Electron distribution function under strong, lower-hybrid turbulence conditions

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A nonmonotonic spike structure has been detected on the time-averaged electron distribution function in the strong, lower-hybrid turbulence regime.

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The appearance of individual peaks observed elsewhere[1,2] in the steady-state, plasma-electron distribution function has been explained by the interaction of particles with the spatial harmonics of plasma waves, and the location of the peaks corresponded to wave phase velocities $v_{phn} = \omega_{pe}/nk_z$, where ω_{pe} is the electron plasma frequency, k_z is the wave number of the fundamental harmonic, and n is the harmonic number; the number n in Ref. 1 was in the vicinity of $n = 23$, whereas this number varied from 4 to 10 in Ref. 2.

In this letter we report the discovery of a nonmonotonic form of the steady-state electron distribution function in the strong, lower-hybrid turbulence regime. The spikes, however, cannot be explained on the basis of the concepts used in Refs. 1 and 2.

The experiments were performed in a helium plasma with a density $n \approx (1\text{–}3) \times 10^9$ cm^{-3} and electron temperature $T_e \approx 4$–15 eV, which was produced in a dielectric tube with a length of 1.8 m and a diameter of 9 cm by using a periodic set of rings that excited the oscillations with $k_z = 2\pi/\lambda_z = 0.63$ cm^{-1}. The helium pressure was $p = (1.7\text{–}5) \times 10^{-3}$ mm Hg and the homogeneous magnetic-field intensity was $H = 1660$ Oe. The pump frequency $\omega_0/2\pi = 5.8$ MHz was in the lower-hybrid resonance band and was close to the ion plasma frequency $\omega_0 > \omega_{pi}$. The steady-state longitudinal electron-velocity distribution function $gf(v_z)$ was determined from the retarding-potential curves, which were measured by means of a multigrid electrostatic analyzer located at the center of the apparatus and which were traced on an x-y recorder.

The pump field excited in the plasma a modulation instability of the lower hybrid oscillations with rather unusual properties

$$\omega_o / k_z < v_{T_e} < \omega_b / k_z , \quad x_E \gtrsim \lambda_z .$$

Here $\omega_b = \sqrt{eE_z k_z/m}$ is the maximum frequency of the electron oscillations near the bottom of the potential well of the wave, E_z is the amplitude of the longitudinal component of the rf electric field in the plasma, v_{T_e} is the thermal velocity of electrons, and $x_E = eE_z/m\omega_0^2$. The observed instability is also characterized by pump-frequency harmonics up to the tenth harmonic, by a high level of plasma-density fluctuations (10–60%, depending on conditions) and by a correlation of all the fluc-

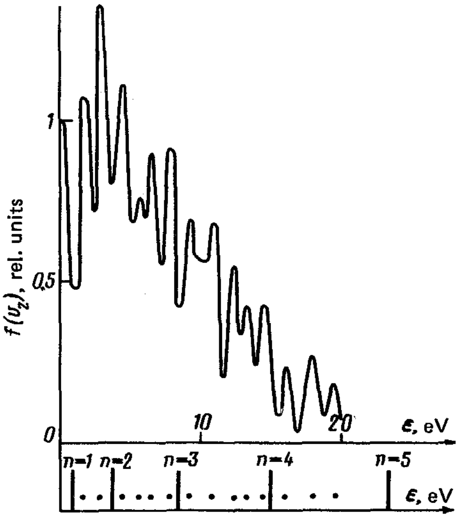

FIG. 1. Electron distribution function for an excitation voltage $U_0 = 180$ V and $p = 5 \times 10^{-3}$ mm Hg.

tuation modes along a tube of force of the magnetic field.[3]

Figures 1 and 2 show the $f(v_z)$ functions at two different levels of instability. The spikes on $f(v_z)$ become less pronounced and the distance between them increases as the turbulence increases in strength with increasing E_z and plasma-density fluctuations $\delta n/n$ and with decreasing scale of the longitudinal correlations. Thus, for the conditions of Fig. 1 in which the peaks are sharper, E_z is such that $\omega_b/\omega_0 \approx 2$ and $\delta n/n \approx 20\%$. In Fig. 2 $\omega_b/\omega_0 \approx 4$ and $\delta n/n \approx 60\%$. The vertical lines in the lower part of these figures show the spectrum of phase velocities of the plasma-wave harmonics $v_{phn} = n\omega_0/k_z$, and the points indicate the location of the peaks. Most of the observed peaks do not coincide with the velocities identified in this manner. In

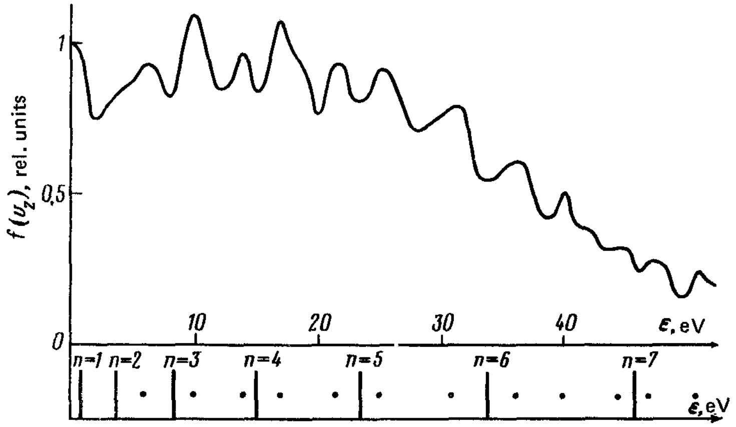

FIG. 2. Electron distribution function for $U_0 = 180$ V and $p = 1.7 \times 10^{-3}$ mm Hg.

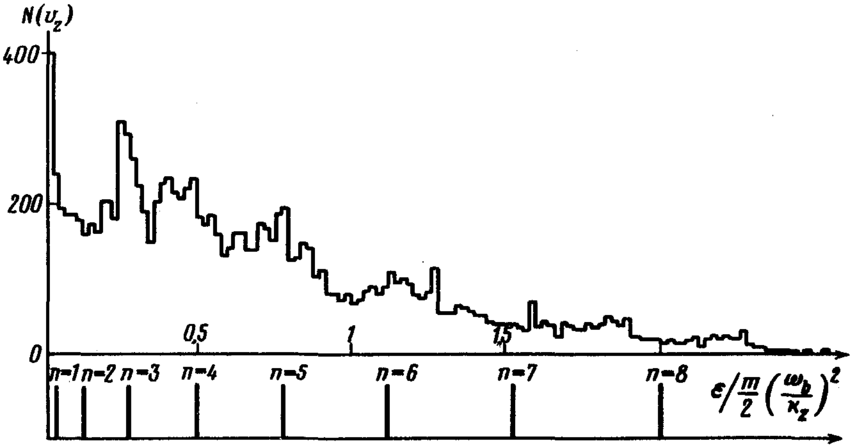

FIG. 3. Result of numerical modeling of the electron distribution function in the field of a standing wave. The number of particles is plotted along the Y axis.

addition, an allowance for the space-time harmonics of the form $n\omega_0/mk_z$, where n and m are integers up to 10, does not make it possible to find a corresponding plasma-wave harmonic for each peak.

The properties of the described turbulent plasma state are determined to a large extent by the trapping of a large number of electrons by the waves and by the correlations between the field and the motion of particles.[3] As experiments have shown,[4] these correlations lead to the formation of a spike structure on the electron distribution function which has not been averaged with respect to time. It can be assumed that the peaks observed by us on the $f(v_z)$ curve have the same nature, but then their steady-state quality is highly unexpected.

We have modeled numerically the possibility of a rapid formation of spikes on the distribution function. Since the turbulent rf fields, when plotted as a function of time, have the form of random bursts which contain up to 10^4 periods $T_0 = 2\pi/\omega_0$, and the amplitude of the field E_z within a burst varies slowly,[3] we examined in the numerical analysis the motion of electrons in the field of a strong standing wave ($\omega_b = 4\omega_0$), whose parameters were taken from the experiment. The second harmonic of the pumping wave was also taken into account. The equation

$$\frac{d^2 z}{dt^2} = -\frac{\omega_b^2}{k_z} \sin k_z z \left(\sin \omega_0 t + \frac{1}{3} \sin 2\omega_0 t \right)$$

was solved for particles with zero initial velocities, which were distributed uniformly at the initial instant of time with a density of 2000 particles per wavelength. The passage of particles through the wave nodes was recorded during two periods T_0, and their kinetic energy was recorded at the moment they passed through the nodes. This method of calculating the particle energy corresponds to the experimental procedure of measuring $f(v_z)$. The distribution function $N(v_z)$ obtained in this manner is shown in Fig. 3. The structure of the $N(v_z)$ function matches qualitatively the function observed experimentally. A cruder calculation with a density of 200 particles per wavelength during several successive periods T_0 showed that the structure of the distribution function is established after about one period T_0 and it then remains stable. Thus, we can conclude that the nonmonotonic distribution function with a spike structure corresponds to the steady-state ensemble of particles in the field of a strong standing wave.

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