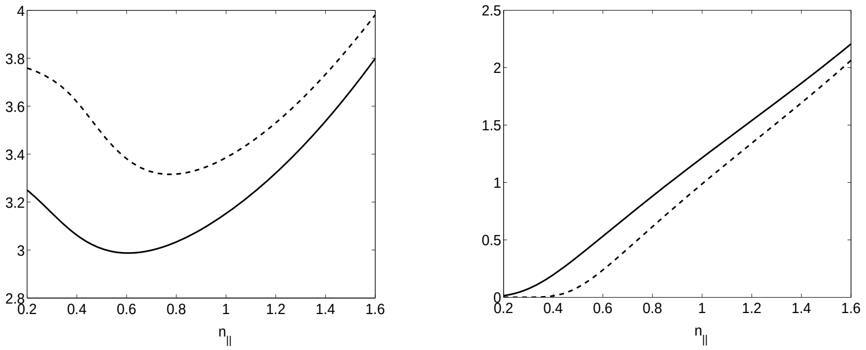


(a) (b)

Figure 1: Dispersion characteristics of EBWs as a function of ω/ω_c for $n_\parallel = ck_\parallel/\omega = 0.2$, $(\omega_p/\omega_c)^2 = 36$, and $T_e = 3$ keV: (a) real part of $n_\perp = ck_\perp/\omega$; (b) imaginary part of $n_\perp$. The solid line represents the solution of the dispersion relation in the fully relativistic case, and the dashed line is for the non-relativistic case.



(a) (b)

Figure 2: Dispersion characteristics of the EBW as a function of $n_\parallel = ck_\parallel/\omega$: (a) real part of $n_\perp$; (b) imaginary part of $n_\perp$. The parameters are as cited in the text. The solid line represents the solution of the dispersion relation in the fully relativistic case, and the dashed line is for the non-relativistic case.