ION CYCLOTRON RESONANCE HEATING*

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Abstract

Ion cyclotron resonance heating of plasmas in tokamak and EBT configurations has been studied using 1-2/2 and 2-1/2 dimensional fully self-consistent electromagnetic particle codes. We have tested two major antenna configurations; we have also compared heating efficiencies for one and two ion species plasmas. We model a tokamak plasma with a uniform poloidal field and 1/R toroidal field on a particular q surface. Ion cyclotron waves are excited on the low field side by antennas parallel either to the poloidal direction or to the toroidal direction with different phase velocities. In 2D, minority ion heating ($v_\perp$) and electron heating ($v_\parallel, v_\perp$) are observed. The exponential electron heating seems due to the decay instability. The minority heating is consistent with mode conversion of fast Alfven waves and heating by electrostatic ion cyclotron modes. Minority heating is stronger with a poloidal antenna. The strong electron heating is accompanied by toroidal current generation. In 1D, no thermal instability was observed and only strong minority heating resulted. For an EBT plasma we model it by a multiple mirror. We have tested heating efficiency with various minority concentrations, temperatures, mirror ratios, and phase velocities. In this geometry we have beach or inverse beach heating associated with the mode conversion layer perpendicular to the toroidal field. No appreciable electron heating is observed. Heating of ions is linear in time. For both tokamak and EBT slight majority heating above the collisional rate is observed due to the second harmonic heating.

I.   Ion cyclotron heating of a tokamak plasma

Ion cyclotron resonance heating of a plasma is one of the most direct ways of heating ions among various electromagnetic wave heating techniques. Experimentally, in fact, it has been the most successful rf heating method to date [1]. An efficient method for heating tokamak plasmas calls for both good wave penetration into a large bulk plasma and good wave absorption by the plasma, preferably, by plasma ions. A fast Alfven wave heating

of a plasma with a lighter minority species utilizing the ion cyclotron resonance for this species is discussed in [2] and [3] satisfies such criteria. In a tokamak plasma the antenna-launched fast Alfven wave is converted at the conversion layer into the electrostatic ion cyclotron wave and another fast Alfven wave. The electrostatic wave will eventually heat ions and absorb energy from the incoming electromagnetic wave.

In order to see the most efficient ion cyclotron resonance coupling/heating, we have conducted a series of computer simulations on runs of fully self-consistent 2-1/2 dimensional electromagnetic particle code. We model the problem by taking a portion of a particular q surface (q ~ 1-2) in the neighborhood of $\omega = \Omega_H$ (hydrogen cyclotron frequency) out of entire tokamak. The portion of the magnetic surface is mapped onto a cartesian x-y plane with the x-direction corresponding to the θ (poloidal) direction and the y-direction to the ϕ (toroidal) direction. The toroidal magnetic field (y direction) varies as $1/(x+x_0)$ and the poloidal field (x direction) is uniform. The electromagnetic field boundary conditions are handled by the Budden turning point technique for complete absorption [4] in the positive and negative x direction and periodic in the y direction. The external antenna current is given on the $x=x_a$ (x_a: antenna position) line, where the current may point to either y or z direction with specified wavenumber k_y and frequency ω. The particles are re-entrying from the other side upon exit. Calculations are carried out on the 2-1/2 D$(x,y,v_x,v_y,v_z,E_x,E_y,E_z,B_x,B_y,B_z)$ electromagnetic code with typically 128 X 128 grid and 8 X 128 X 128 particles.

We have tried cases of a single or double (proton-deuterium) species plasma with an antenna current running along the toroidal (y) or poloidal (z) direction. Our antenna creates the wave magnetic fields δB of the same order of magnitude as the poloidal magnetic fields. A toroidal antenna (parallel to the toroidal direction) has only weak coupling to and weak heating of the plasma for a one-species case. The toroidal antenna primarily launches the slow Alfven waves. A poloidal antenna has penetration into a plasma but not heating for a single species plasma. The poloidal antenna launches both the slow and fast Alfven waves.

For a two-species plasma (proton-deuterium) at $\omega = 2\Omega_D$ (where Ω_D is the deuterium cyclotron frequency) resonance with a toroidal antenna, we see good fast wave penetration and minority protons ($v_\perp$ velocities perpendicular to the toroidal field) and electrons (in $v_\parallel$ parallel velocity and $v_\perp$) heating. In the present case the proton population is 1/9 of the deuterium population. The quantity

$\beta_D/3\epsilon^2\eta_p$ defined in [3] is less than unity (roughly 0.4). The antenna structure is such that it creates a standing wave (no Poynting vector) in the toroidal direction in the present setup. The parallel phase velocity $\omega/k_{||}$ is roughly several times the electron thermal velocity initially. When the launched fast wave structure reaches the singular layer ($\omega \sim 2\Omega_D$) from the antenna, it seems that mode character undergoes some change (see Fig. 1): The wavenumber $k_\perp$ seems slightly different for $\omega < 2\Omega_D$. Since the wave is launched from $x=x_a$ and the antenna is roughly parallel to the toroidal field with a given wavenumber for antenna current, the mode conversion process would be best understood with fixed $k_{||}$, or $N_{||}^2=(k_{||}c/\omega)^2$: the dispersion relation is given in terms of $N_\perp^2$ vs. $\omega/\Omega_H(x)$ as in [2] and [3]. It is, however, noticed that because the magnetic field has shear, the excited wave cannot be said to have a completely fixed parallel wavenumber [5]. Detailed mode structure is under investigations.

While the above is occurring, the perpendicular minority ion temperature rises (Fig. 2). At the same time the electrons are heated in both parallel and perpendicular directions.

With the toroidal antenna in a two-species plasma we have observed more current generation and electron heating and a little less ion heating than with the poloidal antenna in a two-species plasma discussed in the above.

As the electron temperature rises, the parallel mode number reduces (or the parallel wavelength increases) perhaps due to the electron Landau damping (See Fig. 1). By now the parallel phase velocity of the launched wave is in the bulk distribution of electrons. This is accompanied by generation of a toroidally directed current, which amounts to a percent of the antenna current. This current generation seems due to the deviation from 90° of the angle between the electromagnetic Poynting vector leaving the antenna (in the x direction) and the total magnetic field line (tilted from the y direction). The majority temperature rise in the perpendicular direction seems due to the second harmonic (deuterium) cyclotron resonance heating. The collisional heating with the hot hydroden ions would be slower than the observed heating rate (Fig. 2). The late stage electron temperature surge is accompanied by the exponential growth of electromagnetic energy. The growth rate of this thermal instability is $\gamma \sim 1/4\Omega_D$.

In order to understand the origin of this instability, we have reduced the dimensionality from 2-1/2 to 1-2/2. The spatial

variation is in the x-direction only and the toroidal field pointing in the y-direction varies in x. The poloidal field is in the x-direction. The antenna current can be in either y or z direction. The heating results are very similar. The major difference now is that we do not observe the thermal instability nor strong electron heating. This observation (or lack of it) prompts us to suspect that the instability observed in two dimension may be a type of decay instability from the fast Alfven wave into a fast Alfven wave and an electron compton mode. The unstable mode is purely perpendicular to the toroidal direction. Some of the results in this section were also reported in [6].

II. Ion cyclotron heating of an EBT plasma

The basic mechanism of heating ions in mirror geometry is the same as in tokamak geometry. The major differences is that the inhomogeneity along the external static magnetic field contributes an essential role to mode conversion for the Elmo bumpy torus (EBT) configuration, while the inhomogeneity across the external static magnetic field or the toroidal field plays an important role for the tokamak configuration. Because of this geometrical difference for EBT it is advantageous to write the dispersion relation in terms of $N_{\parallel}^2$ as a function of ω/Ω_D with fixed $N_{\perp}^2$. The left-circularly polarized component of the wave has a resonance at $\omega = \Omega_H$ in the cold theory (see Fig. 3).

Wave injection from large ω/Ω_H (weak-side injection) constitutes an inverse beach heating: a portion of wave is reflected near the cut-off back to the weak-side, a portion is transmitted toward the strong-side, and the rest is converted near the resonance and contributes to absorption of wave energy by plasma. Wave injection from small ω/Ω_H (strong-side injection) constitutes a beach heating: a portion of wave is reflected near the conversion layer, a portion directly goes into the slow wave and eventually thermal mode, the rest is transmitted beyond the cut-off point. The wave coupling on the plasma surface is determined by the surface impedance

$$Z_s = \frac{1}{N_{\perp}} = \left[\frac{\frac{1}{2}(\varepsilon_r + \varepsilon_\ell) - N_{\parallel}^2}{(\varepsilon_r - N_{\parallel}^2)(\varepsilon_\ell - N_{\parallel}^2)} \right]^{\frac{1}{2}} , \tag{1}$$

where $\varepsilon_r = 1 + \sum_\sigma \dfrac{\omega_{p\sigma}^2}{\Omega_\sigma(\Omega_\sigma + \omega)}$ and $\varepsilon_\ell = 1 + \sum_\sigma \dfrac{\omega_{p\sigma}^2}{\Omega_\sigma(\Omega_\sigma - \omega)}$.

The fraction of reflection is given by $|R|^2 = |(Z_s-1)/(Z_s+1)|^2$ and $Z_s \sim 1$ means a good coupling.

Electromagnetic, fully self-consistent particle simulation of EBT-ICRH has been carried out. In order to accomodate relevant wavelengths in a manageable memory, we take a quarter of a multiple mirror plasma (mirror ratio ~ 1.4) with an appropriate symmetry dependent on the parity of the EM fields in a two-and-one-half dimension code; we use a particle boundary condition that minimizes unwanted diamagnetic effects. In a two-species case (deuterium-proton), an external current perpendicular to the static magnetic field excites fast Alfven waves and, at the ion-ion hybrid resonance, they are partially converted to thermal modes which will eventually damp near the proton cyclotron resonance. Results of our simulation for a 10% proton concentration show that: (1) the fast waves mainly propagate from the strong mirror field side of the hybrid layer. (2) the perpendicular temperature of the minority most rapidly increases linearly in time. (3) the majority perpendicular temperature as well as the minority parallel one also increase (see Fig. 4). The former seems due to the second harmonic heating, since $(k_\perp \rho_i) \sim 0.1$ and the observed heating is proportional to the ion temperature. (4) no appreciable electron heating is observed. For an increased deuterium concentration and/or mirror ratio, the heating rate decreases accordingly, because the narrower hybrid layer permits easier tunnelling for the fast waves. Some of the results in Sec. II was also reported in [7].

Acknowledgments

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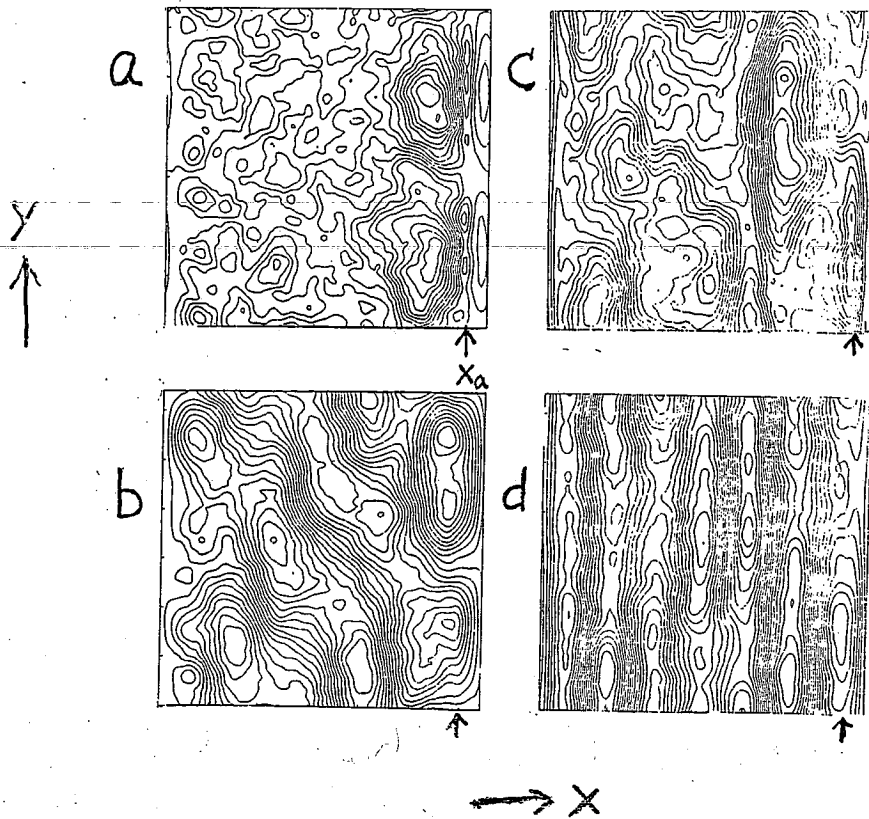7. FUKUYAMA, A. and TAJIMA, T., 1981 Sherwood Meeting paper 2B47 (1981).

Fig. 1   Equicontours of the vector potential A_z in a part of tokamak plasma. The wave is launched from the antenna at x=118Δ. The system size is x $\times$ y = 128Δ $\times$ 128Δ and Δ being the grid spacing. The toroidal direction is the y direction, the poloidal the x. (a) t = 25 ω_p^{-1}, (b) t = 100 ω_p^{-1}, (c) t = 275 ω_p^{-1}, (d) t = 300 ω_p^{-1}.
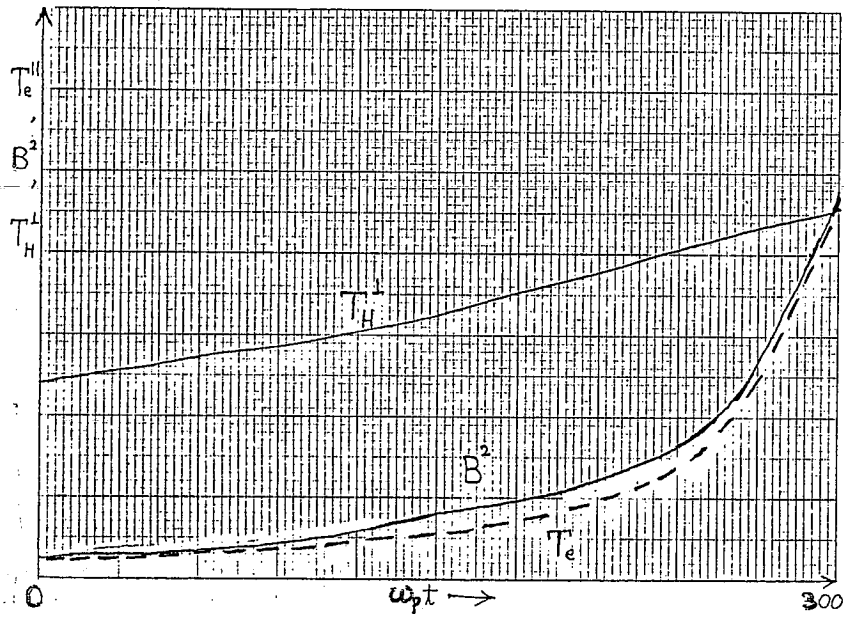
Fig. 2   Heating of minority $H^+(T_H^\perp)$, and electron in time along with the wave energy B^2 in the tokamak plasma.
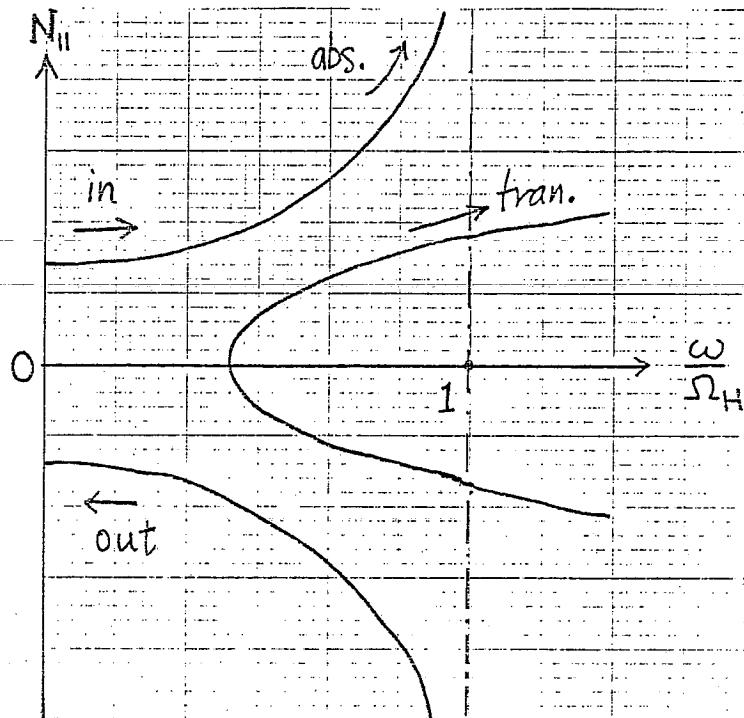
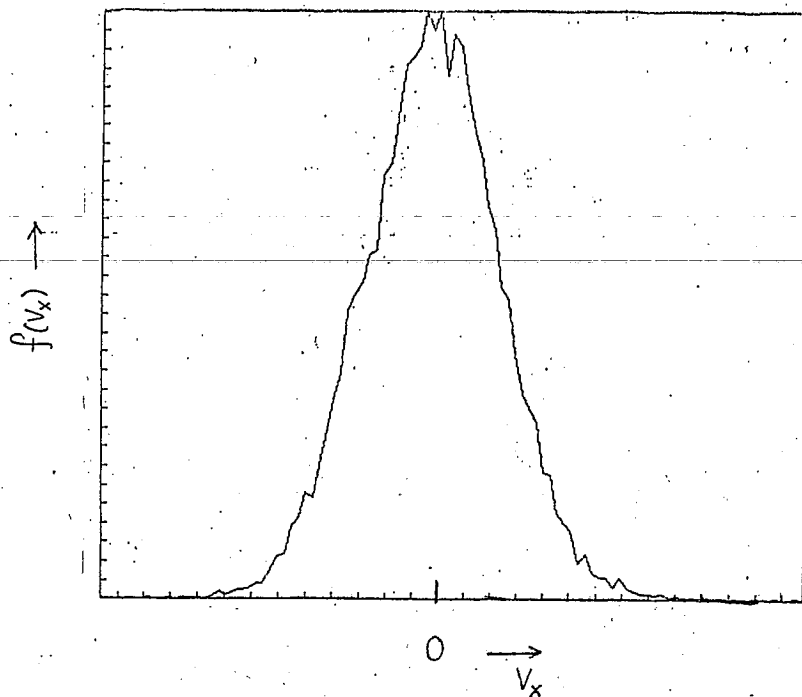Fig. 3   Dispersion relation for fixed $N_\perp^2$ in a cold plasma.

Fig. 4   Perpendicular velocity distribution for majority ions
for an EBT plasma at $t = 300\ \omega_p^{-1}$.