Suppression of a high-frequency instability of an ion beam in a plasma by a low-intensity electron beam

Yu. P. Bliokh, I. N. Onishchenko, I. A. Soloshenko, A. F. Tarasenko, and Ya. B. Faĭnberg

Institute of Physics, Academy of Sciences of the Ukrainian SSR
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The possibility of suppressing a high-frequency instability of a monoenergetic ion beam in a plasma by directing a "hot" electron beam of low intensity approximately parallel to the ion beam has been studied. It is shown theoretically and experimentally that at sufficiently high "temperatures" of the plasma and beam electrons an instability of the ion beam can be suppressed without driving a kinetic instability of the electron beam. If the electron temperature is not very high, and the suppression of the instability of the ion beam is accompanied by a driving of the kinetic instability of the electron beam, the latter instability cannot substantially affect the transport of the ion beam because of the low amplitudes of the waves which are excited and because of the short relaxation lengths of the electron beam. A hot electron beam directed approximately parallel to an ion beam can thus be an effective tool for suppressing a high-frequency instability of an ion beam.

During the transport of intense ion beams, their space charge must be neutralized by charges of the opposite sign; i.e., an intense beam must be an ion-beam plasma.[1] However, the production of a neutralizing component in the path of a beam itself causes instabilities, which have a progressively greater effect on the beam transport as the beam density n_+ increases. At $n_+ \sim 10^7$–10^8 cm^{-3} the excitation of oscillations has comparatively subtle consequences: an additional deneutralization of the space charge[2] and an increase in the effective phase volume.[3] At $n_+ \sim 10^{11}$–10^{12} cm^{-3} the interaction with the ion oscillations of the plasma leads to a significant angular scattering of the ions at a distance as short as[4] $l \sim 10$ cm, and at $n_+ \sim 10^{13}$ cm^{-3} one observes not only a scattering but also a pronounced retardation of the ions at such distances.[5]

Many problems, in particular, the achievement of ion inertial controlled fusion and the development of intense beams of neutral particles, require the transport of ion beams over significant distances without any substantial decrease in intensity. It thus becomes necessary to seek ways to suppress beam instabilities. It was shown theoretically in Ref. 6 that the introduction of a cold electron beam with a velocity v_{0e} equal to the ion beam velocity v_{0i} in the plasma can in fact lead to a cutoff of a high-frequency instability even at comparatively low electron currents. The reason for the stabilization is that at electron beam densities $n_{be} > (m/M)n_+$ (M is the mass of the beam ion) the difference (Δv) which arises between the beam velocity and the phase velocity ($v_{ph} = \omega/k$) of the excited wave is determined by the electron density and is significantly larger than the corresponding difference for the beam ions. There is accordingly no resonant interaction between the wave and the ion beam, and the maximum wave amplitude is determined by the condition for a trapping of the low-energy electron beam by the field of this wave. This amplitude may be several orders of magnitude lower than in the onset of an instability in a purely ion beam. It should be noted, however, that the production of low-energy electron beams with a small energy spread in an ion-beam plasma presents significant difficulties, in particular, because of the rather strong static fields.[1] It thus becomes necessary to examine the corresponding problem with a "hot" electron beam.

It turns out that in this case the instability can be suppressed even in the linear stage of the interaction. Let us examine this interaction, taking into account the circumstances that (first) ion beams frequently are quite monoenergetic and can be described by hydrodynamic equations and (second) their directed velocity is comparable to the thermal velocity of the plasma electrons, even at an energy $eU_0 \approx 100$ keV, so that the electrons must be treated by the kinetic approach. We accordingly write the dispersion relation in the form

$$1+\frac{1}{k^2d_e^2}\left[1+i\sqrt{\pi}\frac{\omega}{kv_e}W\left(\frac{\omega}{kv_e}\right)\right]+\frac{1}{k^2d_b^2}\left[1+i\sqrt{\pi}\frac{\omega-kv_{0e}}{kv_b}W\left(\frac{\omega-kv_{0e}}{kv_b}\right)\right]-\frac{\omega_{bi}^2}{(\omega-kv_{0i})^2}=0, \tag{1}$$

where d_e and d_b are the Debye lengths, v_e and v_b are the velocity spreads of the plasma electrons and of the beam electrons, ω_{bi} is the plasma frequency of the beam ions, and $W(x)$ is the plasma dispersion function.

Before we look at the results of the solution of this equation, let us qualitatively analyze the stabilizing effects which an electron beam could exert. The most obvious effect is the Landau damping of the beam by electrons, which occurs at $v_{0e} < v_{0i}$, where the phase velocity of the waves excited by the ion beam falls in a region of a negative derivative of the distribution function of the beam electrons. The second stabilizing effect is most important at $v_{0e} \approx v_{0i}$ and occurs because the waves excited by the ion beam are slow as far as the hot electrons of the beam are concerned, so that the beam electrons have time to reach a Boltzmann distribution in the field of the wave, compensating for the alternating space

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charge which results from the instability. At comparatively low densities of the beam electrons, this effect should result in an increase in the group velocity and a decrease in the growth rates, while at $1/k^2 d_b^2 \sim 1$ the electrodynamic properties of the system are altered to the extent that the synchronization of the ion beam with the wave may be disrupted, so that the instability may be completely suppressed. Finally, the injection of an electron beam should lead to not only a suppression of the instability of the ion beam but also the onset of a kinetic instability. However, because of the strong Landau damping by the plasma electrons, this instability should occur only after a threshold is reached: The resultant velocity distribution of the electrons must have a region with a positive derivative. Consequently, as we will show below, it is possible to arrange conditions such that the density (n_{be}) of the electron beam is sufficiently high to suppress the instability of the ion beam but not high enough to drive the kinetic instability.

Furthermore, even if the conditions for complete suppression of the instabilities turn out to be difficult to arrange in practice, it should be kept in mind that the kinetic instability may not prove dangerous for the ion beam, for two reasons. First, the phase velocity of the waves in this case can be kept well below v_{0i}; i.e., the interaction will not be a resonant interaction. Second, the amplitude of the waves in the nonlinear stage of the interaction must be substantially lower than in the case of a purely ion beam. In the latter case, the maximum depth of the potential well in the wave, determined by the trapping of plasma electrons by the wave field is[7]

$$e\tilde{\varphi}^{i}_{max} \sim m v_{0i}^2/2. \tag{2}$$

At the same time, in the interaction with a plasma of a hot electron beam which is not dense the circumstance that only a comparatively small fraction of the beam particles participates in wave excitation means that the analogous quantity, described by[8]

$$e\tilde{\varphi}^{e}_{max} \approx 10\left(\frac{\pi}{8}\right)^{1/2} \frac{m\omega_{pe}^2}{k^2}\frac{1}{(kd_e)^6}\exp\left(-\frac{1}{k^2 d_e^2}-3\right), \tag{3}$$

turns out to be significantly lower than the beam energy, i.e., actually significantly lower than $e\tilde{\varphi}^{i}_{\max}$.

The results of a numerical solution of Eq. (1), shown in Figs. 1 and 2, confirm these arguments about the nature of the linear interaction. In all calculations the value $\omega_{bi}^2/\omega_{pe}^2 = 4.55\times 10^{-5}$ was assumed (ω_{pe} is the plasma frequency of the plasma electrons); this value corresponds to the conditions in all the experiments described below. Figure 1 shows (a) the spatial growth rate optimized with respect to ω and (b) the frequency of the most unstable waves as functions of the ratio d_e^2/d_b^2, which is proportional to n_{be}. It was assumed in these calculations that the equality $v_{0e} = v_{0i}$ holds, so that the Landau damping by the beam electrons should not have a stabilizing effect. It can be seen from these figures that at $n_{be} = 0$ the ion beam must excite waves with a frequency slightly above ω_{pe}, while the phase velocity will be slightly below v_{0i}; the relative difference $(v_{0i} - \omega/k)/v_{0i}$ will not exceed 1%. When an electron beam is introduced, the growth rate and frequency of the waves decrease, initially slowly and eventually sharply, reaching zero at some critical value of d_e^2/d_b^2. It can be seen from this figure that the critical value $(d_e^2/d_b^2)_{\rm cr1}$ does not depend on v_{0i}/v_b, but it decreases with increasing v_{0i}/v_e according to calculations for various values of $v_{0i}/v_e \gg 1$ we have

$$\left(\frac{d_e^2}{d_b^2}\right)_{\rm cr\,1} \approx \frac{1}{2}\frac{v_e^2}{v_{0i}^2}\left(1+\frac{3}{2}\frac{v_{0i}^2}{v_e^2}\right). \tag{4}$$

The wave phase velocity monotonically approaches v_{0i} with increasing growth rate.

In addition to suppressing the instability of the ion beam, the introduction of an electron beam drives a kinetic instability at lower phase velocities. As expected, there is a threshold for the onset of this instability; $(d_e^2/d_b^2)_{\rm cr2}$ decreases with increasing v_{0i}/v_b and v_{0i}/v_e. Above the threshold, the growth rates rises sharply, rapidly reaching values well above the growth rate of the waves excited by the ion beam.

As can be seen from Fig. 1a, at $v_{0i}/v_b > 4$ the zones in which waves are excited by the ion and electron beams over-

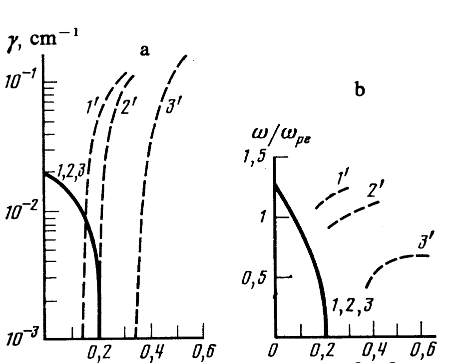

FIG. 1. a: Maximum spatial growth rates of the waves excited by the ion beam (1, 2, 3) and by the electron beam (1′, 2′, 3′). b: Frequency of the most unstable waves. For both parts of the figure, the quantity plotted along the abscissa is the density of the electron beam. 1—$v_{0i}/v_b = 7$; 2—$v_{0i}/v_b = 4$; 3—$v_{0i}/v_b = 2$. $v_{0i}/v_e = 2$, $v_{0e} = v_{0i}$.

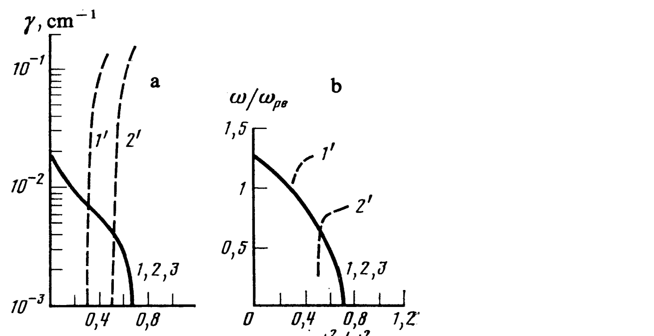

FIG. 2. a: Maximum spatial growth rate of the waves excited by the ion beam (1, 2, 3) and by the electron beam (1′, 2′, 3′). b: Frequency of the most unstable waves. For both parts of the figure, the quantity plotted along the abscissa is the density of the electron beam. 1—$v_{0i}/v_b = 7$, $v_{0e}/v_{0i} = 0.9$; 2—$v_{0i}/v_b = 4$, $v_{0e}/v_{0i} = 0.825$; 3—$v_{0i}/v_b = 2$, $v_{0e}/v_{0i} = 0.6$. $v_{0i}/v_{0e} = 2$. (The kinetic instability does not occur at $v_{0i}/v_b = 2$ over the range of d_e^2/d_b^2 studied).

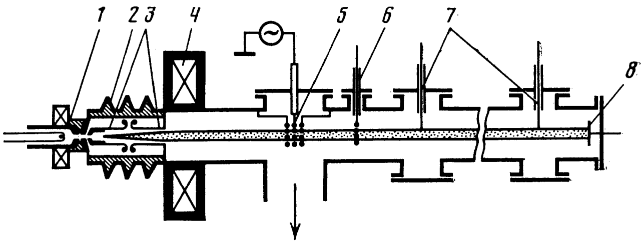

FIG. 3. The experimental apparatus. 1—Ion source; 2—extractor; 3—electrodes of the additional acceleration gap; 4—magnetic lens; 5—three-grid modulator; 6—electron emitter; 7—probes; 8—collector.

lap, while $v_{0i}/v_b < 4$ a stability zone appears between these two excitation zones. The width of the stability zone increases with decreasing v_{0i}/v_b and v_{0i}/v_e.

Let us compare the results described above with the results of calculations for the case $v_{0e} < v_{0i}$ (Fig. 2), in which Landau damping by beam electrons is important. In these calculations, the ratio v_{0e}/v_{0i} was chosen for each value of v_{0i}/v_b in such a way that the phase velocities of the waves excited by the ion beam fell near the maximum of the negative derivative on the velocity distribution of the beam electrons. It can be seen from a comparison of Figs. 1 and 2 that the Landau damping has the consequence that at small values of d_e^2/d_b^2 the decrease in the growth rate with increasing d_e^2/d_b^2 occurs more rapidly than at $v_{0e} = v_{0i}$, but the values of $(d_e^2/d_b^2)_{\rm cr1}$ are significantly higher than at $v_{0e} = v_{0i}$ because of the weakening of the neutralizing effect of the beam electrons. Furthermore, the instability zones in this case cease to overlap at smaller values of v_{0i}/v_e. It would thus be totally appropriate to work under conditions with $v_{0e} = v_{0i}$.

EXPERIMENTAL APPARATUS

Figure 3 is a schematic diagram of the experimental apparatus. A beam of helium ions with a current $I_+ = 10$ mA and an energy $eU_0 = 110$ keV is extracted from a duoplasmatron source 1 by extractor 2, accelerated further in gap 3, focused by magnetic lens 4, and sent through a chamber $L = 200$ cm long and 25 cm in diameter to collector 8. In most of the experiments the beam density is $(3–4)\cdot 10^7$ cm^{-3}. The plasma is produced through the ionization of air by the ion beam. The experiments are carried out at pressures $P = (2–3)\cdot 10^{-4}$ Torr. the corresponding density of the plasma electrons is three or four times n_+.

The electron beam is injected into the ion beam from emitter 6, which consists of several tungsten filaments heated to an emission temperature. The emitter and the chamber are grounded. The electrons are accelerated in the space-charge layer near the filaments to the energy determined by the plasma potential V_p. The potential V_p is measured by an emitting probe which can be moved in the radial direction; it is adjusted by adjusting the collector potential. Since $V_p \approx V_c$, the directed velocity of the electron beam at $V_c = 17$ V is approximately equal to the directed velocity of the ion beam. The electron emission current $I_{\rm em}$ is adjusted by adjusting the current heating the emitter filaments. Several factors can cause a spread in the longitudinal velocities of the beam electrons: 1) the emitter temperature; 2) radial static fields; 3) curvature of the equipotential surfaces near the emitter filaments; 4) a potential drop (ΔU) across the filaments because the filaments are heated by an electric current. Since ΔU is a few volts, the emitter temperature is ~ 0.25 eV, and the radial potential drop in the beam is no greater than -1 V, the fourth of these factors presumably plays a governing role. The value of ΔU can be adjusted by changing the length and diameter of the emitter filaments.

EXPERIMENTAL RESULTS AND DISCUSSION

In accordance with the theory, the ion beam in the absence of an electron beam excites waves which grow exponentially along the beam axis and which have a frequency close to the electron plasma frequency.[9] Under the conditions of these experiments, the spatial growth rate agrees with the calculated value if $v_{0i}/v_e = 2$ (Ref. 9). The introduction of an electron beam results in a decrease in the amplitude of the waves excited by the ion beam in all cases, and at sufficiently high values of $I_{\rm em}$ it leads to a complete suppression of the instability. Simultaneously, in certain cases a kinetic instability occurs in the system beginning at certain values of $I_{\rm em}$, which depend on ΔU. The processes are demonstrated most clearly in Fig. 4, which shows the wave spectra for various emission currents and for a comparatively small potential drop (ΔU) across the emitter filaments. The spectra at the left were measured at a distance $z = 165$ cm from the emitter; the spectra at the right were measured at $z = 25$ cm. All of the frames have, in addition to the peaks at the right, which correspond to the electron plasma waves under consideration here, a peak at lower frequencies, which is caused by a modulation of the ion beam due to an instability of the discharge plasma in the ion source. This low-frequency peak has no bearing on the processes of interest here, and we will not mention it further.

It can be seen from Fig. 4 that with $I_{\rm em} = 0$ the ion beam

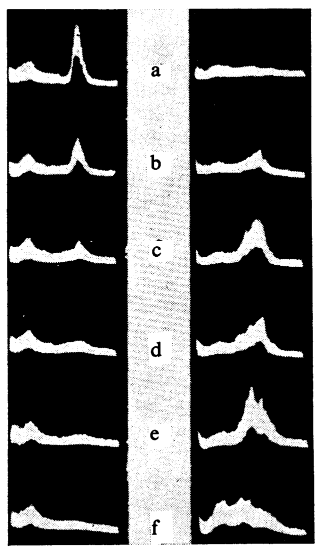

FIG. 4. Wave spectra. $\Delta U = 5$ V, $P = 3\cdot 10^{-4}$ Torr. The frequencies at the left and right edges are 10 and 110 MHz. Frames at left: $z = 165$ cm. Right: $z = 25$ cm. a—$I_{\rm em} = 0$; b—8 mA; c—12 mA; d—16 mA; e—20 mA; f—32 mA.

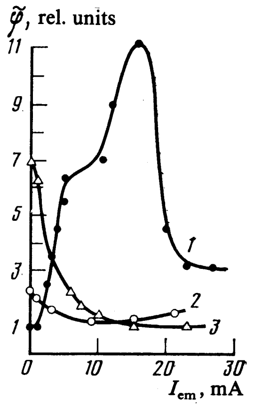

FIG. 5. Amplitude of the potential oscillations versus the electron current from the emitter. $P = 3\cdot10^{-4}$ Torr, $V_c = 17$ V, $\Delta U = 5$ V. The emitter current is a direct current. 1—$z = 25$ cm; 2—$z = 50$ cm; 3—$z = 165$ cm.

excites waves only over a rather large distance: Waves are not excited at $z = 25$ cm. With increasing I_{em}, the amplitude of the waves measured at $z = 165$ cm decreases monotonically to the level of the noise; the waves frequency also decreases slightly. Waves also appear at $z = 25$ cm beginning at $I_{em} = 3$ mA; their amplitude initially increases with increasing I_{em} and then decreases. The spectrum shifts down the frequency scale. The fact that these waves appear after a threshold is reached, their comparatively large growth rate, and the corresponding I_{em} dependence of the wave amplitude demonstrate convincingly that the waves at $z = 25$ cm are excited by the electron beam. In accordance with this conclusion, the frequencies of these waves are typically slightly lower, and their frequency spectrum slightly broader, than in the case of a purely ion beam.

Without going into a detailed comparison of the experimental and calculated results at this point, we would like to point out one important fact which is observed experimentally and cannot be predicted by the theory. It follows that from the spectra given above that, despite the circumstance that waves are excited simultaneously in the system by both of the beams in the interval $3 \text{ mA} \lesssim I_{em} < 10$ mA, their excitation zones are actually separated in space: The ion beam excites waves at a large distance, while the electron beam excites waves only at a small distance. This conclusion is confirmed by Fig. 5, which shows curves of $\tilde{\varphi}(I_{em})$ measured

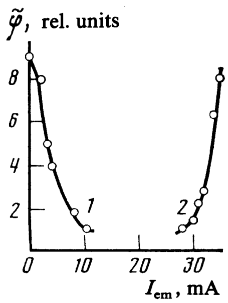

FIG. 6. Amplitude of the potential oscillations versus the electron current from the emitter. $P = 3\cdot10^{-4}$ Torr, $V_c = +17$ V, $\Delta U_{eff} = 7$ V (the emitter is fed an alternating current). 1—$z = 165$ cm; 2—$z = 25$ cm.

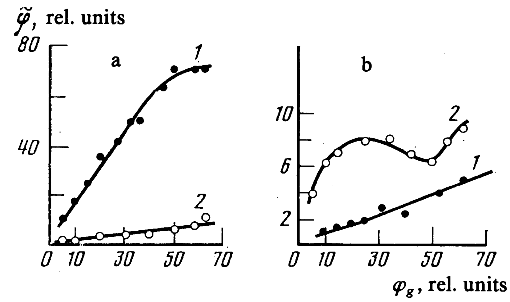

FIG. 7. Amplitude of the potential oscillations versus the oscillator voltage. a) $P = 3\cdot10^{-4}$ Torr, $f = 80$ MHz, $z = 165$ cm, $\Delta U = 5$ V; b) $P = 3\cdot10^{-4}$ Torr, $z = 25$ cm, $\Delta U = 5$ V. 1—$I_{em} = 0$; 2—$I_{em} = 15$ mA.

at three distances along the z axis (the noise level corresponds to $\tilde{\varphi} \approx 1$). The nature of these curves suggests that only at $z = 50$ cm can waves be excited by both the ion and electron beams. Since the amplitudes of the waves of both types are quite low at $z = 50$ cm, it can be assumed that the plane $z = 50$ cm is the approximate boundary between these two spatial excitation zones under these particular experimental conditions. The reasons for this spatial separation are that the distance over which the waves excited by the ion beam grow is quite large, even in the case $I_{em} = 0$, and that the nonlinear-relaxation length for the hot electron beam is quite small. We must emphasize that after the relaxation of the electron beam in our experiments the wave amplitude decreases to the noise level, in contrast with the conclusions of the quasilinear theory of one-dimensional systems[10] and the results of experiments with a low-intensity "hot" electron beam,[11] according to which the final state of the system is characterized by the establishment of a plateau on the electron velocity distribution and by a steady-state wave spectrum. These differences might be caused, in particular, by the nonuniformity of the system studies and by the circumstance that I_{em} is so high that the dispersion of the waves which are excited can vary along the axis of the system as the electron beam relaxes.

By increasing the potential drop across the emitter filaments we can move into a regime in which the excitation of waves by the ion and electron beams occurs not only in different spatial regions but also at different currents of the electron beam. Figure 6 shows some corresponding curves of $\tilde{\varphi}(I_{em})$. A comparison of Figs. 5 and 6 shows that an increase in ΔU does not substantially change the $\tilde{\varphi}(I_{em})$ curve corresponding to the waves excited by the ion beam, but it does cause a substantial increase in the critical current at which the kinetic instability sets in. A further increase in ΔU has the consequence that the electron beam excites waves nowhere in the range of I_{em} which could be studied.

It can thus be asserted that the beam velocity spread is determined primarily by the potential drop across the filaments, and, in accordance with the linear theory, an increase in this spread leads to an increase in $(n_{be})_{cr2}$. Since the electron velocity distribution is not Maxwellian, at least near the emitter, the comparison of experiment with theory can be only qualitative. Nevertheless, we note that the growth rates calculated for the waves excited by the electron beam and the values calculated for $(d_e^2/d_b^2)_{\rm cr2}$ do not differ greatly from the corresponding values found experimentally. In the latter case, $(d_e^2/d_b^2)_{\rm cr2}$ was found from the experimental values of $(n_{be})_{\rm cr2}$ under the assumption $v_b = (v_{0i}/2)(\Delta U/U_0)(M/m)$. At $\Delta U = 5$ V, corresponding to $v_{0i}/v_b = 7$, the experiments yield $(d_e^2/d_b^2)_{\rm cr2} \approx 0.5$, which is essentially the same as the calculated value (curve 1 in Fig. 1). Under the same conditions, and in a similar way, we found $(d_e^2/d_b^2)_{\rm cr1} = 0.5$, which is ~ 2.5 times higher than the calculated value of this quantity (curve 1 in Fig. 1). A reason for this difference may be that the distance over which waves are excited by the ion beam is large, so that this beam actually interacts with the plasma electrons in the presence of an electron beam which has already relaxed. The velocity spread of this beam may be much larger than that near the emitter, so that the actual value of $(d_e^2/d_b^2)_{\rm cr1}$ is much smaller than 0.5. In the same way we might explain the fact that, regardless of ΔU, the instability of the ion beam is suppressed at a fixed value of $I_{\rm em}$, while the theory predicts that the suppression should occur at a fixed value of d_e^2/d_b^2. As for the numerical values of the growth rate of the kinetic instability, we note that the experimental values of γ near the threshold vary over the interval $(0.4–1.5)\cdot 10^{-1}$ cm^{-1}, again in agreement with the calculation (curves 1, 2, and 3 in Fig. 1).

In summarizing the results of the experiments with an unmodulated beam we should say that the results demonstrate, in agreement with the conclusions of the linear theory, that a sufficiently hot electron beam can suppress an instability of the ion beam without simultaneously driving an instability of the electron beam. The results also show that at small values of v_b, at which waves can be excited simultaneously in the system by the two beams, the region in which the waves excited by the electron beam are localized is extremely small, so that the effect of these nonresonant waves on the ion beam may be insignificant, provided, of course, that their amplitude is not very large.

We also carried out some experiments with a modulated beam, in order to determine the maximum possible wave amplitudes in this system. At comparatively low modulation amplitudes the characteristic curves have the same shape as for the case of an unmodulated beam. At high oscillator voltages V_g, nonlinear effects come into play and limit the wave amplitudes. Figure 7a shows curves of $\tilde{\varphi}(V_g)$ measured at $z = 165$ cm in the absence of electron emission (curve 1) and at a high emission current (curve 2). It can be seen from this figure that at $I_{\rm em} = 0$ the wave potential initially increases linearly with the oscillator voltage, and later saturation sets in. The reason for this saturation is the nonlinear trapping of the plasma electrons by the wave field, mentioned earlier [see Eq. (2)].

During the introduction of electrons from the emitter the behavior remains linear over the entire range of V_g, while $\tilde{\varphi}$ is about an order of magnitude lower than in the first case. To determine the maximum amplitude of the waves excited by the electron beam, we measured the corresponding curves at $z = 25$ cm (Fig. 7b). In contrast with the preceding case, the curves of $\tilde{\varphi}(V_g)$ in this case are seen to be linear at $I_{\rm em} = 0$ (curve 1). In the presence of the electron beam, the curve of $\tilde{\varphi}(V_g)$ (curve 2) has the usual nonmonotonic behavior for systems of this type, because of the trapping of resonant electrons by the field of the excited waves.[8] It follows from a comparison of Figs. 7a and 7b that the experimental value of $\tilde{\varphi}^{e}_{\max}$ is about an order of magnitude lower than $\tilde{\varphi}^{i}_{\max}$, in agreement with expression (3).

These results show convincingly that the kinetic instability poses no danger to the ion beam in this system. We can assert that a hot electron beam with a velocity close to that of the ion beam can be an effective tool for suppressing a high-frequency instability of the ion beam.

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