TRANSFORMATION OF ELECTRON BEAM DISTRIBUTION FUNCTION FOLLOWING CYCLOTRON INTERACTION WITH A PLASMA

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Submitted April 20, 1970

Zh. Eksp. Teor. Fiz. 59, 657–660 (September, 1970)

The longitudinal and transverse energy distributions of an electron in a beam, following its interaction with a magnetoactive plasma waveguide, are investigated. It is shown that the energy of transverse motion of the electrons increases appreciably when the beam excites waves in a frequency range $\omega_c < \omega < \sqrt{\omega_p^2 + \omega_c^2}$. This confirms experimentally the effect of conversion of the electron longitudinal energy into transverse energy, as a result of beam-plasma interaction due to the anomalous Dopper effect.

IT is known [1] that instabilities due to the normal and anomalous Doppler effects can appear when an electron beam interacts with a magnetoactive plasma, in addition to Cerenkov excitation of longitudinal plasma waves. In particular, these instabilities can play an important role upon excitation of oscillations in the frequency range $\omega_c < \omega < \sqrt{\omega_p^2 + \omega_c^2}$, corresponding to the reciprocal-wavelength region of the plasma waveguide (ω_c and ω_p are respectively the cyclotron and plasma frequencies); these oscillations were observed in a number of works.[2,3] It is difficult to separate experimentally the Doppler and Cerenkov effects in the interaction between an electron beam and a plasma, for in most cases the frequency bands of the excited oscillations overlap for the different effects.

Theoretical investigations of the cyclotron interaction point to an interesting peculiarity of the anomalous Doppler in fact, namely a transverse buildup of the radiators as a result of the radiation reaction.[4,5] In other words, the freely moving particles can be converted into oscillators that emit simultaneously electromagnetic waves at the expense of the energy of the longitudinal particle motion.[6] The same conclusion results also from the quasilinear theory of collective interaction of a beam with a plasma in the anomalous Doppler effect.

Thus, sufficiently convincing proof of the existence of two-stream instability due to the anomalous Doppler effect may be the increase of the transverse beam-electron energy following the beam-plasma interaction. The purpose of the present study was to investigate experimentally the distributions of the longitudinal and transverse energies in an electron beam following development of two-stream instability in a plasma.

The experiments were performed in a setup (Fig. 1) similar to that described earlier in [8]. The plasma was produced in a discharge tube (2 cm dia) by an electron beam of energy 1.5–2 keV and current 60–100 mA. Unlike the earlier experiments, provision was made for varying the magnetic field H_c at the cathode while keeping the field H_0 constant (2 kOe). The radiation was registered with a horn antenna and a movable probe. The beam electron longitudinal-velocity distribution function and an estimate of the transverse energy

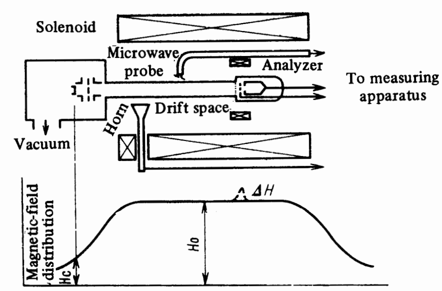

FIG. 1. Experimental setup.

of beam electrons having a longitudinal velocity in the interval from $v_\parallel$ to $v_\parallel + dv_\parallel$ were obtained with an electrostatic analyzer having an additional coil to produce a magnetic mirror with a center in the plane of the grid with a retarding potential U_r. It is easy to show[9] that it is possible to obtain the average energy of the transverse motion of electrons moving with longitudinal velocity $v_\parallel$ from the family of the delay curves plotted at different $h = \Delta H/H_0$:

$$\overline{W}_\perp(v_\parallel) = \frac{\int W_\perp f(v_\parallel, v_\perp)\,dv_\perp}{\int f(v_\parallel, v_\perp)\,dv_\perp} = \frac{\partial I}{\partial h} \Big/ \frac{\partial I}{\partial U_r}\Big|_{h\to 0}$$

where I is the delay current.

Thus, the average transverse energy was obtained in the form $W_\perp = \Delta U_r/h$, where ΔU_r is the voltage needed to compensate for the current change due to the introducing a magnetic-field inhomogeneity of relative magnitude h. The delay curves in a homogeneous magnetic field and in the field with the mirror were plotted with an automatic x-y recorder.

In a good vacuum ($p = 10^{-6}$ mm Hg) the beam-electron distribution function and the average transverse electron energy are shown in Fig. 2 (rear plane). We see that most electrons of the injected beam have an average transverse energy not exceeding 60 eV, and only a negligible fraction of the electrons have an energy reaching 300 eV. It is obvious that the transverse twisting of the beam electrons occurring as the electrons drifted in the region of the inhomogeneous magnetic field and as a result of collisions with the atoms of the residual gas (helium). Integration over the curves

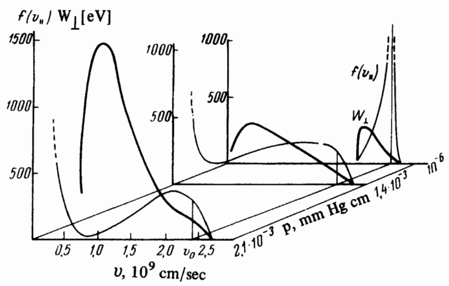

FIG. 2. Longitudinal-velocity distribution function $f(v_\parallel)$ (thin curves) and average transverse beam-electron energy $W_\perp$ (thick curves); v_0 is the average velocity of the unperturbed beam.

(Fig. 2) under these conditions yields the following energy distribution in the unperturbed beam: $E_\parallel \approx 93\%$, $E_\perp \approx 7\%$ of the total energy E_0, where $E_\parallel$ is the energy of the electron drift motion and $E_\perp$ is the energy of rotational motion of the electrons per unit volume,

$$E_\parallel = \sum_{i=1}^{n} \frac{1}{2} m v_{i\parallel}^2, \quad E_\perp = \sum \frac{1}{2} m v_{i\perp}^2.$$

When the residual-gas pressure is increased, two-stream instability develops on the forward longitudinal waves $\omega < \omega_p$, and the characteristics of this regime do not differ qualitatively from those described earlier.[8] This stage terminates with a plateau on the longitudinal-velocity distribution function; the energy of transverse motion of the electrons also increases somewhat and reaches 450 eV for the "slowest" beam electrons (Fig. 2, middle plane). The energies of the longitudinal and transverse motions are distributed as follows: $E_\parallel \approx 55\%$ and $E_\perp \approx 17\%$ of the unperturbed beam energy. Thus, 28% of the beam energy went to excitation of the HF oscillations and to plasma heating.

With further increase of pressure from 2.1×10^{-3} mm Hg upward, a jumplike transition to the backward-wave region is observed, as is evidenced by both the change of the longitudinal electric field distribution into the distribution typical of the backward-wave excitation regime in the system, and by the frequency spectrum of the radiation in the interval from ω_c to $\sqrt{\omega_p^2 + \omega_c^2}$. In this regime one observes predominant polarization of the plasma radiation in a plane perpendicular to the magnetic-field direction. It is difficult to attribute such a polarization to the Cerenkov interaction, which should lead to the appearance of waves having a large longitudinal component of the electric field. On going over into this regime, the electron distribution function contracts in velocity space and assumes the form shown in Fig. 2 (front plane), and the distribution of the electron transverse energy is radically altered. Electrons with high transverse energies appear (up to 1500 eV), whereas the energy of most electrons reaches 500 eV. In this regime, the longitudinal and transverse energies have the following distribution: $E_\parallel \approx 66\%$ and $E_\perp \approx 26\%$ of the unperturbed-beam energy. Thus, 8% of the beam energy went into excitation of the HF oscillations and plasma heating.

The amplitude of the HF oscillations in this regime depends strongly on the value of the field at the cathode H_c. When H_0/H_c changes from 1.3 to 3.25 and the remaining discharge parameters are kept constant, the radiation intensity increases by two orders of magnitude. Since the main parameters of the beam are kept constant in this case, the only beam characteristic dependent on H_0/H_c is obviously the initial energy of the transverse motion of the electrons, which increases with increasing H_0/H_c. It should be noted that the strong dependence of the oscillation amplitude on the transverse component of the injected-beam velocity under approximately the same experimental conditions was observed also by Kornilov et al.[3]

The most probable explanation of these effects is the predominant role of the cyclotron interaction mechanism. Shevchenko[10] has shown that the transverse oscillations of the electrons lower the efficacy of interaction between the beam and the longitudinal waves in the plasma. At the same time, the existence of an average transverse beam velocity makes possible a cyclotron interaction between the beam and the plasma.[10, 11] The efficacy of the latter interaction increases with increasing ratio of the transverse and longitudinal beam energies.

Thus, the present research offers experimental proof that the transformation of longitudinal energy into transverse energy, predicted in 1947 by Ginzburg and Frank,[5] and the increase of the transverse energy of an oscillator as it moves through the medium with superluminal velocity, both due to the Doppler effect, do take place also in the case of collective interaction between an electron beam and a plasma.

The authors thank Ya. B. Faĭnberg for valuable advice during the performance of this work.

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Translated by J. G. Adashko
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