

RESONANT PARTICLES IN ELECTRON CYCLOTRON HEATING OF PLASMA

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A number of investigations of electron cyclotron plasma heating [1-4] have revealed the presence of a group of high-energy electrons (several times 10 keV), exceeding by many orders of magnitude the average energy of the plasma electrons. The cyclotron heating mechanism was analyzed in a number of theoretical papers [5 - 7], but the origin of the hot electrons received no clear physical explanation. We believe the cause to be resonant particles, whose Doppler-shifted frequency coincides with the cyclotron frequency

$$\omega - \omega_c = k_z V_z. \quad (1)$$

We shall show that this assumption leads directly to a correct estimate of the energy of the hot electrons. To this end, we use the dispersion equation for the electron cyclotron waves; this equation can be written with sufficient accuracy for our purposes in the cold-plasma approximation

$$\frac{k^2 c^2}{\omega^2} = \frac{\omega_0^2}{\omega(\omega_c - \omega)} + 1. \quad (2)$$

Near the cyclotron frequency, we can neglect the displacement current, put $\omega = \omega_c$, and write (2) in the form

$$k^2 \approx \frac{\omega_0^2 \omega_c}{c^2 k_z |V_z|}. \quad (3)$$

The wave packet under consideration should, of course, have a sufficient width with respect to k , as is assumed in the quasilinear theory. In the waveguide heating method [8], the wave propagates along the magnetic field, i.e., $k = k_z$; we then get from (3)

$$k \approx \left(\frac{\omega_0^2 \omega_c}{c^2 |V_z|} \right)^{1/3} \quad (4)$$

If the static magnetic field is inhomogeneous (for example, in magnetic-mirror traps), but the length L of the variation of the magnetic field is large enough, then the quasiclassical approximation is valid provided

$$L^2 > \frac{c^2}{4 \omega_0^2} \left(\frac{c \omega_c}{\omega_0 |V_z|} \right)^{2/3}.$$

The electron acquires a transverse velocity component under the influence of both electric and magnetic forces, and a longitudinal component only under the influence of magnetic forces. An estimate of their ratio, based on Maxwell's equation, yields

$$\Delta V_{\parallel} \sim \frac{k V_{\perp}}{\omega} \Delta V_{\perp}.$$

Thus, the contribution of the wave fields to the longitudinal velocity increases with increasing transverse velocity. Let us assume, as was done in [9], that when ΔV_{\parallel} exceeds ΔV_{\perp} there

begins an intensified diffusion of the particle longitudinal velocities, leading to escape from the trap. From this we can estimate the attained value of the transverse velocity at

$$V_{\perp} \sim \frac{\omega}{k} \sim \frac{\omega_c}{k} \quad (5)$$

or, substituting (4),

$$V_{\perp} \sim \left(\frac{\omega_c}{\omega_0} \right)^{2/3} (c^2 |V_z|)^{1/3}. \quad (6)$$

Here $|V_z|$ is determined by the thermal velocity of the bulk of the electrons. From this we get the following estimate for the transverse energy of the hot electrons:

$$E_{\perp}^* / mc^2 \sim \left(\frac{\omega_c}{\omega_0} \right)^{2/3} (\bar{E} / mc^2)^{1/3}, \quad (7)$$

where \bar{E} is the average thermal energy of the electrons.

This explains the main qualitative features of the heating: we see that the energies of the hot electrons should be in the kilovolt range, but the mechanism considered here can never lead to relativistic energies. At an average energy of several hundred electron volts, the proposed estimate leads to a transverse energy $E_{\perp}^* \sim 50$ keV for the hot electrons, which is sufficiently close to the results of the measurement of the plasma x-radiation [3, 4] in the case of cyclotron heating.

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PHONON DRAGGING BY SOUND IN HYDRODYNAMIC FLOW OF A PHONON GAS

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At high frequencies Ω , when $\Omega\tau_p \gg 1$ (τ_p is the relaxation time of the thermal phonons), the absorption of sound in a dielectric can be regarded as the scattering of acoustic phonons of energy $\hbar\Omega$ by thermal phonons [1]. In normal collisions, this process is accompanied by transfer of not only energy but also quasimomentum to the gas of thermal phonons. Usually the transfer of quasimomentum does not lead to any particular phenomena, since the quasimomentum transferred in the elementary collision acts attenuates rapidly as a result of V-processes (by V-process is meant here any type of collision with momentum loss). However, when the V-processes are much less intense than the N-processes, the transfer of quasimomentum from the attenuating sound to the thermal phonons should cause drift of the phonon gas and consequently