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SPATIAL DEVELOPMENT OF PLASMA-BEAM INSTABILITY

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We have investigated the spatial distribution of the intensity and the oscillation spectrum along an experimental tube in which an electron beam interacts with the plasma which it produces. We have observed along the tube, in the stationary mode, the spatial evolution of all the stages of the process of interaction between the beam and the plasma as described by the quasilinear theory. In parallel with the increase in the intensity and with the broadening of the oscillation spectrum, we observed broadening of the beam-electron energy-distribution function. With increasing beam current, the rate of spatial development of the oscillation and the deformation of the beam-electron distribution function increases.

THE known papers dealing with quasilinear theory of the interaction between an electron beam and a plasma are devoted to the temporal evolution of the oscillations and to the relaxation of an unbounded electron beam in an unbounded plasma [1-3]. Experiments confirming this theory reduce essentially to observation of the formation of the plateau on the electron-beam energy distribution function [4-6].

By investigating the intensity distribution and the spectra of the oscillations along an experimental tube in which the electron beam interacted with the plasma produced by it, we succeeded in observing a gradual broadening of the spectrum of the oscillations, as predicted by the quasilinear theory, occurring in parallel with the broadening of the distribution function of the electrons in the beam. Indeed, if the real system in which the electron beam is "injected" in the plasma has convective instability, one can expect to observe along the plasma plus beam system a "spatial sweep" of the temporal process described by the quasilinear theory, and one can observe along such a system, in the stationary mode, all the stages of the plasma-beam interaction, arranged in order from the point where the electron beam enters in the plasma.

1. DESCRIPTION OF EXPERIMENTAL SETUP

The experimental investigations were made with a setup similar to those described in our earlier papers [7-8]. The working part of the tube, in which the beam interacted with the plasma, was a glass tube 25—30 cm long, with inside diameter 10 mm. The tube was filled with hydrogen whose pressure was maintained during the described experiments at 2.5×10^{-2} mm Hg. The plasma was produced by the beam itself. The diameter of the beam as it left the electron gun was approximately 3 mm, and the beam current could be raised to 25 mA, and the accelerating voltage was 1—1.5 kV; the magnetic field was usually of the order of several hundred Oe. The electron concentration in the thus-produced beam plasma, measured with the aid of a cavity resonator, was of the order of $n_p \approx 10^{10}$ cm^{-3}.

To measure the distribution of the oscillation intensity along the tube, a short coil (2.5 cm) was slipped over the tube and could be moved freely over the working part of the tube. Since the power of the oscillations along the tube increased by almost 10 orders of magnitude, special measures had to be taken to screen its collector region, whose radiation produced noticeable interference in the measurement of the oscillation intensity in the gun region of the tube. Since the construction of the tube was such that the moving coil could not be brought closer than 50—60 mm to the gun, a special stationary coil, located inside the tube at the very emergence of the beam from the gun, was used to carry out the measurements at the initial section of the electron beam. This coil had its own coaxial leads and was also carefully screened.

The oscillation spectrum was measured with the aid of a highly sensitive P5-4 receiver of 2.5 MHz bandwidth. The receiver was calibrated against a standard noise generator.

To measure the energy distribution function of the beam electrons reaching the collector, the

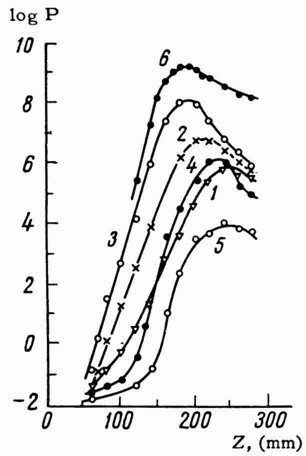

FIG. 1. Spatial distribution of the oscillation power along the tube. Frequencies (MHz): 1–1100, 2–1250, 3–1350, 4–1500, 5–1700, 6–integral oscillation power. i_{beam} = 16.5 mA, U = 1140 V, H = 190 Oe.

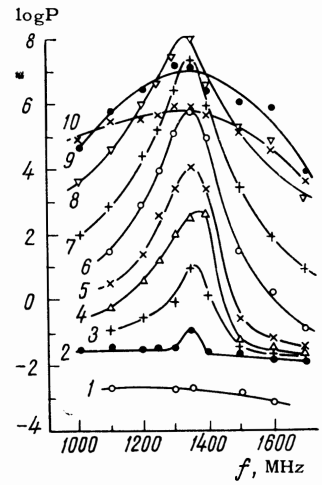

FIG. 2. Oscillation spectrum at different distances from the gun (mm): 1–30, 2–60, 3–80, 4–100, 5–120, 6–140, 7–160, 8–200, 9–230, 10–275. The same conditions as in Fig. 1.

latter had a hole of 0.4 mm diameter. The electrons passing through this hole impinged on an energy analyzer operating on the declerating-field principle. To prevent secondary-electron emission from the electrode of the analyzer, the latter was placed behind a suppressor grid.

2. SPATIAL DISTRIBUTION OF THE INTENSITY AND FREQUENCY SPECTRA OF THE OSCILLATIONS

Typical measured distributions of the oscillation power along the working part of the tube are shown in Fig. 1. The abscissas represent here the distance from the gun outlet to the center of the moving coil, and the ordinates represent the logarithm of the relative oscillation power. The parameter of the curves is the frequency to which the receiver was tuned. We see that the oscillation power increases rapidly with increasing distance from the gun, starting with a certain initial level that is common to all frequencies. The curves always include one which shows the largest growth rate (in this case, this optimal frequency was 1350 MHz). The oscillations at lower and higher frequencies increased more slowly. The conditions under which these measurements were made were chosen in such a way that the optimal frequency was approximately at the midpoint of the P5-4 receiver band.

At a certain distance from the gun, the oscillation growth rate slowed down, and the power picked up by the moving coil reached a maximum followed by a decrease. It should be noted here that the point at which the maximum intensity was reached at the optimal frequency was always closer to the gun than the points for the other frequencies. A similar form is possessed by the plot of the integral oscillation power, measured in a wide frequency range (50—3000 MHz) with the aid of a thermistor low-power meter (curve 6).

The results of the described measurements could be used to plot a second family of curves, showing the oscillation spectra at different distances from the gun (Fig. 2).

In the immediate vicinity of the gun exit, the beam induces in the external coil noise oscillations whose power does not depend on the frequency. Such a "white" spectrum is retained up to $z \approx 50$ mm. Further, at 1350 MHz, a peak is observed of width smaller than 100 MHz; this peak subsequently grows rapidly against the background of all the remaining frequencies. This peak is sharpest in the section where the linear part of the log P curve for the optimal frequency 1350 MHz terminates ($z \approx 160$ mm). The oscillation power at the optimal frequency is at this point 5—6 orders of magnitude higher than the oscillation power at the frequencies corresponding to the end of the range, 1000 and 1700 MHz.

This difference decreases with increasing distance from the gun. In the section $z > 180$ mm, corresponding to the maximum and fall-off of the integral-power curve, the oscillation spectrum again "whitens" and the disparity between the power levels at the optimal frequency and at the frequencies at the end of the range reduces at the point $z = 275$ mm to 1—2 orders of magnitude.

A detailed investigation of the top of the spectral curve with the aid of a spectrum analyzer has shown that the spectral curve can be somewhat cut up. This choppiness increases when the screening becomes worse, and conditions favoring the occurrence of uncontrolled feedback by induction are created in the system. Another possible means of occurrence of feedback is reflection of waves from the collector. However, our measure-

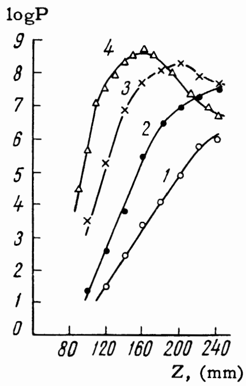

FIG. 3. Spatial distribution of the oscillation power along the tube at different beam currents. f = 1300 MHz; U = 1200 V. 1–i = 10 mA, H = 197 Oe; 2–i = 12 mA, H = 190 Oe; 3–i = 16.5 mA, H = 185 Oe; 4–i = 22 mA, H = 175 Oe.

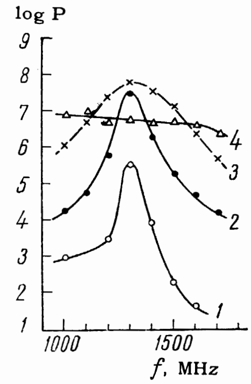

FIG. 4. Oscillation spectra measured near the collector (z = 240 mm) at different values of the beam current. The conditions are the same for Fig. 3.

ments have shown that the attenuation of the waves propagating in a direction opposite to the electron beam is very large. For frequencies corresponding to the optimal frequency, attenuation of the waves located near the collector, and picked up by a similar coil placed near the gun, exceeds 10 orders of magnitude. It can therefore be concluded that in our tube the starting point of the plasma-beam system is quite thoroughly decoupled from the end point, so that feedback by reflection from the collector can hardly play an important role.

The scale of the picture shown in Fig. 1, along the abscissa axis, depends on the intensity of the plasma-beam interaction and is determined primarily by the beam current. Figure 3 shows several curves representing the spatial growth of the oscillations at fixed frequency for a number of values of beam current. Since a change in the beam current should change the electron density in the beam plasma, and with it the optimal frequency, to obtain comparable results in the described measurement run we were forced to maintain the optimal frequency constant at 1300 MHz by suitably regulating the magnetic field intensity. It follows from an examination of the curves of Fig. 3 that at large beam currents the rate of oscillation growth is fast; the oscillation power increases rapidly, reaches a maximum, and then falls off. At smaller beam currents, the growth of the curves is slower, and they reach a maximum near the collector itself, or else do not reach the collector at all; they have no decreasing section. Accordingly, the spectra of the oscillations in a fixed section of the tube also change.

Figure 4 shows a group of spectra measured at a fixed position of the movable coil, z = 240 mm for several values of the beam current. We see that at small beam currents we obtain an "early" oscillation spectrum, having a small width and low intensity. With increasing beam current, the intensity of the oscillations increases and the spectrum broadens. Finally, at a beam current higher than 20 mA, the spectrum is almost uniform in the frequency range from 1000 to 1700 MHz.

The results admit of a simple interpretation, if they are regarded as a "spatial sweep" of those temporal processes which are described in the quasilinear theory. The "white" spectrum observed directly as the beam leaves the gun indicates that when the tube is carefully screened the oscillations in the plasma-beam system evolve from the initial thermal fluctuations. The linear sections of the curves in Figs. 1 and 3 correspond to the linear mode of interaction between the plasma and the beam, when the oscillations develop in time and in space in accord with an exponential law. After the oscillations reach sufficient intensity, the electron distribution function begins to broaden, and this leads to a decrease in the growth rate of the oscillations at the optimal frequency and to an intensification of the oscillations at neighboring frequencies. The oscillation spectrum then begins to become equalized. When the beam-electron energy distribution function reaches the plateau stage, the growth of the oscillations ceases. This is followed by a region in which the oscillation spectrum, owing to the nonlinear interactions, broadens, and the integral power of the oscillations decreases as a result of irreversible dissipative processes.

The transition from the time scale, in which the quasilinear theory is developed, to the space scale can be realized in first approximation by simply multiplying the time by the electron-beam velocity v_0 at which the oscillations are transported along the tube. In particular, the characteristic distance for relaxation of the electron beam and for saturation of the oscillations, z_0, turns out to be

$$z_0 \approx \tau_0 v_0 \approx \frac{v_0}{\omega_p}\frac{n_p}{n_b}\ln\frac{W_m}{W_0},$$

where τ_0 is the electron-beam relaxation time determined by the quasilinear theory [3, 9], and W_m and W_0 denote here the values of the oscillation energy at distances $z = z_0$ and $z = 0$, respectively. This expression is strictly valid for an unbounded plasma; for a bounded plasma, when the plasma wavelength $\lambda = 2\pi v_0/\omega_p$ exceeds the radius a of the plasma column (under the conditions of our experiments $\lambda/a \approx 2$—3), expression (1) can give only a qualitatively correct result.

The substitution into the expression for z_0 of quantities that are characteristic of the conditions of our experiments gives good agreement in order of magnitude of the calculated z_0 and of the measured distance z_{max} at which the intensity of the oscillations experiences saturation. The same expression for z_0 fits qualitatively also the observed dependence of z_{max} on the beam current. Indeed, as seen from Fig. 3, z_{max} decreases with increasing beam current.

We were unable to observe the concentration of the oscillation intensity at the entrance of the electron beam into the plasma, which was predicted in [9]. This is possibly due to the fact that under the conditions of our experiments the oscillations are strongly dissipated and damped, a factor not allowed for in [9]. In addition, the necessary condition for the formation of a narrow oscillation layer is the smallness of the group velocity, whereas the group velocity in a spatially-limited plasma column may be much larger than in an unbounded plasma.

3. DEFORMATION OF THE BEAM-ELECTRON ENERGY DISTRIBUTION FUNCTION

It follows from the quasilinear theory that one should observe along the plasma-beam system, in parallel with the growth of the power and the broadening of the oscillation spectrum, also a broadening of the beam-electron distribution function. Unfortunately, we were unable to move the collector together with the energy analyzer along the tube as we could the removable coil. It was possible, however, by varying the current in the beam, to regulate the rate of development of the oscillations and by the same token to move, as it were (by stretching or compressing), the entire picture of the oscillations relative to the fixed collector.

A family of normalized distribution functions, measured at several values of the beam current, is shown in Fig. 5. The conditions under which these measurements were made correspond to the conditions for which the spectra shown in Fig. 4 were measured.

In the mode with weak beam current, when there were no oscillations (mode 5; since there

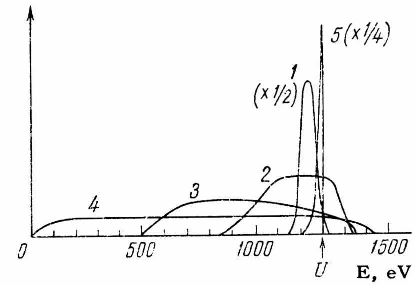

FIG. 5. Normalized beam-electron energy distribution functions measured at a distance 260 mm from the gun at different values of the beam (i_s = 2 mA). The conditions are the same as in Figs. 3 and 4.

are no oscillations, there is no corresponding curve on Fig. 4) the electron distribution is almost monokinetic. When oscillations appear, this monokineticity is violated (mode 1). Comparing Figs. 4 and 5 further, we can see how the broadening of the distribution function is accompanied by a broadening of the oscillation spectrum (modes 3 and 4). On going from mode 3 to mode 4, the distribution function acquires the form of a plateau, which extends almost to zero energy. The growth of the oscillations then stops, and their spectrum becomes homogeneous within the investigated frequency range.

An interesting feature of the measured distribution functions is the fact that when the beam current changes they retain their square-wave form. The left edge of the distribution function gradually shifts towards lower energies, in the manner expected from the calculations presented in [10].

As regards the right edge of the distribution-function curve, it shifts somewhat, with increasing beam current, into the region of energies exceeding the initial beam-electron energy. This effect, which does not fit within the framework of the ordinary quasilinear theory, was observed many times by a number of workers investigating plasma-beam interactions [4,5,11], and is called anomalous scattering of the electrons in the plasma. It is due to acceleration of part of the beam electrons when the beam interacts with the microwave oscillation fields excited by the beam itself.

On the whole, however, the "center of gravity" of the distribution function shifts towards lower energies, thus indicating that the beam electrons lose energy. This energy is lost to buildup of the microwave oscillations described above.

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