# Excitation of waves in a bounded plasma by an electron beam with transcritical initial velocity

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It was observed for the first time that the system "plasma + electron beam", with velocity larger than the maximum phase velocity of the wave in the system, becomes unstable at a certain finite external-signal amplitude. The experimentally obtained amplitudes at which the instability sets in are in good agreement with the theoretical ones.

1. As is well known, infinitesimally small perturbations in a bounded beam + plasma system do not grow if the initial velocity of the beam exceeds a critical velocity, approximately equal to the maximum phase velocity of the space-charge waves

$$V_b > V_c = \omega_p / k_\perp, \quad k_\perp = \pi / d \tag{1}$$

where $d$ is the transverse dimension of the system and $\omega_p$ is the electron plasma frequency. However, as shown in[1], where the possibility of exciting waves by beams with transcritical initial velocities was investigated theoretically, this system is unstable with respect to initial perturbations of finite amplitude, namely, when the initial amplitude exceeds a threshold value determined for the case of a mono-energetic beam by the relation

$$e\phi_c = \frac{m}{4}(V_b - V_{ph})^2 \tag{2}$$

The meaning of this relation is clear: when the initial wave amplitude exceeds $\phi_c$, the particles are captured by the wave and are greatly slowed down during the course of the capture (the asymptotic average velocity of the captured particles tends to $V_{ph}$), and transfer energy to the wave. The energy lost by a fast beam as a result of the development of the instability can exceed by many times the energy lost by a slow beam ($V_b < V_c$) of equal density, since

$$\Delta\epsilon = \frac{m}{2}(V_b^2 - V_{ph}^2) \tag{3}$$

and for a slow beam we have

$$V_b^2 - V_{ph}^2 \approx V_{ph}^2 (n_b/n)^{1/3}, \tag{4}$$

where $(n_b/n)^{1/3}$ is a small parameter for weak beams. For beams with transcritical velocity it is easy to satisfy the relation

$$V_b^2 - V_{ph}^2 \gg V_{ph}^2 (n_b/n)^{1/3}, \tag{5}$$

which proves our statement.

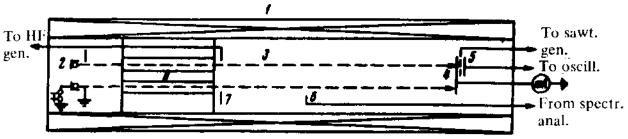

FIG. 1.

We note that effective excitation of finite-amplitude waves by a beam much faster than their phase velocity is possible in any slow-wave system.

2. The experiments were performed with the setup illustrated in Fig. 1. The chamber diameter was 5 cm, the length 100 cm, and the electron-beam diameter 2 cm. The density of the plasma produced by collisions between the electron beam and the neutral gas was $2 \times 10^8$ cm$^{-3}$. The particle energy could range from 300 to 1000 eV. The system was in a constant longitudinal magnetic field of 600 Oe. In such a field, the beam electrons are magnetized, $\omega_{ce} \gg \omega_p$.

At a beam energy up to 400 or 450 eV (beam velocity $V_b = 1.2 \times 10^9$ cm/sec), the usual beam + plasma discharge is produced in the system, accompanied by electron plasma oscillations. However, even at a beam energy 500 eV (velocity $V_b = 1.33 \times 10^9$ cm/sec) and above, there is no excitation of the waves by the beam in the system in the case of fluctuating initial perturbations. To investigate the stability of finite-amplitude waves in a beam + plasma system with transcritical initial beam velocity, a microwave signal of finite amplitude and frequency $\omega \leq \omega_p$ was applied to the modulating electrode. In this case instability developed in the wave when the initial wave amplitude reached or exceeded the threshold value given, with good accuracy, by relation (2). This is evidenced by the experimental results shown in Figs. 2–4.

Figure 2 shows a plot of the threshold initial wave

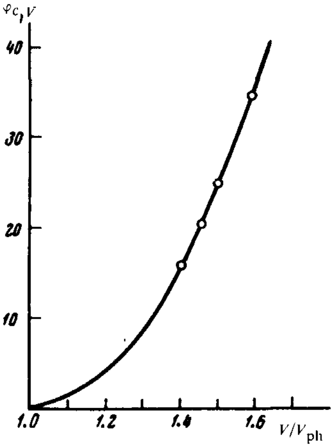

FIG. 2.

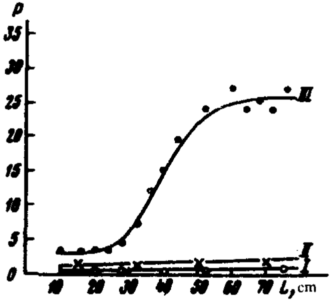

FIG. 3.

amplitude against the initial beam velocity. The solid curve is the theoretical relation, and the measured values are represented by the circles.

The behavior of the wave amplitude along the system at different initial-wave amplitudes and at a beam energy 600 eV is shown in Fig. 3. It is seen that so long as the initial-wave amplitude does not exceed the critical value (in our case $\phi_c = 12.5$ V, the measured phase velocity of the wave in the system is $V_{\text{ph}} = 1.15 \times 10^9$ cm/sec) there is practically no amplification of the wave ($\phi = 1$ V and 10 V for curves I and II, respectively). When the amplitude exceeds the threshold (curve III, $\phi = 15$ V), two-stream instability developes rapidly.

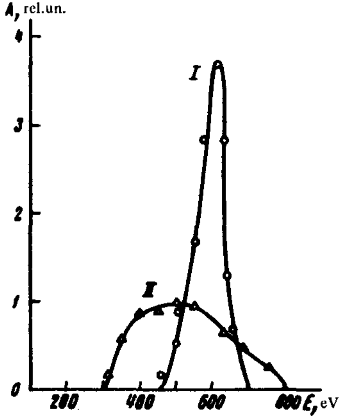

FIG. 4.

Figure 4 shows the beam-particle energy distribution function measured at the end of the system. We see that the characteristic spreading of the distribution function, which accompanies the development of two-stream instability, appears when the initial amplitude exceeds the threshold value. The conditions here are the same as in Fig. 3. The beam energy is 600 eV. Curve I shows the initial amplitude below the threshold and curve II shows the amplitude above the threshold value.