Electron beam excitation of low frequency oscillations in a plasma by application of external perturbations

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The excitation of oscillations is investigated in a plasma-beam discharge (density 10^{11}–10^{13} electrons/cm^3) located in the magnetic field of a mirror-trap and modulated by the electron beam (energy 30 kV, current 20 A) at the frequency of the lower hybrid resonance. It is shown that slow waves can be effectively excited (by external modulation) in volumes that considerably exceed the beam volume. The excitation of the oscillations is due to nonlinear interaction between high-frequency Langmuir waves and the low-frequency waves.

It has been shown previously[1,2] that the effective heating of the plasma ions by an electron beam is observed under conditions of excitation of oscillations with low velocity from the lower-hybrid resonance region ($\omega^2 \sim \omega_{Hi}\omega_{He}$). One of the methods of excitation of this type of oscillations can be the multi-frequency high-frequency modulation of the beam[3] or amplitude modulation of the high-frequency signal.[2,3] These methods are based on the nonlinear transformation of the energy of the high-frequency waves, excited by the beam, into low-frequency ones.

In the work of Haas and Eisner,[4] and Bhatnagar and Getty,[6] the excitation of oscillations by the electron beam was studied at a frequency of the lower hybrid resonance due to the Cerenkov effect ($\omega \approx \mathbf{k}\cdot\mathbf{V}_b$) and a conclusion drawn on the small effectiveness of the given method for $\omega_{0e} > \omega_{He}$ (ω_{He}, ω_{0e} are the electron-cyclotron and electron-plasma frequencies). It seems to us that in this case the methods of excitation of the low-frequency oscillations, based on the nonlinear transformation of the energy of the high-frequency waves into the low frequency, can be rather effective. One of the possibilities of its accomplishment is the imposition of a low-frequency perturbation on the beam, keeping the optimal conditions for excitation of the high-frequency oscillations. As shown in[6], the periodic change in the density of the plasma beam at a low frequency leads to a change in the increment of growth of the high-frequency Langmuir oscillations with the period of these fluctuations, which generates self-modulation of the wave. If the group velocity of the high-frequency wave is identical with the phase velocity of the low-frequency wave, then these waves turn out to be coupled, as a result of which there is a possibility of the amplification of the low-frequency oscillations at the expense of the energy of the high-frequency waves. This process is similar to a decay instability.[7] Qualitative relations between the amplitudes of the low-frequency and high-frequency waves in the given situation were obtained by Bakaĭ.[8]

If we assume that the increment γ_k for the high-frequency waves changes slowly, and

$$\gamma_k=\bar{\gamma}_k+\tilde{\gamma}_k,\qquad \tilde{\gamma}=\frac{\partial\gamma_k}{\partial n_b}(n_b-\bar{n}_b)+\frac{\partial\gamma_k}{\partial V_b}(V_b-\bar{V}_b), \tag{1}$$

where $\tilde{\gamma}$ is the variable part of the increment, and $\bar{n}_b$ $\bar{V}_b$ are the time averages of the density and velocity of the beam, then the amplitude of the high-frequency wave can be represented in the form

$$a_k=a_k(1+\tilde{\gamma}_k/2\bar{\gamma}_k). \tag{2}$$

For $\tilde{\gamma} = g\cos\Omega t$

$$a_k\approx a_k(1+g\cos\Omega t/2\bar{\gamma}_k). \tag{3}$$

In the presence of nonlinear interaction of the high-frequency and low-frequency oscillations, the equation which describes this interaction has the form

$$i\left(\frac{\partial}{\partial t}+\Gamma_\Omega\right)b_\Omega=\sum_k V(\omega_k-\Omega,\omega_k,\Omega)\frac{a_k g}{\gamma_k}\exp(i\Delta_k t), \tag{4}$$

where b_Ω is the amplitude of the low-frequency oscillations with wave vector κ, V is the coupling coefficient between the high-frequency and low-frequency waves, Γ_Ω is the attenuation of the high-frequency oscillations, $\Delta_k = \omega(k+\kappa) - \omega(k)$. Equation (4) for the amplitude of the high-frequency wave gives the relation

$$b_\Omega=g\sum_k\frac{V(\omega_k-\Omega,\omega_k,\Omega)\,|a_k^2|}{(i\Gamma_\Omega+\Delta_k)\gamma_k}. \tag{5}$$

If we assume that V remains unchanged then, denoting the percentage modulation by δ, the relation (5) can be written in the form

$$b_\Omega\sim\delta Va^2, \tag{6}$$

i.e., the amplitude of the low-frequency wave is directly proportional to the coupling coefficient V, the percentage modulation δ and the square of the amplitude of the high-frequency oscillations.

We made an attempt to verify experimentally the effectiveness of such a method of excitation of the oscillations at the frequency of the lower hybrid resonance. The experiment was carried out on the apparatus previously described.[9] The basic parameters of the apparatus are: a beam energy up to 30 kV, current up to 20 A, density of the hydrogen plasma $10^{11}-10^{13}$ electrons/cm^3, magnetic field of the mirror trap with mirror ratio $H_{max}/H_{min} \sim 3$ and intensity at the trap center 0.3–1.5 kOe. The modulation of the electron beam was accomplished with the help of a network at a frequency of 45 MHz. The modulation frequency was chosen from the condition of satisfaction of the lower-hybrid resonance for a magnetic field at the center of the trap. The oscillations excited in the plasma were started by electrical and magnetic probes. The phase velocity of the oscillations in the plasma were determined with the aid of movable magnetic probes, connected in a balanced cable bridge for the comparison of the phase of the oscillations.

The investigations have shown that, under the condi-

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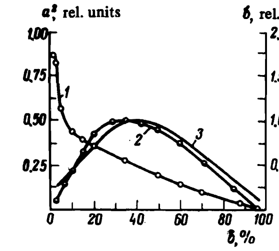

FIG. 1

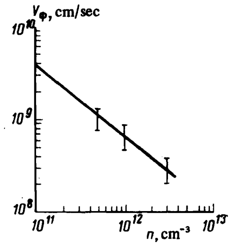

FIG. 2

FIG. 1. Dependence of the amplitude of high-frequency and low-frequency oscillations on the preliminary modulation of the beam: 1—high frequency oscillations; 2—low-frequency oscillations; 3—low-frequency oscillations—computed curve.

FIG. 2. Values of the phase velocity of the wave in the direction of motion of the beam for change in the plasma density.

tions of intense excitation of the high-frequency oscillations ($\omega < \omega_{He} < \omega_{0e}$) in the case of superposition of an external low-frequency modulation on the electron beam, a strong dependence of the amplitude of the low-frequency oscillations at the modulation frequency on the amplitude of the high-frequency oscillations appears ($\omega \lesssim \omega_{He}$, $\omega \sim 0.5$–7 GHz). Figure 1 shows the dependence of the amplitude of the high-frequency oscillations (1—10 GHz, curve 1) and the low-frequency oscillation at a frequency of 45 MHz (curve 2) on the preliminary depth of modulation of the beam. The number 3 indicates a curve obtained for b_{Ω} on the basis of Eq. (6) according to the experimental values of δ, a^2 under the assumption that V is a constant. Curves 1 and 2 of Fig. 1 were obtained for a beam power of 200 kW ($E_b = 25$ keV, $I_b = 8$ A). Curves 2 and 3 (as can be seen) are very close, i.e., the experimental dependences fit well within the framework of theoretical representations on the tight coupling of the low-frequency and high-frequency oscillations.

Figure 2 indicates the values of the phase velocity of the wave along the direction of motion of the beam for a change in the plasma density in the trap region. It is seen that the phase velocity of the excited wave at a frequency of the external perturbation is two orders smaller than the beam velocity. In the region of lower-hybrid resonance the relation

$$k_z > 2\omega_{0i}^2/c^2 - k_\perp^2. \tag{7}$$

is satisfied, in accord with the theory of plasma waves.[10,11] Experimental investigations show that this relation is satisfied in the presence of modulation with a frequency $\omega^2 \sim \omega_{Hi}\omega_{He}$.

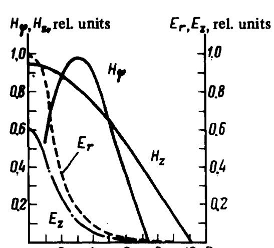

FIG. 3

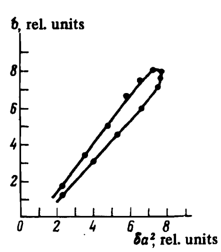

FIG. 4

FIG. 3. Distribution over the plasma radius of the amplitudes of the field components of the excited wave.

FIG. 4. Dependence of the amplitude of the excited wave on the modulation of the beam for fixed beam power.

Both magnetic and electric components of the field of the wave were recorded in the experiment. Also, the spatial region of localization of the wave exceeded many times (by an order of magnitude) the region occupied by the beam. Figure 3 shows the distribution along the plasma radius of the amplitudes of the wave field components at a frequency of 45 MHz. Estimate of the field components E_φ and E_r from probe measurements showed that their values reach 200—500 V/cm for beam power up to 200 kW.

By knowing the field components of the excited oscillations, we can estimate their power. The simplest expression for the power of the oscillations in the cross section of the plasma column is obtained in terms of the magnetic components of the wave field.[12] Under the assumption that the wave field is concentrated in the volume of the plasma,

$$P = \frac{c}{2}\frac{k_\perp}{k_\parallel k}\frac{R}{\varepsilon_\parallel}H_\varphi^2, \tag{8}$$

R is the radius of the plasma column, H_φ the azimuthal component of the magnetic component of the wave field, $\epsilon_\parallel$ the longitudinal component of the dielectric constant.

Estimates of the power, obtained by this formula, show that from 10—30% of the beam energy is transformed into low-frequency oscillations under optimal conditions, i.e., the effectiveness of the excitation of the oscillations is rather high. It is necessary to note that such a coefficient of transformation of the energy was predicted by Onishchenko et al.,[13] who considered the decay of the high-frequency waves with excitation of the low-frequency ones in the beam-plasma system.

Thus, the investigations that were carried out of the excitation of low-frequency oscillations in a plasma by an electron beam upon the imposition on it of external perturbations confirmed the basic conclusions of the theory, while they also showed that there is a number of phenomena in this method of excitation which can be explained only by a further broadening both of the theoretical and the experimental investigations.

Under the assumption that the type of the waves does not change during the course of experiment, i.e., the value of the coupling coefficient for the waves remains constant, there should correspond a single value of the amplitude of the low-frequency oscillations to each value δa^2, in accord with (6). However, as we see from curves 2, 3 of Fig. 1 and the curve of Fig. 4, which is constructed according to curve 2, in the experiment, two values of the amplitude of the low-frequency oscillations correspond to a single value of δa^2. With increase in the percentage modulation, the amplitude of the low-frequency oscillations decreases. At high beam powers (above 200 kW), the linear dependence of the amplitude of the low-frequency oscillations on the percentage modulation is preserved only for small δ. Thus, for a beam power of 500 kW, it is preserved for δ in the range from 3 to 5%. Along with this, an increase is observed in the power of the low-frequency oscillations with increase in the beam power. On the other hand, a significant broadening is observed in the spectrum of low frequencies with increase in the modulation of the beam and the amplitude of the low-frequency oscillations, (see Fig. 5). For $\delta = 80\%$, $\Delta f/f$ reaches a value of 0.34.

It should be noted here that the theoretical considera-

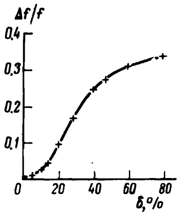

FIG. 5. Dependence of the width of the spectrum of excited oscillations on the modulation of the beam.

tion which we have given is limited to the small amplitude wave, when the reaction of the amplified wave on the distribution function of the beam is not taken into account. It is not excluded that the coefficient V also changes during the course of the experiment. Moreover, the modulation frequency in the experiment is of the order of the increment of growth of the high-frequency waves. A consequence of this fact can be a decrease in the high-frequency amplitude, and therefore in the low-frequency oscillations. A similar effect of the low-frequency on the high-frequency oscillation was observed in[14]. It is not excluded that the broadening of the low-frequency perturbation spectrum during the course of growth of the amplitude (Fig. 5) is connected with the effect of capture of the particles by the field of the excited wave.[15]

We can now draw the following conclusions on the basis of the experiments that have been carried out.

1. With the application of external low-frequency perturbations on the electron beam under conditions of excitation by it of intense high-frequency oscillations, amplification of the low-frequency perturbations is possible. The mechanism of amplification is based on the nonlinear interaction of the low-frequency and high-frequency waves. For a complete description of the given interaction, additional experimental investigations are necessary, including the measurement of the coupling coefficients.

2. The effectiveness of the considered method of excitation of oscillation can be rather high and, as our investigations show, can be used successfully for the excitation of oscillations at the frequency of the lower hybrid resonance and for heating of the high-density plasma in large volumes.[16] It can be expected that the amplification of the low-frequency oscillations, excited by the beam, will be much greater than the frequency of the modulating low-frequency oscillations.[17]

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