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Ion-Bernstein Wave Mode Conversion in Hot Tokamak Plasmas

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Abstract. Mode conversion at the second harmonic cyclotron resonance is studied in a toroidal plasma, showing how the ion-Bernstein wave can dramatically affect the power profile and partition among the species. The results obtained with the gyrokinetic toroidal PENN code in particular suggest that off-axis electron and second harmonic core ion heating should become important when the temperatures in JET reach 10 keV.

INTRODUCTION

Several waves often propagate in a plasma at a fixed frequency, but they usually do not interact because they have very different wavelengths. Where the spatial scale of two waves match, the power associated with one branch may however be transferred to the other in a process called linear mode conversion. It generally takes place in the vicinity of resonances where the spatial scale of the fast wave gets shorter or cut-offs where the scale of the slow wave gets longuer [1], but can also occur at a confluence [2] or be induced by toroidal coupling [3].

In this paper, mode conversion between the fast wave (FW) and the slow ion-Bernstein wave (IBW) is studied at the second harmonic cyclotron resonance, taking into account the specific geometry of the tokamak. It has previously been shown in ref.[4] that the power mode converted to Alfvén waves in a torus cannot simply be calculated with fluid plasma models using resonance absorption [5]; since IBW mode conversion takes place at a slow wave evanescence without a fluid resonance present at all, it is clear that the results will also be very different from toroidal fluid models.

MODEL

To model the wave propagation in a hot tokamak, the gyrokinetic toroidal PENN code [4] solves Maxwell's equations in real space using a bi-cubic finite elements representation of the electromagnetic potentials $(A_n, A_b, A_{||}, \phi)$ avoiding "numerical pollution". A Grad-Shafranov equilibrium [6] defines the plasma response using a second order Larmor radius expansion of the dielectric tensor [7]. The velocity integrals over the resonant denominators $(\omega - l\Omega - k_{||}v_{||})^{-1}$ are evaluated assuming an approximate functional dependence $k_{\|} = n/R$ instead of using the exact operator $k_{\|} = -iB^{-1} \vec{B} \cdot \nabla$, where ω stands for the frequency, $l\Omega$ a multiple of the cyclotron harmonic, n the toroidal mode number, R the major radius and $k_{\|}$ the wave-vector along the local magnetic field $\vec{B}$. The power absorption through electron Landau damping and transit-time magnetic pumping (TTMP) is evaluated in the drift-kinetic approximation with the formulas 50-51 of ref.[8], and completed with the first and second harmonic ion cyclotron absorption [9]:

$$P_c = \sqrt{\pi}\epsilon_0 \int d^3x \frac{\omega_p^2}{4|k_{\|}|v_{th}} \left(|E_+|^2 \exp\left[-\left(\frac{\omega - \Omega}{k_{\|} v_{th}} \right)^2 \right] + \rho_L^2 |\nabla_+ E_+|^2 \exp\left[-\left(\frac{\omega - 2\Omega}{k_{\|} v_{th}} \right)^2 \right] \right)$$

where $E_+ = E_n + iE_b$, $\nabla_+ = \nabla_n + i\nabla_b$, and ϵ_0 is the permittivity of free space, ω_p the plasma frequency, $\rho_L^2 = v_{th}^2/2\Omega^2$ the Larmor radius, v_{th} the thermal velocity. In this form, the code describes the propagation, damping and mode conversion of global fast and slow waves in a tokamak, with a power absorption occurring through resonant Landau, cyclotron and TTMP interactions.

RESULTS

An up-down symmetric deuterium plasma with a low hydrogen concentration is used with the parameters of fig.1. Driving an oscillating antenna current in the low magnetic field side (LFS) vacuum region of the torus, the frequency ω is adjusted so that the cyclotron resonances $\Omega_H = 2\Omega_D$ intersect the mid-plane near the magnetic axis (dashed line in fig.1a-c). Raising the bulk plasma temperature $T = T_e = T_D$ while keeping all other parameters fixed, global wavefields and power deposition profiles are computed with the gyrokinetic PENN [4] and the fluid LION [10] codes.

When the bulk temperature is as low as 200 eV, fig.1a shows that the FW emitted on the LFS is first focused to the magnetic axis, where it is damped by the hydrogen minority cyclotron interactions. Mode conversion is absent, the electron Landau, TTMP and second harmonic deuterium absorptions are all negligible, and both codes agree fairly well as can be seen from the integrated total power $P(s) = \int_{V(s')} P(s', \theta) dV(s', \theta)$ in fig.1d, where $s = \sqrt{\psi}$ refers to the normalized radius and θ to the poloidal angle.

Raising the bulk temperature to 2 keV results in a dramatic change of the wavefield structure: fig.1b shows how mode conversion occurs on the high magnetic field side of the resonance $2\Omega_D$ around $s = 0.25$, with a relatively short wavelength $k_\perp \rho_D < 0.2$ ion-Bernstein wave propagating outwards until it gets reflected at $s \simeq 0.8$. The FW field in the background (barely visible on the plot) remains almost unchanged, which is in agreement with the result obtained from the fluid LION code and explains why the total power profile from LION in fig.1e is only weakly affected by the temperature rise. The mode conversion taking place in the gyrokinetic wavefield however modifies that profile, with the hydrogen minority absorption getting localized around the mode conversion surface due to the IBW polarization $E_+/E \simeq 0.5$, which is more favourable for resonant interactions at $\omega = \Omega_H$ than the FW (first term in P_c). The IBW propagates away with a finite parallel electric field $E_{\|}/E \simeq 0.005$ and deposits a small fraction of the power directly on the electrons through Landau damping.

When the bulk temperature is increased to 10 keV in the core, IBW mode conversion becomes possible further outside: two distinct layers appear in fig.1c at $s \simeq 0.3, 0.6$ where the fast and the slow wave locally match with different poloidal mode numbers. The IBW propagates along the HFS of the resonance $2\Omega_D$, and due to relatively long poloidal evanescence length, extends also somewhat to the LFS of it. The gyrokinetic power profile in fig.1f is then totally different from the fluid prediction, with power absorption due mainly to electrons Landau damping of the IBW at the mode conversion layers, and around $s \simeq 0.3$ due to second harmonic cyclotron interaction with the majority deuterons (second term in P_c). The latter here dominates over the minority hydrogen absorption because of the low hydrogen concentration and the short wavelength $k_\perp \rho_D \simeq 0.5$ of the IBW, still just within the validity limits of the finite Larmor radius expansion [11].

In principle, it is possible to model the scenarios of fig.1 in slab geometry and compute the wavefield for an imposed poloidal mode number. The mode conversion is then homogeneous along the HFS of the resonance $2\Omega_D$, and the IBW propagates away from it horizontally. The toroidal calculations in fig.1 however show that the mode conversion is far from homogeneous and that the IBW needs not in general to propagate away from the resonance. When it is on the contrary approaching it, strong cyclotron interactions occur with the ions, resulting in a heating mechanism which is really a combination of gyrokinetic and toroidal effects.

CONCLUSION

Mode conversion between the fast and the IBW has been studied in a tokamak. The results show that the power deposition calculated for a warm plasma using fluid plasma models is misleading and that a gyrokinetic model is necessary to take the conversion into account. While it has only little effect for low temperatures, the mode conversion modifies dramatically the power profile and the partition among the species when the temperatures get as high as in the tokamaks nowadays. In particular, the PENN code predicts that strong off axis electron heating and second harmonic core ion heating should take place in 10 keV JET-like deuterium plasmas with a low hydrogen concentration.

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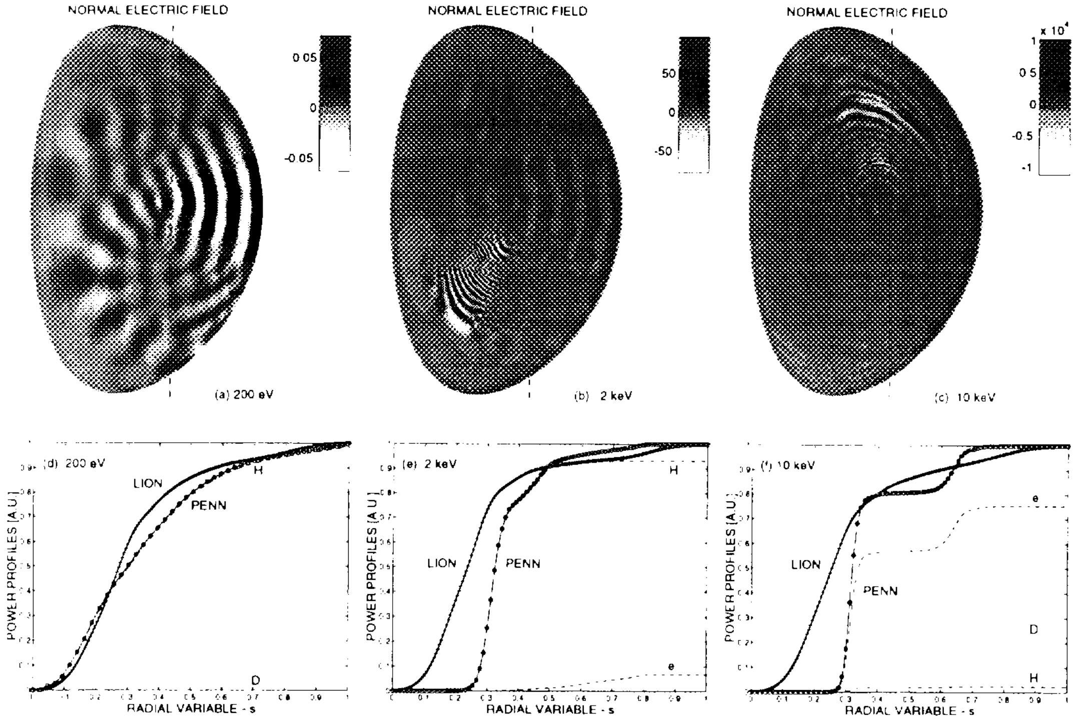

Figure 1: Normal electric field amplitude $\Re e(E_n)$ obtained with the gyrokinetic PENN code (a-c) for an increasing bulk temperature $T_e = T_D = T(1-0.9s^2)$; in (d-f) the corresponding total power absorption profiles (circles) are compared with the fluid LION code (crosses). The kinetic power fractions correspond to power absorbed by the electrons (dashes), minority H-ions (dash-dots) and majority deuterons (dots). The parameters are those of a JET discharge driven with an antenna at 33 MHz with $n_{tor} = 25$ and an equilibrium $B_T = 2.17$ T, $q_0 = 1.03$, $q_a = 2.4$, $n_D = 3(1-0.9s^2)^{0.55}10^{19}m^{-3}$, $n_H/n_D = 0.04$, $T_H = 10(1-0.9s^2)$ keV.

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