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Strong Electron Dissipation by a Mode Converted Ion Hybrid (Bernstein) wave

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Abstract. The fast wave approximation, extended to include the effects of electron dissipation, is used to calculate the power mode converted to the ion hybrid (Bernstein) wave in the vicinity of the ion hybrid resonance. The power absorbed from the fast wave by ion cyclotron damping and by electron Landau and transit time damping (including cross terms) is also calculated. The fast wave equation is solved for either the Budden configuration of a cut-off-resonance pair or the triplet configuration of cut-off-resonance-cut-off. The fraction mode converted is compared for the triplet case and the Budden multi-pass situation. The electron damping rate of the ion hybrid wave is obtained from the local dispersion relation and a ray tracing code is used to calculate the damping of the mode converted ion hybrid wave by the electrons as it propagates away from the resonance. Quantitative results for a range of conditions relevant to JET, TFTR and ITER are given.

INTRODUCTION

There is a strong incentive to make use of the fast wave in the ion cyclotron range of frequencies to provide a seed for the bootstrap current and to modify the current profile. The fast wave has good accessibility properties without any density limit. However, under present tokamak conditions its coupling to the electrons is weak. A method of achieving efficient coupling of fast wave power to the electrons has recently been described by Majeski, Phillips and Wilson[1] who observed strong electron heating in the vicinity of the two ion hybrid resonance. The mechanism believed to be responsible for these observations is mode conversion of the fast wave to the ion hybrid wave. Majeski et al[1] drew attention to the fact that the fast wave cut-off, in the edge region on the high field side, moves towards the hybrid resonance as $k_{\|}$ increases, and suggested that the cut-off-resonance-cut-off triplet could lead to an enhancement of the mode conversion over the Budden value[2,3]. The triplet problem was recently solved in refs 4 and 5.

In a plasma in which the two ion species are present in comparable proportions the two ion hybrid resonance is well separated from both cyclotron resonances. As a result, in the vicinity of the ion hybrid resonance, the ion hybrid wave is damped only by the electrons. Furthermore, the electron damping of the ion hybrid wave is much stronger than the electron damping of the fast wave. An approximate expression for the damping rate of the ion hybrid wave is obtained and results from a ray tracing code quantify electron damping of the ion hybrid wave as it propagates away from the ion hybrid resonance. Mode conversion in the presence of both ion and electron damping is then calculated. This allows the power lost by the fast wave before it reaches the ion hybrid resonance to be obtained. Results are given for JET discharge conditions.

THE PROPAGATION AND DAMPING OF THE ION HYBRID WAVE

For the purposes of simplicity, only the specific case of a deuterium-tritium plasma will be considered. The two ion species are assumed to have equal concentrations and the same temperature. In addition, the small Larmor radius approximation is made for both ion species and only the imaginary parts of the off-diagonal elements of the dielectric tensor which contribute to the $n = 0$ electron resonance are included. The dispersion relation is given by

$$(\omega^2 - c_A^2 k_\perp^2)\left(\omega^2 - \Omega_{ii}^2 - \frac{\Omega_T^2}{4}N_\|^2 + \frac{27}{200}\Omega_T^2\frac{k_\perp^2 v_{TD}^2}{\Omega_D^2}\right) \tag{1}$$

$$= \frac{9}{100}\Omega_T^4 - \left(\omega^2 - \Omega_{ii}^2 - \frac{\Omega_T^2}{4}N_\|^2 + \frac{27}{200}\Omega_T^2\frac{k_\perp^2 v_{TD}^2}{\Omega_D^2}\right)\frac{\omega_{pe}^2}{\omega_{pD}^2}\frac{\Omega_D^2}{\omega^2}\frac{k_\perp^2 v_{Te}^2}{\Omega_e^2} i\frac{\pi^{1/2}}{5}\zeta_{oe}e^{-\zeta_{oe}^2}$$

$c_A^2 = B_0^2/\mu_o(\rho_1 + \rho_2)$ is the Alfvén speed where $\rho_{1,2}$ are the mass densities of the two ion species. $N_\| = c_A k_\|/\omega, \zeta_{oe} = \omega/k_\| v_{Te}$ and Ω_{ii} is the ion hybrid frequency, all other symbols having their usual meanings. Equation (1) is valid for $N_\| \ll 1$. A solution for the ion hybrid wave which is far from the resonance condition with the Alfvén wave is obtained by assuming $k_\perp = k_{\perp o} + \delta k_\perp$ where $k_{\perp o}$ is a solution of Eq (1) with the electron term on the right-hand-side neglected. The required solution is

$$\delta k_\perp \simeq -\frac{i\pi^{1/2}}{15}\frac{1}{(N_{\perp o}^2 - 1)^2}\frac{n_{oe}}{n_{oD}}\frac{T_e}{T_D}k_{\perp o}\zeta_{oe}e^{-\zeta_{oe}^2} \tag{2}$$

where $N_{\perp o} \equiv c_A k_{\perp o}/\omega$. The negative sign of $\delta k_\perp$ is due to the backward wave nature of the ion hybrid wave.

In order to quantify the strength of the damping of the ion hybrid wave as it propagates away from the conversion region a ray tracing code has been used. For parameters relevant to a JET discharge this shows that the value of $k_{||}$ first downshifts to zero and then evolves to larger negative values until $| \zeta_{oe} | \sim 1$ when the wave damps completely, as shown in Fig 1.

MODE CONVERSION IN THE PRESENCE OF ION AND ELECTRON DAMPING

In order to give a realistic estimate for the power mode converted, the energy lost by the fast wave due to ion cyclotron and direct electron damping before it reaches the hybrid resonance must be calculated. This is done with the aid of a generalization of the second order fast wave equation which includes not only fundamental and second harmonic ion cylotron damping of both ion species but all electron dissipation effects.[5]

Integration results for a JET case are shown in Fig 2 for a $D(^3He)$ plasma in which the helium-3 is present at a 25% concentration and the electron density is taken as $4\times10^{19}\text{m}^{-3}$. The other parameters are given in the figure caption. The transmission, reflection and dissipation coefficients are shown as a function of $k_{||}$ for low field incidence. The curves illustrate the transition from a Budden to a triplet configuration which occurs at $k_{||} \simeq 5.5\text{m}^{-1}$. The dissipation coefficient is the sum of all loss mechanisms for the fast wave including mode conversion given by the integral over the hybrid resonance. By integrating $ImQ \mid E_y \mid^2$ just across the hybrid resonance, it is found that most of the fast wave loss is due to conversion.

CONCLUSIONS

The generalized fast wave equation has been used to show that up to eighty per cent of the fast wave power can be mode converted to the ion hybrid wave under existing conditions in JET and TFTR. However, for higher density plasmas, appropriate to the projected ITER conditions, with an electron temperature $T_e = 30$ keV, the fast wave is evidently damped directly by the electrons and ions before reaching the hybrid resonance and there is almost no mode converted power.

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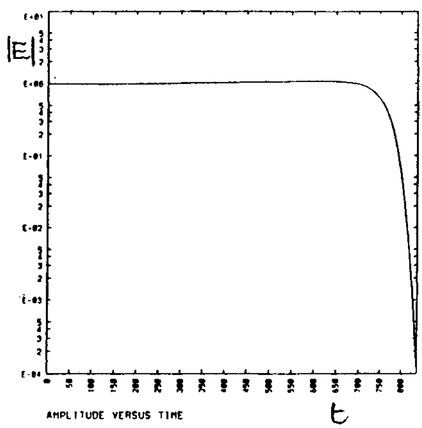

FIGURE 1 Ray tracing calculation of the change of the modulus of the total electric field $| E |$, of the ion hybrid wave, as a function of time along the ray path.

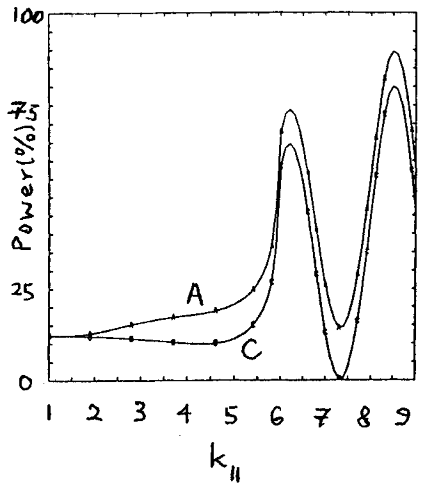

FIGURE 2 Total absorption (A) and mode conversion (C) fractions as a function of $k_{\|}(\mathrm{m}^{-1})$ for a $D(^3He)$ JET plasma $n_e = 4 \times 10^{19}\mathrm{m}^{-3}$, $B_o = 3.45$ T, $T_e = 8$ keV, $T_D = T_{^3He} = 5$ keV and a helium-3 concentration of 25%.