Excitation of ion oscillations in plasma by a fast beam of negative ions

M. D. Gabovich, L. S. Simonenko, I. A. Soloshenko, and N. V. Shkorina

Institute of Physics, Ukrainian Academy of Sciences
(Submitted April 24, 1974)
Zh. Eksp. Teor. Fiz. 67, 1710–1716 (November 1974)

The excitation of ion oscillations in plasma by a beam of negative ions, whose velocity is much greater than the velocity of ion sound, has been detected and investigated. A state which is specific for a negative-ion beam has been established. In this state, the Debye length d_e of electrons is much greater than the radius of the beam and plasma (r_0), and the effect of electrons on oblique perturbations may be neglected at all perturbation frequencies. In accordance with the calculations performed for this state, a standing wave has been detected along the radial direction. The radial structure of this wave is determined only by the initial conditions. It is also shown that, in the opposite case ($d_e \ll r_0$), the system can exhibit progressive ion oscillations in the transverse direction. The dispersion of these oscillations corresponds to the theory of infinite plasma.

We have investigated collective interactions between a fast negative-ion beam and ions in plasma produced by gas ionization by the beam. Such studies are of interest because of the following properties of the ion oscillations excited in such systems.

A beam of fast positive ions, whose velocity v_0 is much greater than the velocity of ion sound, $c_s = (T_e/m_i)^{1/2}$, excites ion oscillations in plasma, which propagate at a large angle to the beam.[1-3] In plasmas produced by a fast beam of negative ions, there are three possible and basically different states, namely:

(1) $n_e/n_i \ll c_s^2/v_0^2$ (n_e and n_i are the electron and ion densities in plasma) for which ion oscillations propagating along the beam are excited (this state can be achieved only at very low gas pressures);

(2) $n_e/n_i \gg c_s^2/v_0^2$ but $d_e > r_0$ for which the excited oscillations are no longer longitudinal with respect to the beam, but the effect of electrons upon these oscillations can be neglected at any perturbation frequency; and

(3) $n_e/n_i \gg c_s^2/v_0^2$, $d_e \ll r_0$ for which, as in the case of a positive-ion beam, the excited oscillations propagate at a large angle to the beam and the effect of electrons can be neglected only at the perturbation frequency equal to the Langmuir ion frequency of the plasma.

By increasing the gas pressure, one can successively realize all three states.

Before we report our experimental results, we must give a more detailed analysis of the above states. Let us suppose that the particles in the beam and in the plasma generated by it are distributed uniformly within a cylinder of radius r_0 which lies inside a metal tube of radius R_0. If we represent small perturbations by $\sim\exp(i\omega t - ik_z z)$, and use the continuity equation and the equations of motion for the cold beam and plasma ions, and the Boltzmann distribution for the electrons, we obtain the Poisson equation in the form

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\varphi}{\partial r}\right)+k_\perp^2\varphi=0; \qquad (1)$$

where

$$k_\perp^2=-k_z^2-1/\varepsilon d_e^2, \quad \varepsilon=1-\omega_{pi}^2/\omega^2-\omega_{bi}^2/(\omega-k_z v_0)^2,$$

and ω_{bi}, ω_{pi} are the Langmuir frequencies of the beam and plasma ions.

Let us begin with state (3). In this case, the wavelength of the excited oscillations is much less than the radius of the beam, and the solution of (1) can be sought in the form of progressive waves propagating in the radial direction [$\varphi \sim \exp(-ik_\perp r)$]. This yields the following well-known dispersion relation for infinite plasma:[4]

$$1-\frac{\omega_{pi}^2}{\omega^2}-\frac{\omega_{bi}^2}{(\omega-k_z v_0)^2}+\frac{1}{k^2 d_e^2}=0. \qquad (2)$$

It follows from (2) that in state (3) a fast beam ($v_0 \gg c_s$) can excite only oblique perturbations with $k_\perp \gg k_3$. In this case, and providing $\omega_{bi}^2 \ll \omega_{pi}^2$, the maximum growth rate

$$\gamma\approx\frac{\sqrt{3}}{2^{4/3}}\frac{\omega_{bi}^{2/3}}{\omega_{pi}^{2/3}}\omega_k \qquad (3)$$

is reached for

$$\omega_k^2\approx\frac{\omega_{pi}^2}{1+1/k^2 d_e^2}\approx k_z^2 v_0^2. \qquad (4)$$

It is clear from (3) and (4) that the maximum growth rate is exhibited by Langmuir ion oscillations ($\omega \approx \omega_{pi}$) for which the effect of electrons can be neglected ($k^2 d_e^2 \gg 1$). As the frequency decreases, the role of the electrons increases, and the growth rate falls.

Now consider state (1). The specific feature of plasma generated by a negative-ion beam is that, at low gas pressures, when the potential on the axis of the beam is negative,[5] positive ions accumulate in the system and electrons are expelled to the chamber walls. The plasma-ion density n_i can then be close to the beam density n_b, and the electron density is $n_e \ll n_b$. This means that it is possible, in principle, to excite longitudinal oscillations even when $v_0 \gg c_s$. It follows from (2) that the necessary condition for this is $n_e/n_i \ll c_s^2/v_0^2$.

State (2) is also specific for a negative-ion beam. Since the wavelength of the excited oscillations for $d_e > r_0$ can be of the order of r_0, the finite radius of the system must be taken into account in this state, and the solution of (1) must be sought in the form of standing waves in the radial direction:

$$\varphi=\begin{cases} AJ_0(k_\perp r) & \text{for } r<r_0 \\ C_1 I_0(k_z r)+C_2 K_0(k_z r_0) & \text{for } r_0<r<R_0 \end{cases}, \qquad (5)$$

where $J_0(x)$ is the Bessel function, $I_0(x)$ is the modified Bessel function, and $K_0(x)$ is the Macdonald function. Since $\varphi = 0$ for $r = R_0$, and if we match the values of the potential and of the transverse components of the electric induction at $r = R_0$, we obtain the dispersion relation which, in the case in which we are interested ($k_z r_0 \ll 1$, $k_z R_0 \ll 1$), has the form

$$\varepsilon+\frac{d_e^2}{r_0^2}\frac{J_0^2(k_\perp r_0)}{J_1^2(k_\perp r_0)}\frac{1}{\ln^2(R_0/r_0)}=0. \qquad (6)$$

It is clear the the maximum growth rate will be exhibited by oscillations for which the second term in (6) can be neglected. We shall therefore seek the solution of (6) in the form $k_\perp r_0 = \alpha_{0n} + x$, where $x < \alpha_{0n} - \alpha_{0(n-1)}$ and α_{0n} is a root of the Bessel function J_0. When $1/|\varepsilon| d_e^2 \gg k_z^2$, this yields the following dispersion relation:

$$\varepsilon+\frac{r_0^2}{d_e^2(\alpha_{0n}+x)^2}=0, \qquad (7)$$

and, consequently, the condition for maximum growth rate can be written in the form

$$\frac{r_0^2}{d_e^2(\alpha_{0n}+x)^2}\ll 1.$$

In the case in which we are interested ($r_0 < d_e$), the above inequality is satisfied for any α_{0n}, i.e., as expected, the effect of electrons is unimportant for any radial structure of the oscillations and any perturbation frequency. It then follows from (6) that

$$x=\frac{r_0^2}{d_e^2\alpha_{0n}^2}\ln\frac{R_0}{r_0}\ll 1. \qquad (8)$$

Finally, we note that, in the opposite case ($r_0 \gg d_e$), the oscillations excited in the radially bounded system should have a high radial mode [$r_0^2/d_e^2(\alpha_{0n}+x)^2 \approx r_0^2/d_e^2\alpha_{0n}^2 \ll 1$]. In that case

$$x=\operatorname{arctg}\left(\frac{r_0^2}{d_e^2\alpha_{0n}^2}\ln\frac{R_0}{r_0}\right). \qquad (9)$$

Therefore, in the radially bounded system, too, the Langmuir ion oscillations ($\omega \approx \omega_{pi}$) are the most unstable. Their growth rate is equal to the corresponding value for an infinite plasma, and the condition for maximum growth rate which, in the last case, was $k^2 d_e^2 \gg 1$, now becomes $\alpha_{0n}^2 d_e^2/r_0^2 \gg 1$.

EXPERIMENTAL RESULTS

Our apparatus is illustrated in Fig. 1. The H_1^- ions were extracted from the source with oscillating electrons 1 by the field of the liner 2 at right-angles to the magnetic field. They were then accelerated further in the gap between the liner and the magnetic screen 4, and were shaped by the magnetic lens 5 into the parallel beam 6 which traversed the interaction chamber until it was intercepted by the target 10. The beam radius was usually 1.5–3 cm and could be reduced continuously by means of the iris diaphragm 7. The modulator 8 was either a grid or a rod connected to an external oscillator. The maximum beam current was $I_i = 10$ mA, the maximum energy was $eU_0 \approx 30$ keV, and the particle density was $n_b \sim 10^7$ cm^{-3}. The plasma was produced by ionization of the neutral gas by the incident beam. When the air pressure was increased from 5×10^{-6} to 3×10^{-4} Torr, the density of slow plasma ions varied between the limits 10^7–10^8 cm^{-3}. The oscillations were investigated with the aid of probes 9 which could be displaced in the radial directions, and the radial distribution of the static potential was measured with thermal sensors.

As expected, when the pressure was increased, the potential on the axis of the beam changed from negative to positive. The pressure corresponding to zero poten-

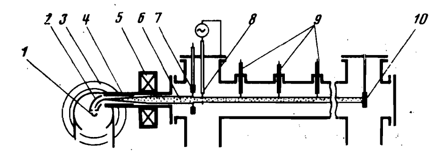

FIG. 1. Apparatus: 1—ion source; 2—extracting electrode and liner; 3—magnetic-field coils of the source; 4—magnetic screen; 5—magnetic lens; 6—beam; 7—iris diaphragm; 8—modulator; 9—probes; 10—collector.

tial value was $p_0 \approx 5 \times 10^{-5}$ Torr for $eU_0 = 20$ keV, which is in agreement with the calculations in[5]. At this pressure, $n_e \approx n_i v_i/v_e \approx 10^{-3} n_i$ (where v_i and v_e are the mean velocities of plasma ions and electrons). For pressures $p \gtrsim 10^{-4}$ Torr, when the potential in the system reached its maximum value,[5] the electron density substantially exceeded the beam density and was roughly equal to n_i. Therefore, when the pressure was altered from 5×10^{-6} to 3×10^{-4} Torr, the electron density varied between the limits 10^3–10^8 cm^{-3}, and the Debye length between 40 and 0.1 cm, so that we could realize experimentally both $d_e/r_0 \gg 1$ and $d_e/r_0 \ll 1$. However, in both cases, $n_e/n_i \gg c_s^2/v_0^2 \sim 10^{-6}$. It follows that only states (2) and (3) could be investigated experimentally.

Experiments show that, even at the very lowest residual gas pressures, low-frequency oscillations were excited in the system and their frequency increased with increasing p. Figure 2 shows typical oscillation spectra obtained at different pressures. Figure 3 shows the amplitude (curve 2) and frequency of the oscillations corresponding to maximum amplitude (curve 1) as functions of pressure. Comparison of the frequency of excited oscillations corresponding to maximum amplitude with the Langmuir frequency of slow ions at $p \approx p_0$, when $n_i \approx n_b$, showed that the two frequencies were equal. The amplitude of the oscillations increased exponentially along the beam with the growth rate given by (3) for $p < 10^{-4}$ Torr. The reduction in the growth rate with increasing pressure for $p > 10^{-4}$ Torr was probably connected with collisional damping of the oscillations. In fact, the collision frequency between beam ions and neutral particles was $\nu \approx 10^6$ sec^{-1} for $p = 10^{-4}$ Torr, which is comparable with the growth rate calculated from (3).

The frequency and amplitude of the oscillations were found to be unaltered when the beam and plasma radius was varied by the iris diaphragm. The above data led us to the conclusion that the negative ion beam did, in fact, excite ion plasma oscillations. Measurements of the dispersion of these oscillations were performed with a modulated beam, which enabled us to vary the amplitude and frequency of the initial perturbation. It was found that the phenomenon was very dependent on the gas pressure, i.e., electron density. At low pressures ($p \lesssim p_0$), when $d_e/r_0 \gg 1$ [state (2)], a standing wave was produced along the radial direction, as expected. The structure of this wave was independent of the modulation frequency: the change in this frequency led only to a change in the growth rate.

Figure 4 shows the radial distributions of amplitude and phase when the beam was modulated by a rod. It is clear that several half-waves fit into the diameter of the beam. In the case of modulation by the grid under comparable conditions, it was possible to realize the state in which one half-wave fitted into the beam diameter. Thus, in accordance with the theory, the radial structure of the wave with $d_e > r_0$ was determined only by the initial conditions. Since, in the case of modulation by a grid, the phase remained constant along the

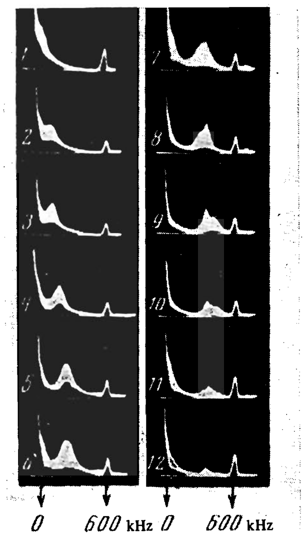

FIG. 2. Oscillation spectra: $I_- = 2$ mA, $eU_0 = 20$ keV; 1) $p = 1.6 \times 10^{-5}$, 2) $p = 3 \times 10^{-5}$, 3) $p = 5 \times 10^{-5}$, 4) $p = 6.2 \times 10^{-5}$, 5) $p = 9 \times 10^{-5}$, 6) $p = 1 \times 10^{-4}$, 7) $p = 1.2 \times 10^{-4}$, 8) $p = 1.4 \times 10^{-4}$, 9) $p = 2 \times 10^{-4}$, 10) $p = 2.2 \times 10^{-4}$, 11) $p = 2.5 \times 10^{-4}$, 12) $p = 3 \times 10^{-4}$ Torr.

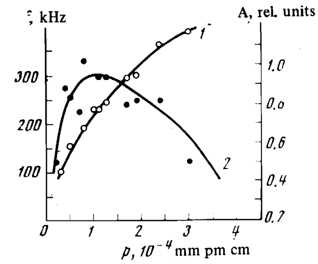

FIG. 3

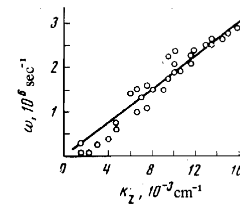

FIG. 5

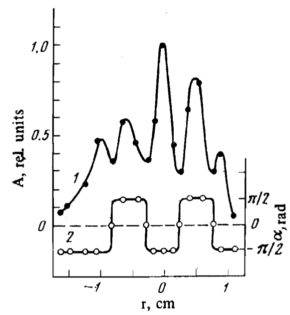

FIG. 4

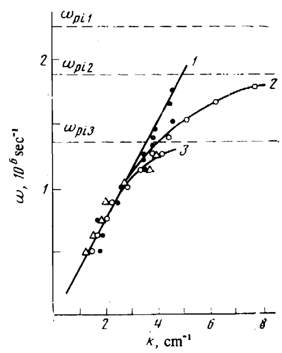

FIG. 6

FIG. 3. Frequency (curve 1) and oscillation amplitude (curve 2) as functions of air pressure. $I_- = 2$ mA, $eU_0 = 20$ keV.

FIG. 4. Distribution of amplitude (curve 1) and phase (curve 2) of the oscillations along the beam radius ($I_- = 2$ mA, $eU_0 = 20$ keV, $p = 5 \times 10^{-5}$ Torr; modulation frequency 150 kHz).

FIG. 5. Frequency of excited oscillations as a function of longitudinal wave number ($I_- = 2$ mA, $eU_0 = 20$ keV, $p = 6.8 \times 10^{-5}$ Torr).

FIG. 6. Dispersion relations. $I_- = 2$ mA, $eU_0 = 20$ keV; 1) $p = 2.6 \times 10^{-4}$, 2) $p = 1.8 \times 10^{-4}$, 3) $p = 1 \times 10^{-4}$ Torr.

entire beam diameter and was reversed only on its boundary, the phase difference between signals received from probes at different distances along the z axis could be used to determine the phase velocity of the wave in the direction of motion of the beam. The dependence of ω on k_z obtained in this way is shown in Fig. 5 (the solid curve corresponds to the beam velocity, and the points are experimental). It is clear that, as expected, the longitudinal phase velocity is nearly the same as the beam velocity.

For $p > p_0$ when $d_e/r_0 \ll 1$ [state (3)], the maximum growth rate should be exhibited by oscillations with wavelength much less than the beam size and, consequently, the system can support progressive waves in the transverse direction. In fact, for $p > p_0$ and beam modulation by the rod at frequencies $\omega < \omega_{pi}$, the transverse progressive wave was detected experimentally.

Since under the experimental conditions $k \approx k_\perp$, the dispersion of these oscillations could be obtained by measuring the phase as a function of distance in the transverse direction. The dispersion relations obtained in this way are shown in Fig. 6 (the broken straight lines correspond to the frequency of oscillations whose amplitude is a maximum under spontaneous excitation). It is clear that, in accordance with (4), the oscillation frequency increases in proportion to k for long wavelengths. The corresponding phase velocity is $\omega/k \approx 3.4 \times 10^5$ cm/sec, which corresponds to the ion sound velocity when the electron temperature is $T_e \approx 3$ eV. Again, in accordance with (4), the phase velocity tends to zero when the modulation frequency approaches the Langmuir ion frequency, which corresponds to the maximum of the oscillation amplitude.

We note that when $d_e/r_0 \ll 1$ and, consequently, the wavelength is small in comparison with the radius of the plasma, the theory cannot provide an unambiguous answer to the question whether a wave excited in the system is a standing or a progressive wave. Under these conditions, one can expect both. In fact, when the modulation frequency was $\omega \approx \omega_{pi}$, a standing wave was usually excited. Its structure was largely determined by d_e/r_0. In accordance with the theory of radially bounded plasma, the number of half-waves fitting into the beam diameter was found to increase with increasing beam radius (varied by the iris diaphragm) and gas pressure. The final radial structure of the oscillations was always found to satisfy the condition $\alpha_{0n}^2 d_e^2/r_0^2 \gg 1$.

The results of the present investigation can, therefore, be summarized as follows:

(1) we have examined the excitation of ion oscillations in plasma formed by a fast negative-ion beam; the oscillations in this system were detected experimentally;

(2) we have established the existence of a state which is specific for a negative-ion beam for which $d_e > r_0$ and the effect of electrons on ion oscillations can be neglected for all perturbation frequencies; a standing wave is formed along the radial direction in this case, and its structure is determined exclusively by the initial conditions;

(3) it has been established that, in the opposite case ($d_e \ll r_0$, when $\omega < \omega_{pi}$, the progressive oscillations are excited in the transverse direction, and the dispersion of these oscillations is the same as in the theory of infinite plasma; a standing wave is produced for $\omega \approx \omega_{pi}$, and its radial structure is determined by the ratio d_e/r_0, in accordance with the theory of bounded plasma.

The oscillations which we have detected and investigated may influence the transport of extended high-intensity negative-ion beams which have found important applications, including, in particular, installations designed for the production of high-temperature plasmas.

In conclusion, we thank A. A. Goncharov for discussions of our results.

[1]M. D. Gabovich, A. A. Goncharov, V. Ya. Poritskiĭ, and I. M. Protsenko, Zh. Eksp. Teor. Fiz. **64**, 1291 (1973) [Sov. Phys.-JETP **37**, 655 (1973)].
[2]M. D. Gabovich, I. A. Soloshenko, and A. A. Goncharov, Zh. Tekh. Fiz. **43**, 2292 (1973) [Sov. Phys.-Tech. Phys. **18**, 1450 (1974)].
[3]M. D. Gabovich, A. A. Goncharov, V. Ya. Poritskiĭ, I. M. Protsenko, and I. A. Soloshenko, Proc. Eleventh Intern. Conf. on Phenomena in Ionized Gases, Prague, 1973.
[4]A. B. Mikhaĭlovskiĭ, Neustoĭchivosti odnorodnoĭ plasmy (Instability of Homogeneous Plasma), Atomizdat, 1970, p. 73.
[5]M. D. Gabovich, A. P. Naĭda, I. M. Protsenko, L. S. Simonenko, and I. A. Soloshenko, Zh. Tekh. Fiz. **44**, 861 (1974) [Sov. Phys.-Tech. Phys. **19**, 546 (1974)].

Translated by S. Chomet.
186