Properties of nonlinear waves excited by injection of electron clusters into a plasma

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We report the first experimental investigation of the interaction of a plasma with pre-shaped electron clusters. It is established that the waves excited by such clusters can propagate without substantially changing the amplitude of much larger distances than the waves in ordinary beam-plasma systems.

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In all beam-plasma experiments performed to date, the electron beam injected into the plasma was either not modulated or self-modulated. According to the numerous data obtained in this manner (see, e.g., [1–4] the amplitude of plasma waves excited by such beams varies strongly (by several orders of magnitude) along the beam direction, so that the oscillations are practically localized in a narrow zone at a certain distance from the coordinate of the beam injection. Yet the process of dispersion in the plasma-beam system gives grounds for raising the fundamental question of the feasibility of the existence in the plasma, under excitation conditions, of nonlinear waves of constant amplitude. Such waves are apparently of interest in connection with problems of applied character (collective acceleration of charged particles, heating of plasma, and a few others).

It is shown in the present paper that the path covered by the wave without a substantial change in the amplitude can be increased by injecting into the plasma a beam in the form of pre-shaped clusters.

We use the equation for the potential electric field E of linear one-dimensional oscillations excited in a cold plasma by a beam with current density j_b

$$\frac{\partial^2 E}{\partial t^2} + \omega_p^2 E = -4\pi \frac{\partial j_b}{\partial t}, \tag{1}$$

where ω_p is the plasma frequency. Recognizing that the density n_b of the beam moving with velocity u is modulated at a frequency ω, we seek the solution of Eq. (1) in form of a traveling periodic wave $E(z,t)=E(\xi)$, $n_b(z,t)=n_b(\xi)$, $E(\xi+2\pi n/\omega)=E(\xi)$ where $\xi=t-(z/u)$. Then the electric field of the wave can be expressed in the form

$$E(\xi) = -\frac{4\pi eu}{\omega_p}\int_0^{\xi} \frac{dn_b}{d\tau}\sin\omega_p(\xi-\tau)\,d\tau \,. \tag{2}$$

The wave will propagate with constant amplitude if the electron clusters move without being deformed. This is possible only when $E=0$ wherever $n_b\neq 0$, and consequently $dn_b/d\tau=0$ where $n_b\neq 0$ (see relation (2)). The beam density in the stationary wave should take the form of rectangular pulses (Fig. 1a). We determine from (2) the electric field of the nonlinear wave

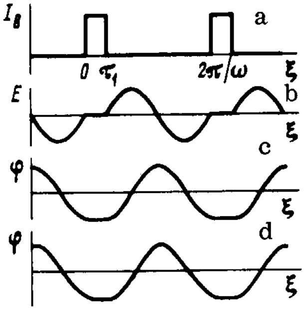

FIG. 1. Calculated (a,b,c) and experimentally measured (d) structure of stationary wave.

$$E(\xi) = \frac{4\pi e u}{\omega_p} n_b \begin{cases} 0 & \text{if } 0 < \xi < \tau_1 \\ \sin\omega_p(\xi - \tau_1) & \text{if } \tau_1 < \xi < \frac{2\pi}{\omega} \\ \sin\omega_p(\xi - \tau_1) - \sin\omega_p(\xi - \frac{2\pi}{\omega}) & \text{if } \frac{2\pi}{\omega} < \xi < \frac{2\pi}{\omega} + \tau_1 \end{cases} \quad (3)$$

The condition that the electric field be periodic imposes the following requirement on the pulse duration τ_1:

$$\omega_p \tau_1 = \omega_p \frac{2\pi}{\omega} - 2\pi n, \quad n \text{ is an integer} \quad .$$

This requirement can be satisfied only if $\omega < \omega_p$. In particular, if $\omega \lesssim \omega_p$, then $n = 1$ and the condition that the cluster shape remain in equilibrium can be expressed in the form

$$\frac{L}{\lambda} \equiv \frac{\tau_1 \omega}{2\pi} = 1 - \frac{\omega}{\omega_p} ,$$

where L is the length of the cluster and λ is the wavelength. The $E(\xi)$ profile for this case is shown in Fig. 1(b).

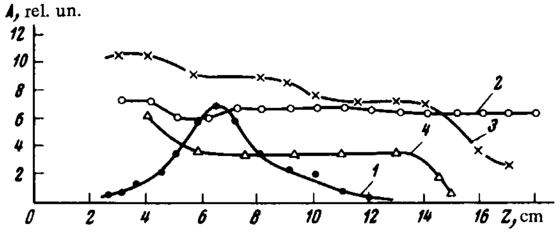

FIG. 2. Plots of the wave amplitude against the distance to the beam-injection coordinate at shallow (curve 1) and deep (curves 2,3,4) modulation. Modulation frequency $f = \tilde{\omega}/2\pi = 420$ MHz. 1,2,3—$I_{b0} = 10$ mA, $U_0 = 340$ eV; 4—$I_{b0} = 5$ mA, $U_0 = 300$ eV; 1—$I_b/I_{b0} = 6\times10^{-3}$; 2,3,4—$I_b/_{b0} \sim 1$; the cluster parameters in regimes 2 and 3 are different.

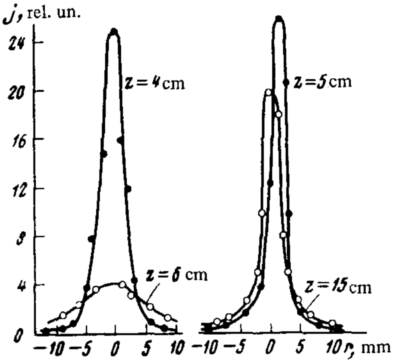

FIG. 3. Distribution of current density j along the radius r at different distances from the coordinate where the beam is injected in the plasma at shallow (a) and deep (b) modulation, $U_0 = 300$ eV, $I_{b0} = 2$ mA, $f = 420$ MHz; a—$I_b/I_{b0} = 1.5\times10^{-2}$, b—$I_b/I_{b0} \sim 1$.

We note that the absence of an electric field inside the equilibrium clusters at $\omega \lesssim \omega_p$ can be interpreted as a result of the superposition of the field of the excited plasma oscillations, which tends to compress the clusters, on the repelling self-field of the clusters.

The experimental investigation of the interaction between the plasma and the pre-shaped electron clusters was carried out by us with a beam energy U_0 of several hundred eV, and a beam current I_{b0} (averaged over the period) of 1 to 10 mA. The beam was shaped by a planar triode system (cathode, control grid, anode). A dc bias voltage and a microwave voltage were simultaneously applied to the control grid. By regulating these voltages we were able to obtain either a small modulation of the beam ($I_b/I_{b0} \ll 1$) or strong modulation in a regime with cutoff of the anode current ($I_b/I_{b0} \sim 1$). By varying the cathode emission current, the beam current was maintained independent of the modulation amplitude. The modulated beam passed subsequently through a gas (argon) at a pressure on the order of 1×10^{-3} mm Hg, producing in the absence of external fields a plasma with concentration 10^9—10^{10} cm^{-3}.

It turns out, as follows from the theory, that the properties of the waves, which are excited in one case by negligible modulation of the beam and in the other case by periodic injection of individual electron clusters into the plasma, are greatly different. Figure 2 compares the spatial dependences of the wave amplitudes in these two cases, obtained with a moving high-frequency probe at a gas pressure sufficient for the production of a plasma with $\omega_p \gtrsim \omega$. Whereas at shallow modulation this dependence has a sharp maximum, due to the consecutive processes of formation of electron clusters and their decay in the longitudinal and transverse directions,[5] in the case of modulation with $I_b \approx I_{b0}$, at the same average beam current, the excited waves have from the very outset an amplitude close to the maximum value of curve 1, and preserve this amplitude over distances at which the initially growing wave is almost completely damped.

Using an oscilloscope with a bandwidth up to 3.5 GHz, we have determined the time profile of the oscillations received by the probe under the conditions of Fig. 2, curve 4. It is seen that this profile (Fig. 1d) is close to the theoretically predicted profile of the potential ϕ (Fig. 1c). Some difference is quite natural, inasmuch as in the experiment the required equilibrium shape of the clusters is reached only approximately. It appears that the latter circumstance is also the cause of the noticeable changes in the amplitude over the distance (Fig. 2).

The experimentally observed preservation of the wave amplitude over a considerable distance indicates one more important system feature, predicted theoretically[6] but not yet observed experimentally, namely the existence of transverse equilibrium of the clusters at $\omega \lesssim \omega_p$. As a confirmation of this fact, Fig. 3 shows the radial distributions of the beam current density measured by us in the case of shallow and deep premodulation.

Thus, in contrast to clusters produced when beam-plasma instability develops clusters that are shaped beforehand can exist in equilibrium in the wave fields for a long time. It must be noted at the same time that, starting with a certain distance, the wave attenuates quite rapidly (Fig. 2), this being apparently a manifestation of an instability peculiar to such a system.[7]

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