Observation of induced *ls* scattering near the lower hybrid resonance

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Heating of electrons in a magnetoactive plasma, in which thermodynamically nonequilibrium ion-sound noise is excited, is investigated. It is shown that the final state of the turbulent oscillations of the plasma, its thermal conductivity, and the electron heating are determined by induced scattering of oblique plasma waves by electrons.

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In this paper, we present experimental data on observation of induced scattering of oblique plasma waves by electrons accompanied by their conversion into ion-sound waves as well as the results of a theoretical analysis of the conditions for excitation of *ls* scattering in a magnetoactive plasma near the lower hybrid resonance in closed magnetic traps.

The experiment was carried out using the setup described in Ref. 1. The plasma column was created by a discharge from the hot cathode in argon at pressures of (3-6) $\times 10^{-4}$ Torr. The cathode potential was 60-120 V, the magnetic field intensity was 0.08 T, the plasma concentration was $(1\text{-}2)\times 10^{-10}\text{cm}^{-3}$, and the initial electron temperature was $T_e = 3\text{–}6$ eV. An oblique plasma wave with frequency $\omega_0/2\pi = 24$ MHz was excited as the pumping wave. The electron heating was determined from the change in temperature of the bulk of the distribution function, recorded by electrical differentiation of the characteristic of a planar probe. Data on the wave numbers were obtained from measurements of spatial correlation with a narrow-band signal at a given frequency separated out of the turbulent noise spectrum.

The distribution function of the thermal electrons before the pump is switched on is asymmetrical, which indicates the existence of a longitudinal current with a drift at a velocity $v_0 \sim 0.1\ v_{T_e}$. The drift of electrons is responsible for excitation of ion-sound turbulence. At energies exceeding 5 T_e, a wide plateau is recorded in the distribution function, which, as measurements have shown, is related to the kinetic instability of the electron beam, arising in the region of the cathodic voltage drop. This instability excites a

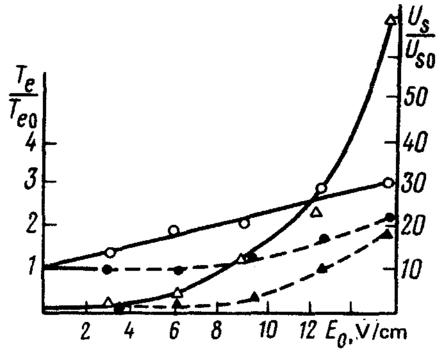

FIG. 1. The relative change in temperature and intensity of ion-sound oscillations as a function of E_0 for different initial states of the plasma. I (continuous curves), T_{e0} = 4.2 eV; II (dashed curves), T_{e0} = 6.5 eV; U_{s0}(II)/U_{s0}(I) = 6.

broad spectrum of plasma waves with frequencies in the range 0.1-1 GHz. The energy density of plasma noise, determined from energy lost by the electron beam, scaled to nT_e, is governed by the beam parameters, and varies within the range $W_l/nT_e = 0.1$-0.02.

Superposition of an rf field increases the electron temperature and the ion-sound noise intensity (Fig. 1), while the intensity of plasma noise, excited by the electron beam, remains unchanged. An increase in the drift velocity increases the initial sound noise level and the initial electron temperature and, in addition, as the rf field of the pumping wave is increased, the relative increase in both the sound noise level and the electron temperature decreases.

The spatial correlation in the longitudinal coordinate was determined from a series of measurements of the radial correlation functions for different distances between probes along the z axis. Figure 2 shows the results of such measurements for ion-sound oscillations at a frequency of 1 MHz for two values of the rf field. Spectra over the component wave vectors were obtained from the spatial correlation functions by a Fourier transformation. Figure 3 shows two spectra of ion-sound oscillations over the z com-

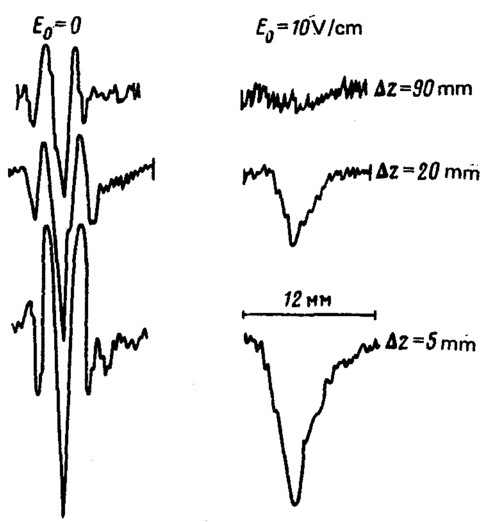

FIG. 2. Radial correlograms for different distances between probes along the magnetic field.

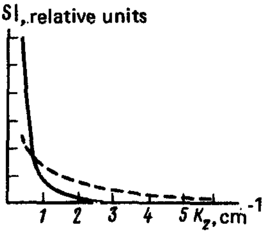

FIG. 3. Normalized spectra over component wave vectors along the magnetic field for rf oscillations at a frequency of 1 MHz; ——$E_0 = 0$; – – –$E_0 = 10$ V/cm.

ponent for two values of the rf field. It can be seen from the spectra presented (Fig. 3) that in an rf field the relative intensity of short-wavelength sound oscillations increases considerably. At the same time, the radial component of the wave vectors decreases, so that for $E_0 \sim 10$ V/cm, $k_s \sim k_z$. Measurements of the wave numbers of the three participating in the interaction (ion-sound wave and 2 rf pumping waves, and the "red" satellite) showed that the matching conditions are not satisfied. The wave vector components of the rf oscillations along the z axis turn out to be small, 0.1 cm^{-1}, while for the ion-sound waves $k_{sz} \sim 2$ cm^{-1}, if rf pumping is increased.

We now turn to the results of a theoretical analysis of the conditions for the occurrence of *ls* scattering and to a discussion of the experimental data presented above.

As calculations carried out in Ref. 2 for an isotropic plasma show, the probability of this process increases considerably under conditions when the electron distribution function is anisotropic. In contrast to an unmagnetized plasma, long-wavelength sound waves with wave vectors $k_s < r_{de}^{-1}$ ($r_{de} = v_{te}/\omega_{pe}$, v_{te} is the thermal velocity of electrons, ω_{pe} is the plasma frequency of electrons) also participate in scattering processes near the lower hybrid resonance. Indeed, for thermal electrons, which we will assume to be magnetized, the matching condition has the form

$$|(\omega_0 \pm \omega_s)| \,/\, |(k_{0z} \pm k_{sz})| \simeq v_z = v_{te}\,, \tag{1}$$

where ω_0, k_{0z}, ω_s, and k_{sz} are the frequency and longitudinal wave vector of the rf and sound waves, and v_z is the phase velocity of waves along the magnetic field. For the case of lower hybrid and oblique plasma waves, $\omega_0 \ll \omega_{pe}$, while $\omega_s \ll \omega_0$. Assuming that $k_{sz} \gg k_{0z}$, we have $k_{sz} \simeq \omega_0/v_{te} \ll r_{de}^{-1}$. As a result, the coefficient of quasilinear diffusion increases and, therefore, the heating efficiency increases as well.

The coefficient of quasilinear diffusion, related to induced *ls* scattering, and the nonlinear increments can be found for a nearly Maxwellian distribution function with a directed electron velocity v_0, if it is assumed that

$$k_{0z} \ll k_{sz}\,, \quad \left(\frac{m}{M}\right)^{1/2} \frac{k_s}{k_{sz}} \ll \frac{v_0}{v_{te}} \text{ and } \left(\frac{k_{0z}}{k_{sz}}\right)^2 (k_0 r_{de})^{-1} \ll v_0\,. \tag{2}$$

Then, the expression for the heating rate and the rate at which electrons lose momentum can be represented in the form

$$\frac{d}{dt}(\ln n T_e) = \nu_E \approx \frac{1}{2}\omega_{pe} U_s U_e (2); \qquad \frac{d}{dt}(\ln \mathrm{v}_0) = \nu_p \approx \frac{1}{6}\frac{\omega_{pe}^3}{\omega_0^2} U_s U_e . \tag{3}$$

Here, n and T_e are the density and temperature of electrons; U_e and $U_s = (\delta n/n)^2$ are, respectively, the energy density of plasma and sound waves, scaled to nT_e, δn is the mean-square value of density fluctuations in the sound noise. The approximate expressions (2) and (3) were obtained under the condition that $\Omega_e \approx \omega_{pe}$, where Ω_e is the electron gyrofrequency.

The occurrence of *ls* scattering under the conditions of the experiment is confirmed primarily by the results of measurements of the wave vectors of excited waves. If, in the initial plasma, most of the energy is taken up by waves with $k_{sz} < 1$ cm^{-1}, then under the action of rf pumping, the values of k_{sz} increase, which satisfies the condition for *ls* scattering, $k_{sz} > \omega_e/\mathrm{v}_{te} \approx 1$ cm^{-1}. The role of the process being examined is confirmed by the relation between the change in T_e and the intensity of ion-sound oscillations (Fig. 1).

The magnitude and characteristics of the electron heating can be estimated with the help of expressions (2) and (3), if the fact that heat losses from the plasma column are determined by the electronic thermal conductivity along the magnetic field is taken into account. Keeping in mind the fact that under the conditions of the experiment, we have $W_e/nT_e > W_0/nT_e = E_0^2/4\pi nT_e$, $\mathrm{v}_E < \mathrm{v}_{en}$, and $\mathrm{v}_p \gg \mathrm{v}_E$, where $W_0 = E_0^2/4\pi$ is the energy density of the pumping wave, and ν_{en} is the electron-neutral collision frequency; the heat balance equation can be written as follows:

$$\frac{W_e}{nT_e}\nu_{en} = \frac{\mathrm{v}_{te}^2}{\Lambda_{\|}[\nu_{en} + \nu_p]}, \tag{4}$$

where $\Lambda_{\|}$ is the characteristic size of the longitudinal temperature inhomogeneity. The magnitude and dependence of the electron heating on the pumping field, characteristic of the experiment (see Fig. 3), agree with expression (4).

In summary, the results of the investigations presented above indicate, in our opinion, the observation of induced *ls* scattering and the appreciable role that this process can play in nonlinear heating of electrons near the hybrid frequency.

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