Suppression of low-frequency instability of a fast ion beam exciting a high-frequency wave in a plasma

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Nonlinear interaction of ion and electron oscillations excited in a plasma by a fast ion beam are investigated theoretically and experimentally. It is shown that the low-frequency instability is suppressed when the electron oscillation intensity is sufficiently high.

1. Nonlinear interactions between high-frequency (rf) and low-frequency (lf) oscillation modes, including strong turbulence effects due to modulational instability, were extensively investigated in electron-beam-driven plasma systems not only theoretically but also experimentally (see, e.g., Refs. 1–7). To illustrate the importance of these nonlinear processes in the relaxation of electron beams we note, for example, that transfer of the energy of unstable Langmuir oscillations to the short-wave region of the spectrum via two-stream instability can increase appreciably, on the one hand, the beam relaxation length[2] and ensure, on the other hand, efficient heating of the plasma.[3,6]

We report here the first theoretical and experimental investigations of the effects of strong linear interactions of plasma electron and ion oscillations excited by a fast ion beam. Suppression of the lf ion-beam instability is observed at high rf oscillation excitation levels. This effect can be used to improve the transport conditions for fast ion beams, since ion oscillations play the dominant role in the radial spread of such beams.

2. We dwell first briefly on the nonlinear properties of lf and rf oscillations of an ion-beam plasma. As shown in Ref. 8, at low frequencies the dispersion equation takes the form

$$1+\frac{1}{q^2d_e^2}-\frac{\omega_{pi}^2}{\Omega^2}\left(1-i\frac{\omega_{pi}}{\Omega}\frac{2}{\omega_{pi}\tau}\right)-\frac{\omega_{pb}^2}{(\Omega-q_\parallel v_0)^2}=0, \qquad (1)$$

where Ω and q are the frequency and wave number of the lf wave, ω_{pi} and ω_{pb} are respectively the Langmuir frequencies of the plasma ions and of the beam, and d_e is the Debye radius of the plasma electrons. In the terms that describe the plasma ions, the second term in the parentheses takes into account the finite ion lifetime τ due to their radial collisionless escape from the system.[8]

Bearing in mind experimental applications, we consider the spatial instability of the oscillations. In our case the beam velocity satisfies $v_0 \gtrsim v_e$ (v_e is the electron thermal velocity), so that the lf oscillations are almost transverse, $q_\perp \gg q_\parallel \sim \Omega/v_0$ ($q_\parallel$ and $q_\perp$ are the wave-vector components along and across the beam-propagation direction). Introducing the quantity $\varkappa = q_\parallel - \Omega/v_0$, we obtain from (1)

$$\varkappa^2 v_0^2/\omega_{pb}^2=(a+ib)^{-1}, \qquad (2)$$

where

$$a=1+\frac{1}{q_\perp^2 d_e^2}-\frac{\omega_{pi}^2}{\Omega^2},\qquad b=\left(\frac{\omega_{pi}}{\Omega}\right)^3\frac{2}{\omega_{pi}\tau}. \qquad (3)$$

At fixed Ω, the maximum growth rate is reached at a certain optimal $q_\perp$. If the equation $x^3-x+(2/3^{1/2}\omega_{pi}\tau)=0$ has real positive roots $x_{1,2}$ (this calls for $\omega_{pi}\tau>3$, which is indeed the case under experimental conditions), in the range $x_1<(\Omega/\omega_{pi})<x_2$ ion-acoustic oscillations attain the maximum growth rate

$$\gamma_m=(\omega_{pb}/v_0)(3\cdot 3^{1/2}\omega_{pi}\tau/16)(\Omega/\omega_{pi})^{7/2}$$

when the transverse wave number satisfies

$$q_\perp^2 d_e^2=[(\omega_{pi}/\Omega)^2(1-2/3^{1/2}\Omega\tau)-1]^{-1}.$$

If $(\Omega/\omega_{pi})>x_2$, the growth rate continues to increase with increase of Ω all the way to $\Omega\approx\omega_{pi}$, where it reaches an absolute maximum

$$\gamma_{am}\approx(\omega_{pb}/v_0)(\omega_{pi}\tau/2)^{1/2},$$

while the unstable oscillations are short-wave ion plasma oscillations with $q_\perp^2 d_e^2 \gg 1$. With further increase of Ω the growth rate decreases rapidly, and in the region $(\Omega/\omega_{pi})<x_1$ it drops monotonically to zero as $\Omega\to 0$.

Note that these results are valid if the ion lifetimes are not too long: $\omega_{pi}\tau \ll v_0\omega_{pe}/v_e\omega_{pb}$. Otherwise a finite growth rate as $\tau\to\infty$ is ensured by taking into account $q_\parallel$ in the denominator of the second term of Eq. (1). For the experimental situation described below, however, the above equations suffice, since $\omega_{pi}\tau\sim 10$ holds and the indicated inequality, the right-hand side of which is greater than $2\cdot 10^2$, is indeed valid.

Excitation of rf oscillations by an ion beam is described by the dispersion equation[9]

$$1+\delta\varepsilon_e-\omega_{pb}^2/(\omega-k_\parallel v_0)^2=0,$$

where $k_\parallel$ is the longitudinal wave number of an rf wave of frequency ω, and the electron term $\delta\varepsilon_e$ takes the standard kinetic form. Far from resonance (the rf oscillations were excited in the experiments at a frequency $\omega\approx\omega_{pe}/2$), the spatial growth rate is

$$\Gamma=\frac{\omega_{pb}}{v_0}\left[\frac{(\alpha^2+\beta^2)^{1/2}-\alpha}{2(\alpha^2+\beta^2)}\right]^{1/2}, \qquad (4)$$

where

$$\alpha=1+\frac{1}{Q^2d_e^2}\left(1-2ye^{-y^2}\int_0^y e^{t^2}dt\right),\qquad \beta=\frac{\pi^{1/2}}{Q^2d_e^2}ye^{-y^2}. \qquad (5)$$

$$y=\omega/2^{1/2}Qv_e,\qquad Q=[(\omega/v_0)^2+k_\perp^2]^{1/2},$$

and $k_\perp$ is the transverse wave number. The spatial growth rate increases with decrease of $k_\perp$. Note the longitudinal scales of the waves vary substantially, $k_\parallel\approx\omega/v_0\gg q_\parallel\sim\Omega/v_0$, a fact we shall find important later on.

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3. We examine now nonlinear interaction of the rf and lf oscillations. We consider first the case $\Omega = \omega_{pi}$, when the spatial growth rate is a maximum and $q \gg k$. Wave interaction of this type was considered in weak-turbulence theory within the framework of the mechanism of induced scattering by electrons (see, e.g., Refs. 10 and 11). In interactions between electron and ion plasma waves, however, this mechanism contributes noticeably only to the evolution of the rf oscillations, while the lf oscillation level does not change significantly. In our case, the weak-turbulence approximation is inapplicable (in the experiments $E^2_\omega/4\pi n_{0e} \times T_e \gtrsim 10^{-2}$, where E_ω is the amplitude of the rf-wave electric field). In addition, the beats of the rf and lf oscillations are produced in the region of the natural modes of the system, so that a stronger decay-type interaction mechanism is present.

Indeed, nonlinear interaction of lf and rf waves produces oscillations with beat frequencies $\omega_\pm = \Omega \pm \omega \approx \pm \omega$ and wave vectors $\mathbf{k}^\pm = \mathbf{q} \pm \mathbf{k}$. Since $k^\pm_\parallel \approx \pm k_\parallel$, the beat waves are in resonance with the beam ($\omega_\pm \approx \mathbf{k}^\pm \mathbf{v}_0$) and are consequently close to the natural oscillations of the system. At $\Omega \sim \omega_{pi}$ ($|\mathbf{k}^\pm|d_e \approx qd_e \gg 1$) they are beam space-charge waves, $k^\pm_\parallel \approx (\omega_\pm \pm \omega_{pb})/v_0$. The plasma electrons take practically no part in the ion plasma oscillations, so that the main contribution to the interaction is made by the nonlinearities in the dynamics of the beam ions. Accordingly we describe the electrons by the nonlinear Vlasov equation and the plasma ions by the linearized hydrodynamic equations; the nonlinear terms are taken into account only in the hydrodynamic equations for the beam ions. We close the system of Poisson equations. We represent the beam variables as superpositions of oscillations of fundamental and combined frequency, and assume in the equations for the plasma components that the plasma ions and electrons take part respectively only in the rf or lf oscillations at the fundamental frequencies. Next, excluding the variables that describe the plasma components and the electric field, we introduce dimensionless beam variables:

$$n = \frac{q}{k}\frac{\delta n_b}{n_{0b}}, \quad N = \frac{\delta N}{n_{0b}}, \quad n_\pm = \frac{\delta n_\pm}{n_{0b}},$$

$$g = \frac{kq}{\omega_{pb}}\psi, \quad G = \frac{q^2}{\omega_{pb}}\overline{\Psi}, \quad g_\pm = \frac{q^2}{\omega_{pb}}\psi_\pm, \quad x = \frac{\omega_{pb}}{v_0}z,$$

where δn_b, δN, and $\delta n_\pm$ are the variations of the beam densities at the respective frequencies ω, Ω, and $\omega_\pm$; ψ, $\overline{\Psi}$, and $\psi_\pm$ are the potentials of the beam-velocity perturbations at the same frequencies; z is the distance along the beam-propagation direction. As a result we obtain a set of equations that describes the wave interaction at the fundamental and combined frequencies:

$$\frac{\partial n}{\partial x} - g + \theta(n_+G^* - n_-^*G - N^*g_+ + Ng_-^*) = 0, \quad \frac{\partial g}{\partial x} - An = 0; \tag{6}$$

$$\frac{\partial N}{\partial x} - G + \theta(n_+g^* - n_-g) = 0, \quad \frac{\partial G}{\partial x} - BN + \theta(g^*g_+ - gg_-) = 0; \tag{7}$$

$$\frac{\partial n_\pm}{\partial x} - g_\pm \mp \theta N(\mathrm{Re}\, g \pm i\, \mathrm{Im}\, g) = 0, \tag{8}$$

$$\frac{\partial g_\pm}{\partial x} + D_\pm n_\pm \mp \theta G(\mathrm{Re}\, g \pm i\, \mathrm{Im}\, g) = 0. \tag{9}$$

Here $\theta = \mathbf{kq}/kq$, $A = 1/3$ ($\omega = \omega_{pe}/2$). In the case considered here ($\Omega = \omega_{pi}$) we must put $D_\pm = 1$ in (8) and (9), and use the coefficient $B = 5i$ for $\tau = 10/\omega_{pi}$, in approximate agreement with the experimental value. We emphasize that the system (6)–(9) describes strong coupling of the waves, since two modes participate in the interaction at each of the frequencies. For the fundamental frequencies these are pairs consisting of a growing and a damped wave, and for each of the satellites these are a fast and slow beam space-charge wave.

The system (6)–(9) was solved numerically in a wide range of boundary conditions for $\theta = \frac{1}{2}$. The boundary conditions were set for the quantities

$$g(0) = qv_\omega/\omega_{pb}, \quad G(0) = qv_\Omega/\omega_{pb},$$

where $v_{\omega,\Omega}$ are the amplitudes of the beam-velocity modulation at frequencies ω and Ω on entering the system. The remaining variables are assumed to be zero on the boundary. The calculations were performed for $0.125 \leqslant g(0) \leqslant 2$. $10^{-3} \leqslant G(0) \leqslant 0.5$. A typical solution for $g(0) = 0.5$ and $G(0) = 10^{-2}$ is shown in Fig. 1. It can be seen that starting at $x = x_*$, for which $n(x_*) \gtrsim 1$ or

$$\frac{\theta^2 E_\omega^2}{4\pi n_{0e}T_e} \geqslant \left(\frac{n_{0b}}{n_{0e}}\right)^2 \frac{1}{q^2 d_e^2}\left(\frac{\omega_{pe}^2}{\omega^2} - 1\right)^{-2}, \tag{10}$$

the lf-wave amplitude growth rate decreases substantially compared to the linear rate (trace 1). The satellites increase in space first more rapidly than the lf wave, and at $x = x_*$ their growth rates become equal. More frequent oscillations at all amplitudes are observed at the same time.

The degree of suppression of the lf instability depends on the rf-wave amplitude at the input to the system. Trace 1 of Fig. 2 shows the numerically obtained lf-wave amplitude at a distance $z = 5v_0/\omega_{pb}$ (approximately 150 cm in the experiment) as a function of the amplitude limit of the rf waves. Trace 2 of this figure shows the corresponding dependence of the satellite amplitude.

The characteristic features of this process remain the same throughout the entire region $\Omega \sim \omega_{pi}$ in which $q^2 d_e^2 \gg 1$. We consider now the singularities of wave interaction at $(\Omega/\omega_{pi}) < x_2$, when $q_\perp d_e \lesssim 1$. Since in this we also have $|\mathbf{k}^\pm|d_e \lesssim 1$, the phase velocities of the combined waves, which are close as before to the natural waves of the systems, are comparable with the electron thermal velocity v_e. [The

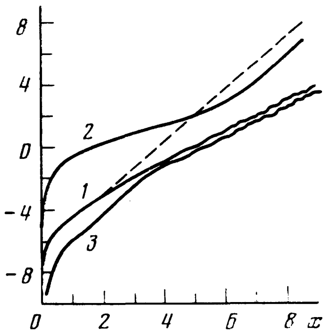

FIG. 1. Beam-density oscillation amplitude at the ion (curve 1), electron (2), and combined (3) frequencies vs the longitudinal coordinate. The dashed curve corresponds to the linear solution [$g(0) = 0.5$, $G(0) = 0.01$].

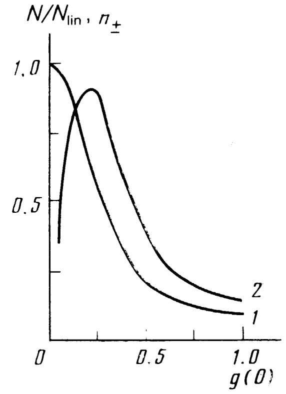

FIG. 2. Oscillation amplitude at the ion (curve 1) and combined (2) frequencies vs the initial pump-wave amplitude [$\Omega = \omega_{pi}$, $G(0) = 0.01$].

satellites become unstable or, more accurately, the slow space-charge wave grows in space, while the fast ones are attenuated. The growth rates of these waves are calculated from Eq. (4) in which α and β are replaced by $\alpha_\pm$ and $\beta_\pm$, with the latter obtained by substituting $\omega_\pm$ and $k^\pm$ in (5) for ω and k.

As Ω decreases the spatial growth rates of the satellites increase, their amplitude increase more rapidly, and the nonlinear action on the lf waves, proportional to these amplitudes, becomes more effective. As Ω decreases, however, $q_\perp$ also decreases, so that the coupling coefficient of the lf and rf waves becomes smaller; in other words, the threshold of the suppression effect (10) increases. An optimal dependence of the degree of suppression of the lf instability on Ω is therefore to be expected. This is confirmed by numerical calculations (Fig. 3) based on the system (6)–(9) with an appropriate change of variables:

$$D_\pm = (\alpha_\pm + i\beta_\pm)^{-1}, \quad B = (a + ib)^{-1}.$$

It should be noted that lf waves of the ion-acoustic type are excited if $\Omega/\omega_{pi} < x_2$ ($q_\perp d_e \lesssim 1$). An important role in such lf oscillations is played by the motion of the electrons, and it must therefore be ascertained that the linear description is applicable to them. Calculations show that nonlinearities become noticeable in electron dynamics if

$$\frac{\theta^2 E_\omega^2}{4\pi n_{0e} T_e} \gtrsim \frac{1}{2}\left(\frac{\omega_{pe}^2}{\omega^2} - 1\right)\left(\frac{\omega}{\omega_{pe}}\right)^4 .$$

Comparing this inequality with (10), we verify that under the experimental conditions ($\omega \approx \omega_{pe}/2$) the electron nonlinearities are important only at low frequencies $\Omega \approx 0.2\omega_{pi}$ ($q_\perp{}^2 d_e{}^2 \approx 0.1$). This region, however, is of little interest, since the growth rate of the lf instability is quite insignificant here ($\gamma_m \approx 0.1\gamma_{am}$).

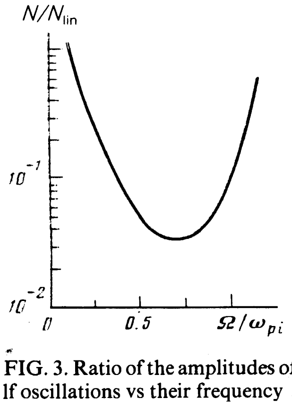

FIG. 3. Ratio of the amplitudes of the nonlinear oscillations and the linear lf oscillations vs their frequency [$G(0) = 0.01$].

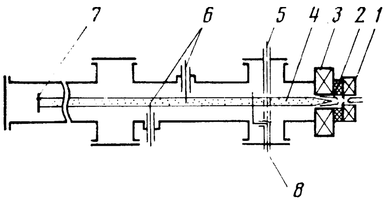

FIG. 4. Diagram of setup: 1—duoplasmatron ion source, 2—extracting electrode, 3—magnetic lens, 4—ion beam, 5—modulator, 6—probes, 7—collector, 8—modulator.

4. The experiments were performed with the setup shown schematically in Fig. 4. A helium-ion beam was extracted from duoplasmatron source 1 by the field of extractor 2, was focused by magnetic lens 3, and passed through a chamber ~500 cm long and ~35 cm in diameter to collector 7. The beam current was 10–20 mA, the energy $eU_0 = 25$ keV, and the ion density $(2\text{–}3)\cdot 10^7$ cm^{-3}. The plasma was produced by ionizing air whose pressure in the principal experiments was $\sim 2\cdot 10^{-4}$ torr, with the plasma density 5–10 times higher than the beam density. The plasma electron temperature T_e was measured with a three-electrode probe–analyzer whose plane was parallel to the ion-velocity direction. With the collector grounded, $T_e \approx 3$ eV, and when the collector potential was raised or when electron oscillations of sufficiently high amplitude were excited, the value of T_e could reach 8 eV. The fluctuations of the potential were investigated with probes 6. The beam velocity was modulated at the electron frequencies by a three-grid modulator 5 connected to an rf oscillator, and at the ion frequency by modulator 8 consisting of two plates connected to a low-frequency oscillator. The plates were placed in the ion beam in such a way that the sinusoidal electric field in the resultant capacitor was perpendicular to the beam-ion velocity; the distance between the plates was of the order of the electron Debye radius (3 mm).

In the absence of modulation, both electron and ion oscillations were spontaneously excited in the system, with amplitudes that increased in space. The linear characteristics of these oscillations were investigated in detail in Refs. 8, 12 and 13. It was shown that at low frequencies ($\Omega \sim \omega_{pi}$) the maximum growth rate is possessed by ion Langmuir oscillations ($q_\perp^2 d_e^2 \gg 1$), the oscillation damping is due mainly to the finite lifetime of the ions in the system, and the dispersion and growth rate agree well with the theory expounded above. Beam modulation excited in the system quasi-plane waves with a wave vector almost perpendicular to the beam. At high frequencies ($\omega \sim \omega_{pe}$), axisymmetric modes are excited with a transverse wave number $k_\perp \sim 2.4/r_b$ ($r_b \approx 2\text{–}3$ cm is the beam radius). Since we have $k_\parallel r_b \gtrsim 5$ under the experimental conditions, the radial confinement of the system did not affect the excitation of the oscillations,[13] and the spatial growth rate in the frequency region $\omega < \omega_{pe}$ agreed well with the hydrodynamic value assumed in the calculations above. Note that in the experiment the rf wave had a cylindrical structure, whereas in the theory it was assumed to be planar. This difference, however, has little effect on the nonlinear interaction, since the transverse dimensions of

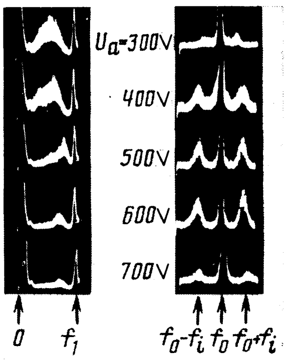

FIG. 5. Spectra of low-frequency (left) and high-frequency (right) oscillations at various modulating voltages ($f_1 = 1$ MHz, $f_0 = 38$ MHz, air pressure $p = 2\cdot 10^{-4}$ torr, $z = 150$ cm).

both the ion wave the satellites are considerably smaller than the rf wave ($q_\perp \gg k_\perp$, $k_\perp^\pm \gg k_\perp$).

To observe the nonlinear interaction of the wave, the beam was modulated at a frequency $\omega \approx \omega_{pe}/2$. The use of modulation permitted a substantial increase of the pump-wave amplitude. The rf effect on the lf instability is most clearly demonstrated in Fig. 5, which shows the spectra of the ion (left) and electron (right) oscillations at different modulation amplitudes U_a. It can be seen that for sufficiently large U_a the high-frequency part of the spectrum contained, besides the signal at the modulation frequency, satellites of frequency $\omega \pm \Omega$. According to the theory above, the amplitudes of the two satellites are equal. Likewise in accord with the calculations, the appearance of satellites is accompanied by a decrease of the lf-oscillation amplitude. The quantitative features of the observed effects are demonstrated in Fig. 6, which shows the rf (curve 3) and lf (curve 2) oscillation amplitudes and the satellite amplitudes (curve 1) as functions of the rf oscillator voltage. The measured dependences are seen to be similar to the analogous ones derived in the theory (cf. Fig. 3). The parameter that characterizes the pump-wave level at which the lf instability is suppressed ranges here from 0.01 to 0.1, which agrees in order of magnitude with condition (10).

For a more detailed comparison with the theory, we investigated the dispersion properties of the satellite waves.

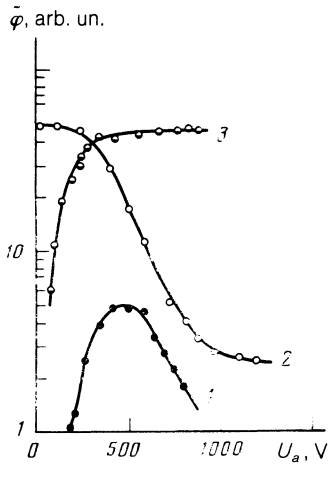

FIG. 6. Amplitudes of potential oscillations at the combined (curve 1) ion (2) and electron (3) frequencies vs the modulation voltage ($p = 2\cdot 10^{-4}$ torr, $z = 150$ cm).

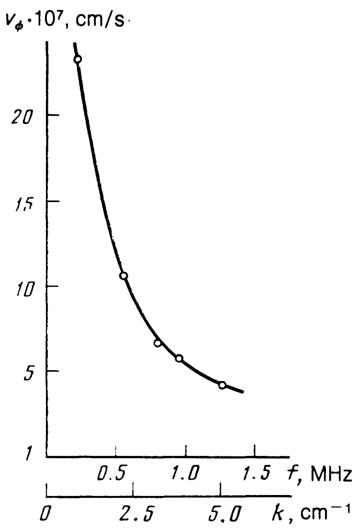

FIG. 7. Satellite-wave transverse phase velocity vs wave number (frequency) of the ion oscillations.

The transverse wavelength was measured by microwave interferometry using two probes, one fixed and the other radially movable. The resulting dependence of the transverse phase velocity v_{ph} of the satellites on the wave number or frequency of the ion oscillations is shown in Fig. 7. As expected, the phase velocities are in the region $v_{ph} \lesssim v_e$ with v_{ph} decreasing with decrease of the ion-oscillating frequency. The extent to which the lf instability is suppressed as a function of the ion-oscillation frequency agrees with the measured dispersion characteristics, hence also with the theory (Fig. 8). As the frequency is lowered, the suppression first increases as a result of the increase of the phase velocity, and hence of the growth rate of the satellite waves. Subsequently, as the interaction of the ion and electron waves weakens, the suppression decreases again. At an electron temperature 3 eV, the stabilization is strongest for oscillation of frequency $f = 0.75$ MHz (curve 1), corresponding to $v_{ph} \approx 7\cdot 10^7$ cm/s $\approx 0.7 v_e$. Raising T_c by applying to the collector a positive potential shifts the resonance towards lower frequencies (curve 2).

To prove that the observed suppression of the lf instability is due to nonlinearities in the beam-particle dynamics, we performed calibration experiments which demonstrated that nonlinearities in the plasma-particle dynamics did not

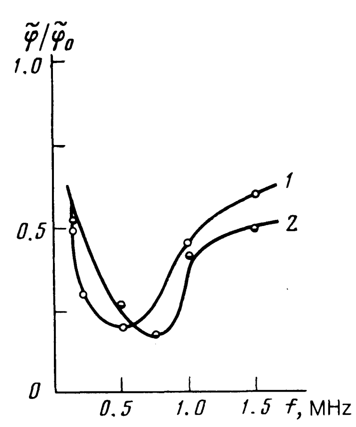

FIG. 8. Ratio of the amplitude of the low-frequency oscillations in the presence and absence of pumping ($p = 2\cdot 10^{-4}$ torr, $z = 150$ cm).

play a decisive role. The experiment consisted of measuring the characteristic damping times of the ion oscillations, using the procedure developed in Ref. 14. A signal from a square-wave generator was applied to a low-frequency modulator. At sufficiently long pulse durations, the perturbations produced by the leading and trailing edges are transported independently of one another and spread in space. Solution of the corresponding problem with the initial and boundary conditions yields the following dependence of the lf-wave potential on position and time[14]:

$$\varphi(t',x)=\frac{\varphi_0}{(6\pi x\xi)^{1/2}}\left(\frac{x}{t'}\right)^{5/6}\exp\left(t'\xi\sin\eta-\frac{\Delta}{2}t'\right)\times\sin\left(t'\xi\cos\eta+\frac{\eta-\pi}{2}\right), \qquad (11)$$

where

$$\xi=\left[1-\left(\frac{x}{t'}\right)^{2/3}+\left(\frac{x}{t'}\right)^{4/3}\right]^{3/4},\qquad \eta=\frac{3}{2}\operatorname{arctg}\frac{3^{1/2}(x/t')^{2/3}}{2-(x/t')^{2/3}},$$

$$t'=\omega_{pi}(t-z/v_0),\ x=\omega_{pb}z/v_0,\ \Delta=\bar{v}_i/R\omega_{pi}.$$

It can be seen from (11) that the potential at a fixed point in space first increases with time and then decreases. The characteristic fall-off time is equal to the plasma-ion lifetime $R/\bar{v}_i$ ($\bar{v}_i$ is the characteristic ion escape velocity in the transverse direction). Experiments performed in the absence of a pump wave led to good agreement between the signal waveform and the expression of Ref. 14. Typical potential oscillograms obtained in such experiments are shown in Fig. 9a. If the suppression of the instability were due mainly to nonlinear effects in the plasma-particle dynamics, a pump wave of sufficient amplitude would shorten the oscillation damping time substantially. Yet it is seen from Fig. 9b that the nonlinear wave interaction does not change the oscillation damping time much, so that the stabilization of the ion oscillation is due mainly to nonlinear effects in the beam-particle dynamics.

5. These experimental data agree on the whole with the results of the theory, but no account was taken in the latter of the possibility of a nonlinear interaction between the satellites and the electrons. Interest attaches to the question of the validity of such a theory. It is natural to assume that when not only the electron but also the ion oscillations have large amplitudes, the satellite-wave amplitudes can become so large the oscillation time of the resonant electrons in the potential of these waves becomes comparable with the time they take to travel across the beam $(2ek_{\pm}^2\varphi/m)^{-1/2}\langle R/v_{ph}\rangle$ i.e., the satellite waves become capable of capturing these electrons. In our experiments this condition is met already at $\varphi > 0.02$ V for satellites with $k_{\pm}\approx 3$ produced by interaction of the pump wave with the ion Langmuir oscillations. It is also natural to expect, in the case of nonlinear interaction of the waves with the particles, a change in the character of the nonlinear interaction of the waves with one another. In particular, this can be manifested by a loss of wave-vector resonance as a result of the nonlinear shift of the wave number, and consequently by a weaker suppression of the lf instability. That electrons are trapped by satellite-wave fields was revealed in experiment by the change of the electron distribution function at low energies, i.e., in the region of the resonance with the waves in question. These experiments were performed with allowance for the fact that raising the pump-wave level does not by itself cause electron heating or an increase of the static potential φ_{sp} of the space.[15] The experiments were therefore performed at a fixed pump-wave level and with variable level of the lf oscillations that influenced neither T_e nor φ_{sp}. Figure 10 shows plasma-electron delay curves measured with an analyzer probe. Curve 1 was obtained in the absence of modulation and curve 2 in the presence of lf modulation of relatively high amplitude. It can be seen from the figure that the curves overlap at high delay potentials, but that at low U the plot obtained under nonlinear wave interaction conditions lies much higher, and the saturation current is correspondingly larger in this case. At constant electron density and temperature, the increase of the saturation current can be attributed only to the appearance of a directed velocity, i.e., to electron trapping. This increase of the transverse electron flux was accompanied by a decrease of the longitudinal flux (i.e., a decrease of the electron current to the collector). The character of the nonlinear interaction of the waves is fundamentally changed when electrons are captured by satellite ions—there is no suppression of the lf instability in this case. The satellite amplitudes reach a rather high level, up to 30% of the pump-wave level.

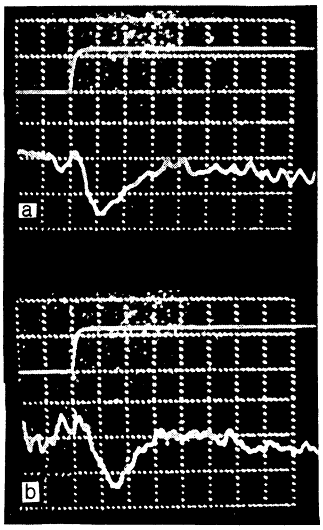

FIG. 9. Oscillograms of probe signal (lower trace) and of the modulating signal (upper): a—$U_a = 0$, b—$U_a = 1000$ V ($z = 150$ cm, $p = 2\cdot 10^{-4}$ torr).

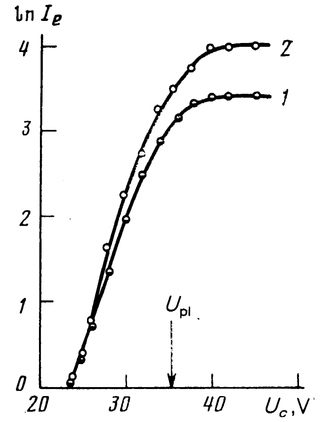

FIG. 10. Analyzer probe delay curves in the absence of modulation at the low frequency (curve 1) and in the presence of modulation (2) ($U_a = 1000$ V, $p = 2\cdot 10^{-4}$ torr).

6. We have thus investigated for the first time, theoretically and experimentally, the nonlinear interaction of ion and electron waves excited in a plasma by a fast ion beam. We have shown that for sufficiently large electron oscillations a decay-type interaction suppresses the low-frequency instability. Good agreement was found between the theoretical and experimental dependence of the lf-instability suppression on the rf-oscillation amplitude and on the frequency of the ion oscillations. Experimental confirmation was obtained for the theoretically deduced dominant contribution to the interaction by the nonlinearities in the beam-ion dynamics. It was established that if the ion oscillations are large enough the resonant electrons are trapped by satellite waves, and in this case there is no suppression of the lf instability.

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