Strong Langmuir turbulence excited by microwave field

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(Submitted 31 January 1990)
Pis'ma Eksp.Teor. Fiz. **51**, No. 6, 301–306 (25 March 1990)

When a spatially bounded microwave field with a frequency near the plasma frequency is applied to a plasma, effects characteristic of strong Langmuir turbulence are observed in the plasma surrounding the microwave pump. These effects include fast electrons, ion sound, and bursts of rf emission which are associated with the threshold and growth rate of a modulational instability.

Strong Langmuir turbulence[1,2] is a plasma state characterized by a repeated random generation of density cavities in which Langmuir waves (plasma waves) of a plasma are trapped. A fundamental property of these cavities is collapse;[1,3] a self-contraction of the trapped field, accompanied by the simultaneous contraction and deepening of the cavities themselves.

The collapse of an individual cavity was studied experimentally in Ref. 4. Experiments with a real laboratory plasma,[5,6] in which, plasma waves were excited through the injection of an electron beam, showed that above the threshold for a modulational instability of the excited waves one observes manifestations of a strong Langmuir turbulence associated with repeated collapses of the plasma-wave field in cavities.

Our purposes in the present study were to observe and study manifestations of strong Langmuir turbulence of a plasma during the application of a microwave field to a bounded region in which plasma waves were excited by a decay instability of the plasma.[7,8] The propagation of waves outside the pump region raises the possibility of studying the turbulence under conditions such that the external field is no longer having a direct effect on the turbulence.

The experiments were carried out with a column of decaying plasma of a pulsed beam-plasma discharge [Fig. 1(a)] in a weak static magnetic field ~ 100 G, in xenon at a pressure of 5×10^{-4} torr. When a negative voltage pulse with a height of -3 kV was applied to the hot cathode, the discharge current I injected by this cathode had an amplitude up to 10 A and a length ~ 100 μs. When the microwave pulse was applied, 100 μs after the beginning of the decay, the temperature of the plasma electrons decreased by a factor of five to $T_e = 25$ eV, while the density at the center of the column decreased by a factor of two, reaching a value close to the critical value, $n \lesssim n_c = m\omega_0^2/4\pi e^2 = 4.5\times 10^{11}$ cm^{-3}. The ratio of the ion and electron temperatures was $T_i/T_e \approx 0.1$, and the size of the density fluctuations $\delta n/n_c$ did not exceed 5×10^{-3}.

The plasma waves (Langmuir waves) were excited by a pulsed microwave field of frequency $f_0 = \omega_0/2\pi = 6$ GHz, power $P_0 \leqslant 4$ kW, and duration $\tau_0 = 2$ μs. The microwave power was launched in the plasma by the open end of a waveguide (3) with a cross section of 1.5×3.5 cm; the electric vector of the field was oriented parallel to the

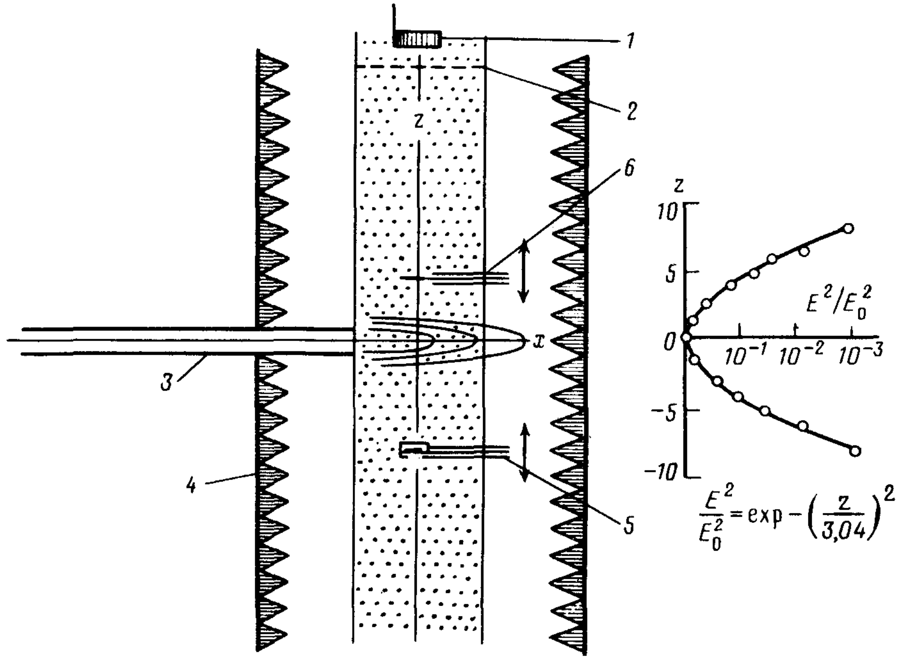

FIG. 1. Experimental layout. 1—Hot cathode; 2—grid anode; 3—waveguide; 4—anechoic rf-absorbing screen; 5—shielded plasma probe, 6—microwave antenna. Shown at the right is the profile of the microwave field intensity along the axis of the plasma column.

axis of the column. The plasma density was homogeneous in a region 6 cm in size along the radius and ± 20 cm in size along the length of the column. The high degree of localization of the microwave field [Fig. 1(b)] was achieved by introducing an "anechoic" rf-absorbing screen 4, which surrounded the plasma laterally. The threshold microwave intensity $E_{\rm th}^2/(4\pi n_c T_e = (8\pi m/M)^{1/2} \cdot \nu_e/\omega_0$ for the decay instability,[7,8] associated with the excitation of long plasma waves ($kr_{De} \lesssim 0.2$), is determined by the collisional damping with an electron collision rate ν_e. When the threshold for the (aperiodic) modulational instability,[7] $E_{\rm th}^2/4\pi n_c T_c) = 4\nu_e/\omega_0$, is crossed, plasma waves can go into a turbulent state. Over the time between electron collisions, the plasma waves propagating along the column at a group velocity $v_{\rm gr}$ traverse a distance $L\text{-}v_{\rm gr}\nu_e^{-1} = 3kr_{De}\Lambda_e$, where Λ_e is the mean free path of an electron between collisions. Here L is ~15 cm.

In these experiments it was expected that streams of accelerated electrons resulting from the collapse of waves would be ejected in a symmetric fashion (along the direction of the wave vector, **k**, and in the opposite direction) from the cavities produced in the escaping plasma waves outside the pump region. To observe the streams of accelerated electrons moving in the "backward" direction (from the periphery toward the center of the pump region), we used a shielded probe 5, which was protected from the forward-moving streams of accelerated electrons. Electrons resulting from secondary emission from the chamber wall were excluded.

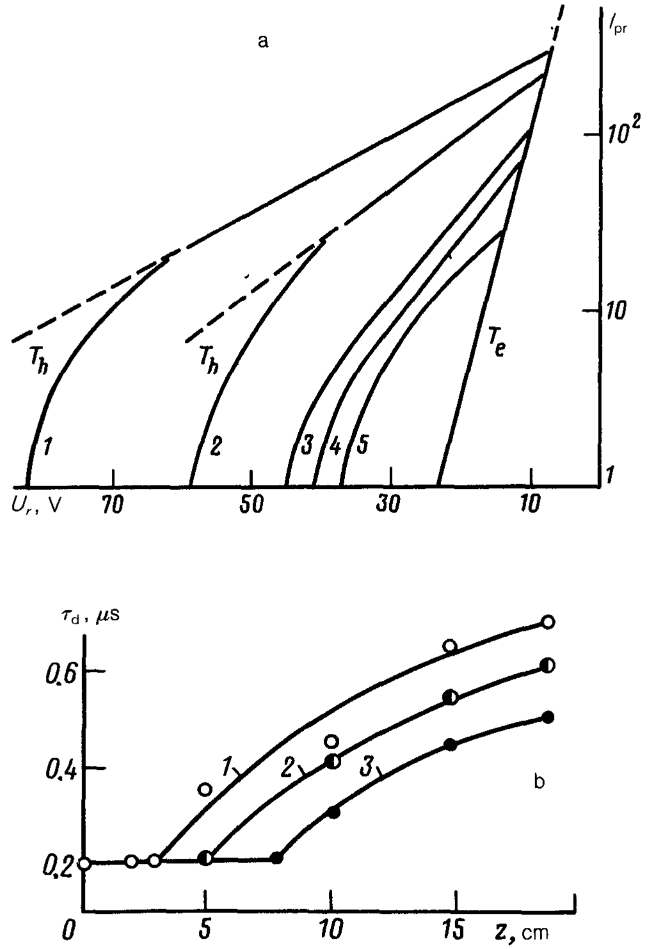

FIG. 2. a: Electronic characteristics of the shielded Langmuir probe for the backward electron streams with $E_0^2/(4\pi n_c T_e) = 4\times10^{-2}$ at various coordinates z. 1—$z = 0$; 2—$z = 4$; 3—$z = 8$; 4—$z = 12$; 5—$z = 16$ cm. b: Delay in the appearance of the backward streams of accelerated electrons versus z for three values of the parameter $E_0^2/(4\pi n_c T_e)$. 1—5×10^{-3}; 2—2.5×10^{-2}; 3—10^{-1}.

The expectation was rewarded. The intensity and distribution function of the forward-directed and backward-directed streams of accelerated electrons turned out to be approximately the same, as can be seen, in particular, from a comparison of the retardation curves of the probe current for various coordinates z [Fig. 2(a)]. Curve 1 ($z = 0$) is the resultant current of the forward-directed and backward-directed streams of electrons in the pump region. At the periphery ($z = 16$ cm) the current of backward electrons has decreased by an order of magnitude, while the intensity of the pump field has decreased by no less than four orders of magnitude. There is accordingly a transport of microwave energy along the plasma column out of the pump region. From the delay of the appearance of the current of the backward electrons to the probe at various values of z [Fig. 2(b)] we can easily find the transport velocity $v_t = \partial z/\delta\tau_d$ as a function of z. If we assume $v_t = v_{gr}$, we conclude that the wave numbers lie in the interval $0.1 \lesssim kr_{De} \lesssim 0.2$; this conclusion agrees with the customary assumption of a collisional damping of plasma waves. At each point in the region of the microwave pump at which the threshold for the modulational instability is exceeded, the delay in the appearance of the fast electrons turns out to be essentially independent of the external field, having a value $\tau_d = 0.2$ μs. This result agrees satisfactorily with the reciprocal of the growth rate of the modulational instability: $\Gamma^{-1} 1/2\omega_{pe}^{-1}[(m/3M)(E_0^2/8\pi n_c T_e)]^{1/2} \sim 10^{-7}$. The beginning of the rise of the $\tau_d(z)$ curves in Fig. 2(b) always corresponds to that value of z at which the microwave intensity exceeds the threshold for the modulational instability. As the intensity is increased, this value of z moves further away from the center.

It should be noted, however, that a generation of weak streams of accelerated electrons also occurs before the threshold for the modulational instability is reached, but in this case the process is limited to only the pump region. We know[9] that the excitation of plasma waves may be accompanied by a so-called weak turbulence involving the formulation of a "Langmuir condensate" with $kr_{De} \to 0$, with a lowering of the threshold for the modulational instability of plasma waves: $E_{l\text{th}}^2/(8\pi n_c T_e = 3(kr_{De})^2$. Clearly, however, the direct excitation of the modulational instability of plasma waves propagating out of the pump region would lead to the generation of a strong turbulence outside this region. Since the strong-turbulence processes (the formation of cavities) are determined by the ion dynamics, the plasma waves manage to propagate a distance ~ 10 cm out of the pump region along the column. The explanation for the nonconstant wave propagation velocity apparently lies in nonlinear processes associated with the trapping of wave energy in the cavities which are nucleated.

The current density and average energy of the electrons accelerated in the back-

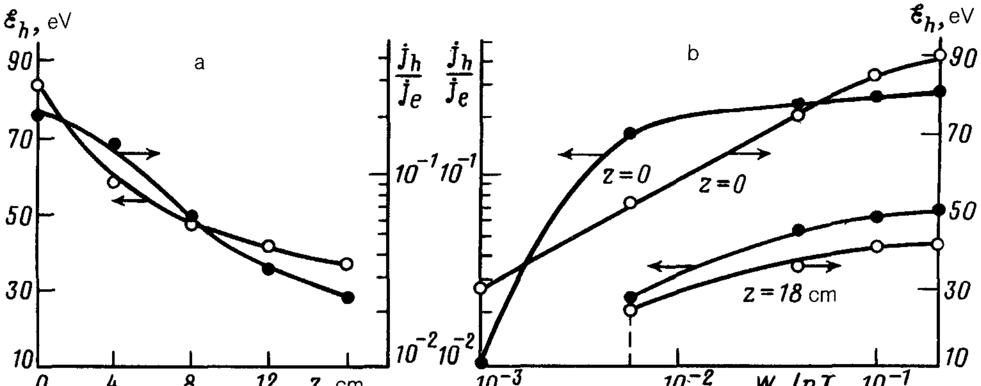

FIG. 3. Relative change in the current density j_h and the energy $\mathscr{E}_h$ of the accelerated electrons moving in the backward direction. a: The independent variable is the probe coordinate z, with $E_0^2/(4\pi n_c T_e) = 4 \times 10^{-2}$. b: The independent variable is the microwave field level, determined by the parameter $E_0^2/(4\pi n_c T_e)$, at the two extreme positions of the probe. 1—$z = 0$; 2—$z = 18$ cm.

ward direction are plotted in Figs. 3(a) and 3(b) versus the probe coordinate (including the case $z=0$) and versus the pump intensity. The results reveal a pronounced, order-of-magnitude, change in the current of accelerated electrons and a relatively slow change in their average energy over the interval $30 \leqslant \mathscr{E}_h \leqslant 80$ eV. The current density of accelerated electrons reaches saturation in the pump region. Both the rapid decay of the current density $j_h(z)$ and the saturation in the pump region probably reflect the cavity distribution $N_k(z)$. The maximum density of cavities in the saturation regime should not exceed $N_{km} = \lambda^{-3} = [2\pi/(kr_{De})]^{-3} r_{De}^{-3}$. An upper estimate of the energy acquired by the plasma electrons passing through collapsing cavities in the final stage of the collapse, under the condition for a Čerenkov resonance, is given by

$$\Delta \mathscr{E}_{hm} = eE_{lk} l_k = (W_{lk}/n_c T_e)^{1/2} T_e (l_k / r_{De}),$$

where W_{lk} and l_k are respectively the energy density of the plasma-wave field in a cavity and the size of the cavity in the final stage of the collapse. According to numeri-

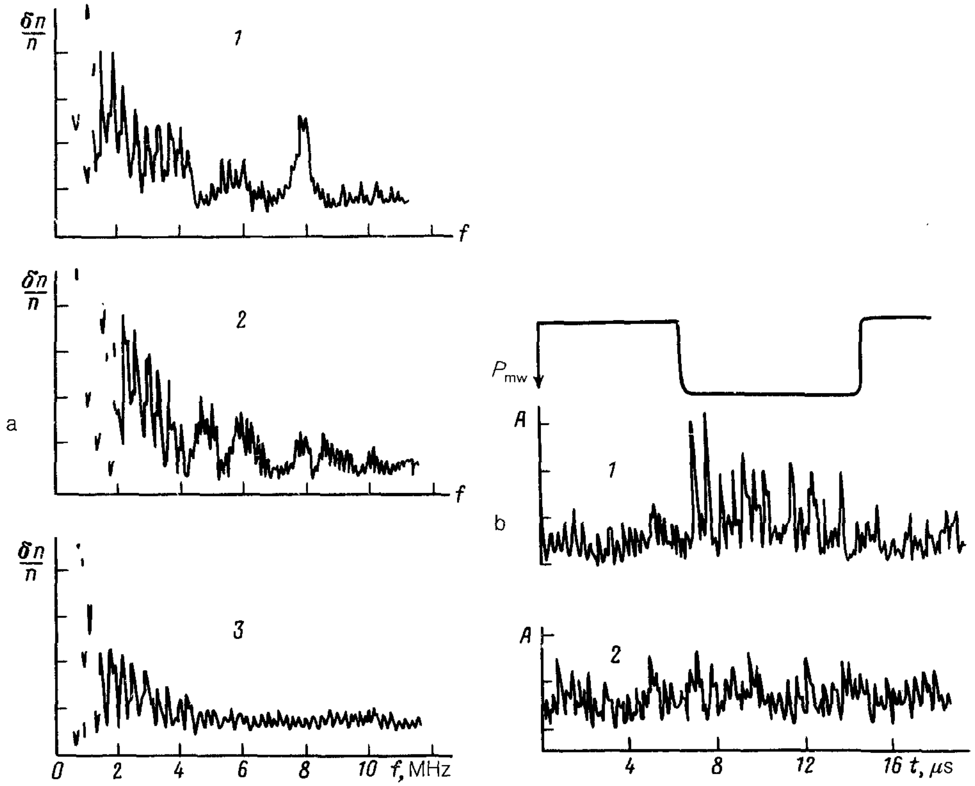

FIG. 4. a: Spectra of ion acoustic waves of the (xenon) plasma at a microwave field level $E_0^2/(4\pi n_c T_e) = 4\times10^{-2}$. 1—$z=0$; 2—$z=15$ cm; 3—receiver noise. b: Oscilloscope traces of (1) the envelope of the microwave emission from the turbulent plasma and (2) the receiver noise. Shown at the top is the envelope of the microwave pump pulse.

cal simulations,[3] these quantities have the values $W_{lk}/n_c T_e \approx 2$ and $l_k/r_{De} \approx 14$. The energy acquired by the electrons should thus be about 20 T_e, in agreement with the measurements. The further increase in the energy of the electrons may be due to repeated acceleration in the multitude of cavities. A proportionality[10] $\mathscr{E}_h \propto N_k^{1/6}$ is possible here.

Measurements of the spectra of the ion acoustic waves of the plasma, through a spectral analysis of the saturation ion current drawn by a probe [Fig. 4(a), for (1) $z = 0$ and (2) $z = 18$cm], along with the dispersion relation for ion acoustic waves, $\omega_s = \omega_{pi}/(1 + k_s^2 r_{De}^2)^{1/2}$ make it possible to determine the characteristic wavelengths of the waves which are excited. They lie in the interval $(7\text{–}15)r_{De}$. These wavelengths reflect the typical dimensions of the collapsing cavities. The fact that the cavity dimensions found from these measurements are smaller than those predicted[3] for the final stage of collapse indicates that the dynamics of the cavities in the stage of the "burn-up" of the plasma-wave field which follows the collapse must be taken into account.

Because of the additional measures taken to filter the noise out of the external microwave field, it was possible to clearly receive bursts of electromagnetic radiation from the periphery of the plasma column [Fig. 4(b)]. We observed a good correlation between the beginning and end of the series of bursts, on the one hand, and the leading and trailing edges of the microwave pulse, on the other. The typical properties of the bursts correspond to those observed in experiments with beams.[5] The frequency of the radiation in these bursts is near the plasma frequency.

In summary, experiments on the excitation of a strong Langmuir turbulence through the injection of an electron beam[5,6] and by microwave pumping have shown that the thresholds and growth rates of the processes which are observed are associated with the threshold and growth rate of the modulational instability. The deformation of the electron distribution function of the plasma observed in the process takes the form of an outgrowth of tails of accelerated electrons due to Čerenkov acceleration in cavities in the final stage of collapse. These electrons may be accelerated further as a result of a repeated stochastic acceleration in the multitude of collapsing cavities, with the result that an "effective temperature" T_h is formed in these tails. The generation of short ion acoustic waves with $k_s r_{De} \sim 1$ agrees with the theory of strong Langmuir turbulence. In particular, it agrees in terms of the dimensions of the collapsing cavities. The bursts of electromagnetic radiation at frequencies near the plasma frequency are characterized by local sources of small dimensions, $\lesssim 100 r_{De}$, and a short duration, $\omega_{pi} t \sim 10$, which corresponds to the duration of the final stage of collapse.

We wish to thank D. M. Karfidov, A. M. Rubenchik, and also some American scientists, A. Y. Wong and P. Y. Cheung, for useful discussions of these results.

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Translated by Dave Parsons