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COLLISIONAL DAMPING OF THE FAST MAGNETOSONIC WAVE IN THE TOKAMAK EDGE PLASMA*

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ABSTRACT

The collisional absorption of the fast magnetosonic wave in the tokamak edge region is re-examined. This is of concern in either fast wave current drive (FWCD) experiments with weak central absorption (i.e., DIII-D) or in high density minority heating experiments in compact, high field devices (i.e., Alcator C-Mod). Using a simple Krook-type of collision model, the present calculations indicate negligible (i.e., less than 0.1%) single-pass absorption due to collisions under typical experimental conditions.

I. INTRODUCTION

Recent experiments on fast wave current drive (FWCD) in the DIII-D tokamak,[1] and fast wave ICRF heating experiments at high densities in Alcator C-Mod,[2] raised the question of the importance of single pass damping of the fast magnetosonic wave due to collisions in the tokamak edge plasma. This is of particular concern in the case of weak single pass damping in the bulk plasma when edge damping could compete and perhaps even dominate. For example, in the DIII-D tokamak FWCD experiments at $B_T = 1.1$ T and $f = 60$ MHz, a decrease in both the global heating efficiency and current drive efficiency can be modeled by an edge loss of 3-4% per pass.[1,3] Past numerical results indicate single pass collisional losses of the order of several percent for typical tokamak edge plasmas.[4] In this paper we have reexamined the collisional damping of the fast wave and find that typical edge damping per pass is at most of the order of ~0.1%. This is more than an order of magnitude less than the predictions of previous calculations[4] and thus edge damping by this process is considered to be unimportant. Full wave code (FELICE)[5]calculations have been used to support these results.

II. COLLISIONAL EFFECTS IN FLUID THEORY

We consider inclusion of collisional effects by a simple momentum-loss type of collision term, $\nu_{eff} \sim \nu_e$. The dominant momentum-loss term enters mainly through electron-ion collisions, hence $\nu_e \sim \nu_{ei} \sim \nu_{ee}/2$. Ion-electron collsions are smaller by the electron-ion mass ratio, ion-ion collisions are reduced by finite-Larmor radius effects[6] (i.e., $\nu_{ii\ eff} \sim k_\perp^2 r_{ci}^2 \nu_{ii}$ and $k_\perp^2 r_{ci}^2 \sim (\omega^2/\omega_{ci}^2)(v_{ti}^2/V_A^2) \ll 1$, and unlike ion-ion collisions, or ion-neutral collisions are typically smaller than ν_e even in the presence of impurity ions.[4] Under these circumstances, in the cold plasma limit the effective electron-ion collision frequency can be introduced through an effective electron mass,

$$m_{eff} \rightarrow m_e(1 + i\nu_{eff}/\omega) \ . \tag{1}$$

For the parallel component of the cold-plasma dielectric constant in the Stix notation, we have

$$\tilde{P} = 1 - \frac{\omega_{pe}^2}{\omega^2(1 + i\nu_e/\omega)} \tag{2}$$

where $\nu_{eff\ \parallel} \simeq \nu_{ei} \simeq \nu_e$.

The perpendicular component of the cold-plasma dielectric constant is somewhat more problematic. We can gain some insight into this problem if we follow the treatment of the cold lower-hybrid wave propagation discussed by Harms[6]. Using a Fokker-Planck treatment, he has shown that in the high phase velocity limit of cold lower hybrid waves, the perpendicular component of the dielectric constant is corrected for collisions by the expression

$$\delta\varepsilon_\perp \simeq \left(\frac{i\nu_{eff\perp}}{\omega}\right)\left(\frac{\omega_{pe}^2}{\omega_{ce}^2}\right) \tag{3}$$

where $\nu_{eff\perp} \simeq (2/3\pi^{1/2})\nu_{ee} \approx \nu_{ee}/2 \simeq \nu_{ei}$. Thus, the effective collision frequency can again be replaced to a good approximation by Eq.(1). Therefore we shall use the following forms of the Stix cold dielectric tensor elements:

$$P + iP_c = \tilde{P} \simeq 1 - \frac{\omega_{pe}^2}{\omega^2}\left(1 - \frac{i\nu_e}{\omega}\right), \qquad 4(a)$$

$$R + iR_c = \tilde{R} \simeq 1 + \sum_i \left(\frac{\omega_{pi}^2}{\omega_{ci}(\omega+\omega_{ci})} + \frac{i\omega_{pi}^2\nu_e}{\omega\omega_{ci}\omega_{ce}}\right), \qquad 4(b)$$

$$L + iL_c = \tilde{L} = \simeq 1 - \sum_i \left(\frac{\omega_{pi}^2}{\omega_{ci}(\omega-\omega_{ci})} - \frac{i\omega_{pi}^2\nu_e}{\omega\omega_{ci}\omega_{ce}}\right), \qquad 4(c)$$

$$S + iS_c = \tilde{S} \simeq 1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} - \sum_i \left(\frac{\omega_{pi}^2}{\omega^2-\omega_{ci}^2} - \frac{i\omega_{pi}^2\,\nu_e}{\omega\omega_{ci}\,\omega_{ce}}\right). \qquad 4(d)$$

Here we expanded terms in powers of m_e/m_i, and assumed $\nu_e/\omega \ll 1$ which is a good approximation for typical edge plasma conditions, $n_e = \lesssim 5 \times 10^{18}\mathrm{m}^{-3}$, $T_e \simeq 10 - 50$ eV.

The fast wave (FW) dispersion relationship is given by[7,8]

$$\left(n_x^2 + n_z^2\right)\left(n_x^2\tilde{S} + n_z^2\tilde{P}\right) - \tilde{R}\tilde{L}n_x^2 - \left(n_x^2 + 2n_z^2\right)\tilde{P}\tilde{S} + \tilde{P}\tilde{R}\tilde{L} = 0\,, \tag{5}$$

where $n_z(n_x)$ is the parallel (perpendicular) component of the index of refraction, namely $n_z = ck_z/\omega$, etc. Multiplying out, and collecting terms the real part gives the usual dispersion relationship,

$$n_r^2 \simeq n_{xRe}^2 \simeq (n_z^2 - R)(n_z^2 - L)/(S - n_z^2) \qquad 6(a)$$

and the imaginary part gives

$$2\frac{n_{im}}{n_r} = \frac{\frac{\nu_e}{\omega}\frac{\omega^2}{\omega_{pe}^2}\frac{n_z^2 D^2}{n_z^2 - S} + \frac{\nu_e}{\omega}\frac{\omega_{pi}^2}{\omega_{ci}\omega_{ce}}\frac{(n_r^2 + 2n_z^2 - 2S)}{n_r^2}}{(n_z^2 - S) + \eta} \qquad 6(b)$$

where $D = (R - L)/2$, we assumed $\omega_{pe}^2/\omega_{ce}^2 \ll 1$, and

$$\eta = \frac{\omega^2}{\omega_{pe}^2}\left(RL - n_z^2 S + 2n_r^2 S\right) , \qquad 6(c)$$

$$D = \sum_i \frac{\omega}{\omega_{ci}} \frac{\omega_{pi}^2}{(\omega^2 - \omega_{ci}^2)} . \qquad 6(d)$$

Usually η is a small term unless $n_z^2 = S$ (which corresponds to the ion-ion hybrid, or the shear-Alfven wave resonance and is not important near the edge unless $\omega < \omega_{ci}$ (majority)).

Note that typically the second term in the numerator is also small and may be neglected. Assuming that η can be ignored, and that $n_z^2 \neq S$, the spatial damping decrement can be put in the following approximate form:

$$2k_{im} \simeq \frac{\nu_e n_r}{c} \frac{\omega^2}{\omega_{pe}^2} \frac{n_z^2 D^2}{(n_z^2 - S)^2} . \qquad (7)$$

III. RESULTS OF KINETIC THEORY

While Eq.(7) holds in the fluid limit, namely $1 \ll \omega/k_{\|}v_{te}$, usually well satisfied in the plasma edge, a similar result has been obtained from kinetic theory using a particle conserving Krook model (see, for example, Ref. 9). Following the procedures outlined for the Landau absorption of the fast magnetosonic wave[7,8] we have obtained the following damping rate for arbitrary phase velocities in the presence of collisions:

$$2k_{im} = \frac{1}{2}\beta_e |\zeta_e| n_r \frac{\omega}{c}\left\{ Im Z(\zeta_e') + \frac{D^2 (m_e c^2 \omega_{ce}/\kappa T_e \omega)^2}{|K_{zz}'|^2 (S - n_z^2)^2} Im\left[\frac{Z(\zeta_e')}{1 + i\eta_e Z(\zeta_e')}\right]\right\}$$

$$+ \frac{\nu_e n_r}{c} \frac{\omega_{pe}^2}{\omega_{ci}^2}\left(\frac{2}{n_r^2} + \frac{1}{n_z^2 - S}\right) \qquad (8)$$

where $\zeta_e = \omega/k_{\|}v_{te}$, β_e is the electron beta, $\eta_e = \nu_e/k_z v_{te}$, $\zeta_e' = \zeta_e + i\eta_e$, D and S are the cold plasma dielectric constants, and

$$K_{zz}' \simeq \frac{2\omega_{pe}^2}{\omega^2} \zeta_e^2 [1 + \zeta_e' Z(\zeta_e')] \frac{1}{1 + i\eta_e Z(\zeta_e')} . \qquad (9)$$

It is easy to show that in the cold plasma limit, Eq.(8) reduces Eq. 6(b). We find that in the core plasma where $\zeta_e \simeq 1$, collisional absorption is completely negligible as compared to Landau absorption, and near the edge where collisions may be important the cold plasma treatment is valid.

IV. NUMERICAL RESULTS

We have evaluated numerically the above expression for typical DIII-D and Alcator C-Mod parameters. For example, in DIII-D, in deuterium plasmas at $B_{edge} = 0.8$ T, $n_e \simeq 2 \times 10^{18} \mathrm{m}^{-3}$, $T_e \simeq 30$ eV, $n_z = 5.5$, $Z_{eff} \lesssim 5, f = 60$

MHz, $\nu_e \simeq 1 \times 10^7 \text{sec}^{-1}, n_r \simeq 18,\ 2k_{im} \simeq 3.4 \times 10^{-5}\text{cm}^{-1}$. Taking a typical width for the "edge" region of $\Delta r \simeq 5$ cm, we obtain $2\Delta r k_{im} \simeq 2 \times 10^{-4}$, or a power loss of 0.02% per pass on the low field side. Damping on the high field side is weaker than on the low field side, and this result does not change. Allowing for some range of parameters in edge conditions, we conclude that the edge damping is at most 0.1% per pass. Similar results hold for the Alcator C-Mod experiment.

V. FULL WAVE CODE MODELING OF EDGE DAMPING

We have modeled the edge damping of fast waves by a collisional version of the FELICE full wave code.[5] The same collisional model was used as describe above, namely a Krook-type of model was used. Essentially the same results were obtained as above. The single pass absorption for DIII-D parameters at $B_0 = 1.0$ T, $T_{eo} = 2.5$ keV, $n_{eo} = 1.6 \times 10^{19}\text{m}^{-3}$, $f_0 = 60$ MHz, was 10.5% on the bulk plasma, and the absorption was 0.03% in the edge for $T_e \simeq 50$ eV, $n_{sep} = 3.0 \times 10^{18}\text{m}^{-3}$, $Z_{eff} = 3$, $L_n = 3.5$ cm, $L_T = 6.0$ cm. Edge damping at $B = 2.1$ T was less by nearly an order of magnitude. Similar modeling of damping in Alcator C-Mod was carried out and edge damping was also found to be negligible.

CONCLUSIONS

We have examined the importance of edge collisions on the damping of the fast magnetosonic wave using a simplified Krook type collisional model. Analytic expressions of the damping decrement have been obtained in both cold plasma, and kinetic treatments. It is found that under typical experimental conditions the single pass damping is less than 0.1%; hence this process cannot compete with bulk absorption due to electron Landau damping, minority absorption or mode conversion. Modeling the FELICE full wave code further corraborates these results. Thus, collisional damping cannot explain the apparent 3-4% parasitic absorption which may be operative in the experiments reported in Ref. 1.

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