Excitation of ion Langmuir oscillations by a fast ion beam

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The instability of ion Langmuir oscillations in a system consisting of plasma and a fast ion beam in a longitudinal magnetic field is investigated. It is shown that a beam of helium or argon ions with energies in the range 1–15 keV excites ion Langmuir oscillations in the plasma which it produces when it passes through its own gas at a pressure of 10^{-4}–2×10^{-3} mm Hg. An increase in the magnetic field leads to the suppression of such oscillations. The experimental data are in satisfactory agreement with the theoretical analysis given in this paper.

The excitation of ion-acoustic oscillations by an ion beam[1-5] has been extensively investigated both theoretically and experimentally. When an ion beam passes through plasma with velocity V_0 which does not appreciably exceed the phase velocity of the nonisothermal ion sound, $c_s = (T_e/m_i)^{1/2}$, it excited almost longitudinal ($\mathbf{k} \parallel \mathbf{V}_0$), and for $V_0 > c_s$ oblique, waves whose growth rate is proportional to $V_0^{-2/3}$.[6,7] It is well known that the ion oscillations of plasma pass over in the short-wave limit to ion Langmuir oscillations of frequency $\omega \approx (4\pi e^2 N_i/m_i)^{1/2}$,[8] the excitation of which by an ion beam has not until now been observed. Whilst the excitation of the longitudinal ($\mathbf{k} \parallel \mathbf{V}_0$) ion Langmuir oscillations is, in fact, difficult, for example, because this requires very slow ion beams ($V_0 \ll c_s$), it can be shown that Langmuir oscillations propagating almost at right-angles to the direction of the beam should be excited by a fast ($V_0 \gg c_s$) ion beam with a growth rate typical for two-stream instability.

These ion oscillations can be identified against the background of the ion-acoustic oscillations not only because the growth rate for the latter decreases under these conditions but also by using the dependence of the frequency of the ion Langmuir oscillations on the charged-particle density. To this we must add that such oscillations must be susceptible to suppression by a magnetic field parallel to the beam. Analysis of the excitation of ion Langmuir oscillations by a fast ion beam and the experimental confirmation of the results of this analysis was the aim of the present work.

THEORY

Consider the stability of a spatially homogeneous ion beam of density n_b traveling through homogeneous plasma with slow ion density N_i and electron density $N_e = N_i + n_b$ (quasineutral condition) along a magnetic field $\mathbf{H}_0 \parallel \mathbf{V}_0$ with unperturbed hydrostatic velocity $V_0 \gg c_s$ [but $V_0 < v_e$, where $v_e = (2T_e/m_e)^{1/2}$ is the mean thermal velocity of electrons]. The dispersion relation for nearly potential (curl $\mathbf{E} \approx 0$) oscillations of such a system is:[8]

$$k_\perp^2\varepsilon_\perp + k_z^2\varepsilon_\parallel = 0. \tag{1}$$

At relatively high frequencies $\omega_{Hi} \lesssim \omega \ll \omega_{He}$ (where ω_{Hi}, ω_{He} are the ion and electron cyclotron frequencies) and longitudinal phase velocities in the range $c_s \ll \omega/k_z < v_e$ the expressions for the transverse ($\epsilon_\perp$) and longitudinal ($\epsilon_\parallel$) permittivities are ($k_z d_e \ll 1$):

$$\varepsilon_\perp \approx 1 + \omega_{pi}^2/[\omega_{Hi}^2 - \omega^2] + \omega_{bi}^2/[\omega_{Hi}^2 - (\omega - k_z V_0)^2], \qquad \varepsilon_\parallel \approx (k_z d_e)^{-2}. \tag{2}$$

In these expressions $\omega_{pi} = (4\pi e^2 N_i/m_i)^{1/2}$, $\omega_{bi} = (4\pi e^2 n_b/m_i)^{1/2}$ are, respectively, the ion Langmuir frequencies for the plasma and beam, and $d_e = (T_e/4\pi e^2 N_e)^{1/2}$ is the Debye length for electrons.

Assuming that for $T_e \gg T_i$ we have $k_\perp d_e > 1$, and the fast ion density is $n_b \ll N_i$ for oscillations which are in resonance with the beam $\omega \approx k_z V_0$ [But $\delta\omega \equiv (k_z V_0 - \omega) \ll \omega$], we find from Eqs. (1) and (2) that the quantity $\delta\omega$ in the range

$$\left[\frac{\omega_{pi}^2}{(1+1/\mu)^{1/2}} + \omega_{Hi}^2\right]^{1/2} < \omega < (\omega_{pi}^2 + \omega_{Hi}^2)^{1/2}, \tag{3}$$

is complex, where $\mu = (\omega_{Hi}/\omega_{bi})^2$. This corresponds to the hydrodynamic instability of "transverse" ($k_\perp \gg k_z$) axially symmetric perturbations developed during the passage of the ion beam through the plasma along the magnetic field. The growth rate is a maximum near the upper boundary of the instability region expressed in terms of frequency

$$\omega \approx (\omega_{pi}^2 + \omega_{Hi}^2)^{1/2}, \tag{4}$$

which in dense plasma ($\omega_{pi} \gg \omega_{Hi}$) corresponds to the excitation of ion Langmuir oscillations by the beam. Under these conditions the maximum growth rate can be obtained from the following cubic equation:

$$\delta\omega^3 - \omega_{Hi}^2\delta\omega - \tfrac{1}{2}\alpha\omega_{pi}^3 = 0, \quad \alpha = n_b/N_i. \tag{5}$$

As we can see, in the case of low magnetic fields, when $\delta\omega \gg \omega_{Hi}$,

$$\gamma_{max}^0 \approx 3^{1/2}2^{-4/3}\alpha^{1/3}\omega_{pi}, \tag{6}$$

which is the same as the expression obtained by Mikhaĭlovskiĭ,[9] who considered the instability of an ion beam in plasma with zero magnetic field. The dependence of the maximum growth rate on the magnetic field is shown in Fig. 1 for different values of α. It is clear that γ_{max} decreases with increasing ω_{Hi} and $\gamma_{max} = 0$, where $\omega_{Hi}^* = 2^{2/3}\gamma_{max}^0$. Consequently, an increase in the magnetic field leads to a stabilization of the ion Langmuir oscillations excited by the ion beam in the plasma.

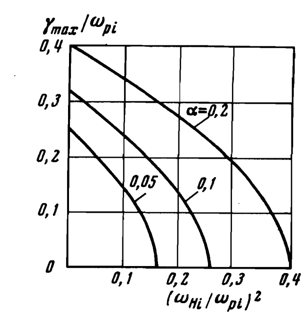

FIG. 1. Maximum growth rate of oscillations as a function of the magnetic field, $\alpha = n_b/N_i$.

Further increase of the magnetic field may lead to the development of axially asymmetric gradient instabilities, discussed in detail in[10,11].

Analysis of the dispersion relation for zero magnetic fields shows that, even for ion beam velocities $V_0 > v_e$, the excitation of the high-frequency "longitudinal" ($k_\perp = 0$) electron Langmuir oscillations[12,13] should be accompanied by "transverse" ($k_\perp >> k_z$) ion Langmuir oscillations (compare this with[9]) with the resonance growth rate determined by Eq. (6).

EXPERIMENT

The experiment was carried out using apparatus shown schematically in Fig. 2. A beam of helium or argon ions with energy in the range 1–15 keV and current up to 5 mA produced by a plasma ion source (1) was passed through a diaphragm (3) having an aperture of 24 mm in diameter into a metal chamber 14 cm in diameter and 80 cm long. The beam then entered a collector (2) which was preceded by an isolated diaphragm (4). The chamber and ion source were placed in a uniform magnetic field whose intensity could be varied between 1 and 10 kOe. With a constant pressure in the ion source, the helium gas pressure in the chamber could be varied independently between 10^{-4} and 2×10^{-3} mm Hg. The density of the plasma produced by the ion source ($N_i \approx 4 \times 10^7 - 1 \times 10^9$ cm^{-3}) was a function of pressure in the chamber, and under our conditions was substantially greater than the ion beam density ($n_b \approx 2 \times 10^7$ cm^{-3}).

The electron temperature was estimated with the aid of probes, and was of the order of $T_e \approx 10$ eV. As regards the plasma ion temperature, it may be assumed that the mean energy of the slow ions did not exceed about 1 eV.[14] The oscillations were recorded with the aid of movable (along the radius, azimuth, and length) electrostatic probes. The frequency spectra were observed on the S4-8 panoramic spectrum analyzer.

When the ion beam passed along the magnetic field through the plasma generated by it, one observed oscillations with a sufficiently broad spectrum and amplitude maximum at frequencies exceeding the cyclotron frequency of ions by a factor of 3–10. Measurements carried out with the aid of the movable probes showed that these were volume oscillations with axial symmetry and azimuth mode m = 0.

Typical spectra of the excited oscillations obtained at different helium pressures in the chamber are shown in Fig. 3. Similar results are obtained in the case of argon, but the frequencies in this case are lower by a factor of two or three. Figure 4 (full points) shows the

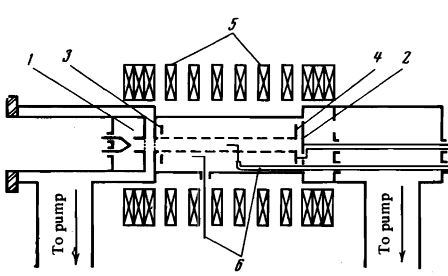

FIG. 2. Schematic illustration of the experimental setup: 1—ion source, 2—ion beam collector, 3, 4—diaphragms, 5—magnetic field coils, 6—probes.

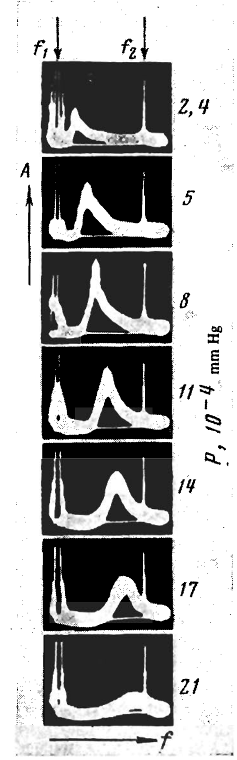

FIG. 3. Spectra of excited oscillations for different pressures of helium in the chamber. Beam energy 5 keV, magnetic field $H_0 = 1.1$ kOe. Frequency markers $f_1 = 0$, $f_2 = 4$ MHz.

oscillation frequency corresponding to maximum amplitude as a function of pressure for helium. The broken curve shows the theoretical dependence of the frequency on the plasma density (curve 1) calculated from Eq. (4) using the measured probe saturation current (ion-beam plasma density) as a function of pressure. Since the plasma density is radially inhomogeneous, the theoretical curve in this figure is tied down to one of the experimental points (this point corresponds in Fig. 4 to $p = 9 \times 10^{-4}$ mm Hg). We shall see that the experimental points are in good agreement with the theoretical relation.

Curve 2 in Fig. 4 illustrates the dependence of the amplitude of the excited oscillations on the pressure in the chamber (plasma density), The nature of this dependence is governed, on the one hand, by the increase in the growth rate during the increase in plasma density (Fig. 1), and, on the other hand, by the reduction in the ion current due to charge transfers which may occur at higher frequencies. Thus, for example, when $p = 2 \times 10^{-3}$ mm Hg, the helium ion mean free path between charge transfers is about 40 cm.

It is clear from Fig. 1 that the oscillation growth rate decreases with increasing magnetic field, which should lead to a reduction in the amplitude of the oscillations and to the suppression of instability. According to Eq. (4), the oscillation frequency should then increase somewhat. Experimentally, the dependence of the amplitude and oscillation frequency on the magnetic field is as shown in Fig. 5 and, as can be seen, this is in good agreement with these theoretical predictions. The experimental fact that, as the beam and plasma densities increase, the suppression of the oscillations occurs at higher magnetic fields, is also in agreement (Fig. 1).

The experimental dependence of frequency and amplitude on the velocity of the ion beam at constant beam density is shown in Fig. 6. According to Eq. (4), the frequency of the excited oscillations corresponding to the

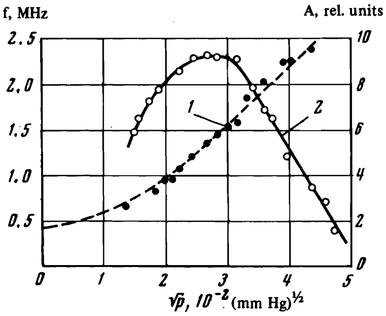

FIG. 4. Oscillation frequency at maximum amplitude as a function of pressure (curve 1, broken line represents theoretical prediction) and dependence of the oscillation amplitude on the helium gas pressure in the chamber (curve 2). Beam energy 5 keV, H_0 = 1.1 kOe.

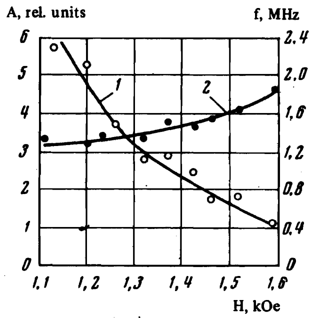

FIG. 5. Amplitude (1) and frequency (2) of oscillations as functions of the magnetic field. Helium gas, beam energy 4.2 keV, p = 6.5 × 10^{-4} mm Hg (A = 1 corresponds to noise level).

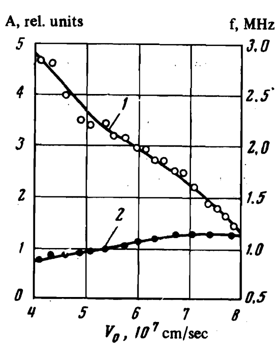

FIG. 6

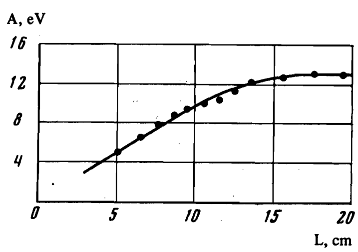

FIG. 7

FIG. 6. Frequency (2) and amplitude (1) of oscillations as functions of ion beam velocities. He, H_0 = 1.1 kOe, p = 1 × 10^{-3} mm Hg.

FIG. 7. Distribution of oscillation amplitudes along the direction of the ion beam. He, beam energy 5 keV, H_0 = 1.1 kOe, f = 1.8 MHz.

maximum growth rate does not depend on the beam velocity. On the other hand, the observed slight increase in frequency with velocity is connected with the increased plasma density due to an accompanying increase in the ion beam current (for given beam density).

The measured distribution of the amplitudes of the oscillations along the direction of motion of the ion beam is shown in Fig. 7. The growth rate deduced from this is greater by a factor of 1.5 than that predicted by the calculation. The restriction on the oscillation amplitude is probably due to the nonlinear effect associated with the interaction between the oscillations and the plasma ions and the accompanying heating of the latter. Detailed studies of these effects will be carried out in the future.

We note that the excitation of these oscillations is not connected with the current of secondary electrons from the ion-beam collector. The oscillations are observed both in the presence of the secondary electrons and when these are cut off. It is striking that, when the secondary-electron current is present, the spectrum of the oscillations is somewhat narrower and their amplitude rises very suddenly along the length.

Thus, the above comparison of experimental data with theoretical predictions enables us to conclude that we have observed for the first time the excitation by a fast ion beam of ion Langmuir oscillations propagating nearly at right-angles to the beam.

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