Study of the Langmuir turbulence by means of an electron probe beam

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Strong Langmuir turbulence in a plasma which occurs in the field of an electromagnetic wave is studied by means of an electron probe beam. A modulation instability can be generated by exciting a nonlinear Langmuir standing wave in the plasma when the amplitude of the electric field of the pump wave is on the order of the threshold amplitude. An increase in the amplitude of the field of the pump wave generates a broad spectrum of plasma waves.

In the study of a nonlinear interaction of intense electromagnetic waves with a plasma at plasma resonance, the most important information is that about the amplitude and spatial spectrum of the excitable Langmuir waves. In this experiment we have used an electron probing beam to determine the structure of a strong Langmuir turbulence. The diagnostic procedure involves measurement of the deformation of the energy spectrum of the electrons of the beam transmitted through a turbulent region of the plasma as a function of the initial electron energy. The amplitude of the electric field and the scale of the excited Langmuir waves can be determined from the magnitude of deformation of the energy spectrum and from the initial energy of the beam.

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Experimental studies of the interaction of intense electromagnetic waves with the plasma are carried out in a vacuum chamber 1500 mm long and 200 mm in diameter. A plasma with an electron temperature $T_c = 10$ eV and ion temperature $T_i = 1$ ev is produced in helium at a pressure of 10^{-2} torr. The plasma column ($d = 100$ mm) is in a weak magnetic field $\omega_{H_e} \ll \omega_{P_e}$, where ω_{H_e} and ω_{P_e} are the gyrofrequency and plasma frequency of the electrons). The focused ($L_E = 10$ mm) electromagnetic radiation of the pump wave ($\lambda = 8$ mm) is introduced perpendicularly to the plasma column, with the polarization of the electric field $\mathbf{E} \| \mathbf{H}$.

In the experiments carried out previously using this setup,[1-3] we have detected several nonlinear effects occuring at plasma resonance upon exceeding the threshold field in the pump wave $v_{\sim}/v_{T_e} \cong 1.5 \times 10^{-2}$ ($v_{\sim}$ and v_{T_e} are the oscillator velocity and thermal velocity of the electron): the generation of epithermal electrons, the presence of clearly identifiable groups on the energy distribution function of the accelerated particles, amplification and saturation of the rf electric field ($v_{\sim}/v_{T_e}$ is as high as 2.5×10^{-1}), and excitation of ion-acoustic waves ($\delta N_s/N_e \sim 10^{-4}$). On the basis of the experimental data, taken collectively, we draw the conclusion that a modulation instability, which can generate a nonlinear plasma standing wave,[4] develops near the plasma resonance in a pump field.

The electron probe beam ($N_b/N_e = 10^{-5}$, where N_b and N_e are the electron densities of the beam and the plasma), which is used to diagnose the principal characteristics of the excited Langmuir waves, is directed along the magnetic field and along the axis of the vacuum chamber. The initial beam energy can be varied between 500 and 6000 eV. The integral energy spectrum of the electrons was analyzed in terms of the longitudinal energies (those directed along the magnetic field) with use of a multigrid analyzer which was placed at the end of the chamber. We should point out that no effects associated with the quasilinear relaxation of the beam were observed, but the observed broadening of the energy spectrum [see Fig. 1(a)] was determined from the collisions of the beam electrons with the neutral helium atoms.

The turbulent region of the plasma was probed by an electron beam with different initial energies at different amplitudes of the pump wave. The results yielding the most

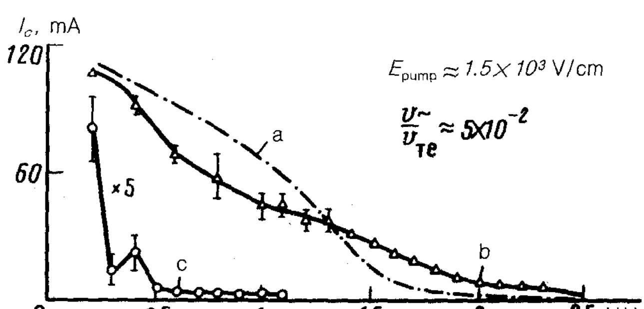

FIG. 1. Integral energy spectra of electrons. 2—Probing beam without pumping; (b)—probing beam at an amplitude of the electric pump field $E = 15$ kV/cm; (c)—epithermal plasma electrons.

information were those that were obtained at pump fields three times as high as the threshold value determined previously[1–2] ($v_{\sim}/v_{T_e} = 5\times 10^{-2}$). We found that there is a clearly identifiable energy region of the beam ($W_b \sim 1200$ V) in which the energy spectrum of the electrons is deformed [Fig. 1(b)]. This circumstance allows us to assume that a narrow packet ($\Delta k \ll k_{\rm plasma}$) of Langmuir waves with a scale length[1)] $\lambda_{\rm plasma} \sim 100 r_{de}$ (r_{de} is the Debye radius), which apparently has a maximum of the modulational-instability increment, is excited by a pump wave in the plasma. The amplitude of the field of the traveling plasma wave, which is determined from the size of the capture region, is $E_{\rm plasma} \cong 3$ kV/cm. It is clear that a Langmuir standing wave, whose total field is twice as large, is excited in a plasma. The result obtained by us is in reasonably good agreement with the optical measurements in which the field in the plasma was found to increase and to reach a saturation level[2] of 7 kV/cm ($v_{\sim}/v_{T_e} \cong 2.5\times 10^{-1}$).

To determine the dissipation mechanism of the excitable plasma wave, we analyzed the distribution of the epithermal plasma electrons. We found that accelerated electrons appear at ($v_{\sim}/v_{T_e} = 5\times 10^{-2}$. The maximum energy of these electrons is as high as $W_{\max} = 400$ eV [Fig. 1(c)]. This result is evidence that the excitable plasma wave, whose phase velocity is considerably higher than the thermal velocity because of the onset of modulational instability, is a nonlinear wave and the presence of higher harmonics in its spatial spectrum leads to an acceleration of the plasma electrons due to the Landau damping. If the regions in which the higher-order spatial harmonics are found ($k_N = N k_0$, where N is the number of the harmonic, and k_0 is the basic scale of the nonlinear plasma standing wave) overlap, the thermal plasma electrons may accelerate along the overlap region. Estimates show that the regions in which the second harmonic ($W_2 \cong 300$ eV), third harmonic ($W_3 \cong 130$ eV) and higher harmonics are found do indeed overlap, while the regions in which the first harmonic ($W_1 \cong 1200$ eV) and the second harmonic are found do not overlap. In this case the plasma electrons can be accelerated to a velocity on the order of the phase velocity of the second harmonic, which corresponds to an energy $W_{\max} \sim W_2 + (W_2 - W_3)/2 \cong 400$ eV.

From the results of the experiment we thus conclude that at plasma resonance a nonlinear plasma standing wave, whose energy dissipates because of the Landau damping involving thermal plasma electrons, is excited at the amplitude of the electric field of the pump wave ($v_{\sim}/v_{T_e} \leqslant 5\times 10^{-2}$).

After increasing the amplitude of the electric field of the pump wave ($v_{\sim}/v_{T_e} > 5\times 10^{-2}$), we found with use of the electron probe beam that the energy spectrum of the beam is deformed over a broad range ($500\ {\rm V} < W_b < 4000$ V) of the initial energies; i.e., the continuous spectrum of the Langmuir waves is excited. An increase in the amplitude of the pump wave leads to an increase in the fraction of acceleratad epithermal plasma electrons whose maximum energy reaches 4000 eV. This result may stem from the fact that at a high amplitude of the pump-wave field a random structure of localized unphased packets of rf field (solitons) forms in the plasma (see, e.g., Ref. 5).

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[1)]The scale is determined from the matching condition for the electron beam and the plasma wave.

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