EXPERIMENTAL INVESTIGATION OF THE EFFECTIVE SLOWING DOWN OF AN ION BEAM IN A PLASMA DURING ION-ACOUSTIC INSTABILITY

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We investigated experimentally the interaction of an ion beam with a plasma under conditions when the beam excites an ion-acoustic instability. It is shown that at beam velocities comparable with the velocity of the nonisothermal ion sound, the interaction leads to establishment of an ion-velocity distribution function in the form of a plateau, i.e., to effective transfer of the ion-beam energy to the plasma.

OBTAINING an effective collective interaction between ion beams and a plasma is of interest from the point of view of plasma heating and the problem of injection of ions into magnetic traps. The theory indicates that collisionless thermalization of an ion beam in the plasma can be attained under conditions when the beam excites ion-acoustic instability[1-4]. It is of interest to demonstrate this possibility experimentally.

The most effective exchange of energy between an ion beam and a plasma can occur in resonance interaction between ions and excited ion-acoustic waves propagating in the direction of motion of the beam. Such conditions are realized at beam velocities v not exceeding in order of magnitude the velocity of the non-isothermal ion sound $c_s \sim (T_e/M)^{1/2}$, i.e., at beam energies ϵ comparable with the thermal energy of the electrons (T_e—plasma electron temperature, M—ion mass). To satisfy the indicated ratio of the parameters ϵ and T_e, we used in our experiments a low-pressure gas-discharge plasma into which a monoenergetic beam of alkali ions was introduced.

The experimental setup is illustrated in Fig. 1. The plasma was produced in a copper vacuum chamber 1 with the aid of a discharge between incandescent cathode 2 and the main anode 5 and the auxiliary anodes 3 and 4. The chamber diameter was 5 cm and the length 20 cm. The cathode was placed in a side stub to eliminate flow of primary electrons in the working volume. The discharge current could be regulated in the range 0–3 A. By lowering the working-gas (argon) pressure in the range 10^{-3}–10^{-4} mm Hg, it was possible to vary the temperature of the plasma electrons from 4 to ~14 eV at a plasma concentration $n_e \lesssim 2\times10^{10}$ cm^{-3}.

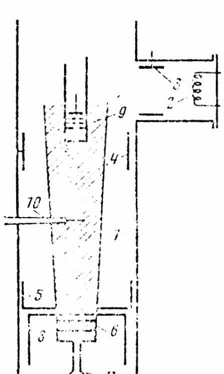

FIG. 1. Experimental setup.

The source of the potassium-ion beam was an incandescent porous tungsten emitter 6 (diameter 8 mm), a vapor tube, and a reservoir with liquid potassium 7. The ions were drawn from the surface of the emitter by the field of a flat reticular drawing electrode 8, held at a sufficiently high negative potential (300–500 V) relative to the emitter and to the plasma. The energy of the ion beam introduced into the plasma was regulated in the range 10–100 eV by changing the potential of the emitter relative to the potential of the main anode of the discharge, which is close to the potential of the space. The beam current ranged from 0 to 2 mA, and the initial angular divergence was $\alpha/2 \approx 7°$. The use of a source with surface ionization has made it possible to obtain an ion beam with a minimum initial velocity spread and ensured dissimilarity of the beam ions and of the neutral-gas atoms, thereby excluding resonance charge exchange.

The ion energy spectrum was analyzed with the aid of a moving three-probe electrostatic analyzer 9 with a decelerating field. The flat system of electrodes of the analyzer was placed in a cylindrical tube—screen—of 8 mm diameter. Prior collimation limited the angle of entrance of the analyzed particles to 17°. The diameter of the collimator openings was 3 mm. The resolving power of the analyzer in the indicated beam-energy range was ~7 eV. The measurements of the plasma parameters and indication of the oscillations were effected with the aid of a movable single probe 10.

The passage of the ion beam through the plasma is accompanied by excitation of low-frequency oscillations. Figure 2 shows examples of the frequency spectra obtained from the screen of the S4-8 analyzer. Frame 1 demonstrates the spectrum of the plasma oscillations in the absence of the ion beam, 2—with ion beam ϵ = 30 eV, 3—ϵ = 70 eV ($n_e \sim 5\times10^9$ cm^{-3}, h = 5.3 cm, f_1—frequency marker of 2.9 MHz). The interaction of the ion beam with the plasma leads to an appreciable increase of the intensity of the low-frequency noise. With increasing beam energy, the spectrum shifts towards higher frequencies. In a non-isothermal plasma in the absence of a magnetic

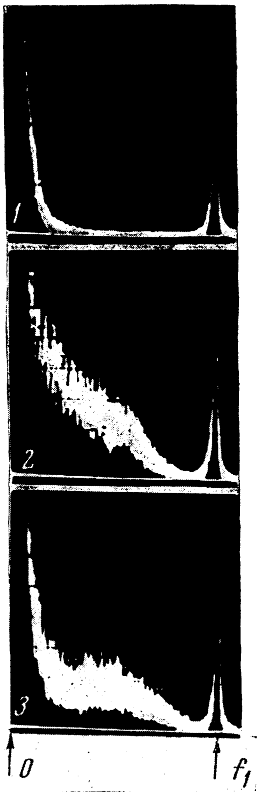

FIG. 2. Spectra of oscillations excited in the plasma by the ion beam.

field, the oscillations in the range $f < f_i$ (f_i—Langmuir frequency of the ions) have an ion-acoustic nature.

The interaction of the beam with the excited ion-acoustic oscillations leads to deceleration of the beam. Figure 3 shows the ion-beam velocity distribution functions obtained at different distances $h \approx 4-7$ cm from the ion source. The quantity dI_c/du_d, which is proportional to the ion-velocity distribution function F(v), was obtained by graphically differentiating the analyzer delay curves—plots of the collector current I_c against the decelerating potential u_d. In Fig. 3, u_d is reckoned from the potential of the main anode of the discharge; at sufficiently low values of u_d, passage of plasma ions into the analyzer is observed. The ion-emitter potential is +40 V; curves 1–5 are referred to the same value of the total current I_c. As seen from Fig. 3, with increasing distance traversed by the beam in the plasma, the distribution function of the beam ion velocities broadens because of the appearance of slower and slower particles. The maximum of the function shifts towards lower energies. At sufficiently large distances from the source, the velocity distribution function has the form of a plateau. Further development of the process of beam-plasma interaction leads to a state with negative derivative of the ion distribution function $dF/du < 0$.

By choosing the corresponding redistribution of the currents in the anode system, the discharge regime during the measurements is established in such a way that the electric field in the plasma is minimal along the path of the motion of the beam, i.e., the possibility of static acceleration of the plasma ions is eliminated. Confirming the latter, Fig. 3 (curve 6) shows the ion-velocity distribution function obtained at a distance h = 7.3 cm, with the ion-emitter heater turned off, i.e., in the absence of a beam. A comparison of curves 1 and 6 shows that the plasma ions experience practically no acceleration in the axial direction.

Under conditions when there is effective deceleration of the ion beam in the plasma (curves 4 and 5 of Fig. 3), the theory predicts the possibility of heating of the plasma ions[3,5], i.e., a broadening of their distribution function. This effect, however, cannot be investigated with the aid of the experimental procedure employed in this paper, which did not make it possible to separate the distribution functions of the plasma ions and of the beam.

At a fixed flight distance in the plasma, the distribution function of the beam ions acquires the form of a plateau only at sufficiently low initial beam energies. Figure 4 shows the distribution functions obtained at distance h = 7.6 cm for initial beam energies ϵ = 30–70 eV (the dashed lines indicate the value of the ion emitter potential). We see that the state with $dF/du \leq 0$ takes place only at beam energies $\epsilon < 40$ eV. The flight distance necessary to reach a plateau-like distribution function for the beam ions increases with increasing initial energy of the beam.

In the described experiments, the effective deceleration of the ion beam in the plasma could be obtained only at the maximal attainable electron temperatures. Figure 5 shows the ion velocity distribution functions obtained at gas pressures $p = 3.2 \times 10^{-4}$ (curve 1) and 1.8×10^{-4} (curve 2) mm Hg and the corresponding values T_e = 6 and 13 eV (h = 5.3 cm). Beam deceleration takes place only in the latter case. It should be noted that the indicated behavior of the distribution function at different pressures excludes paired colli-

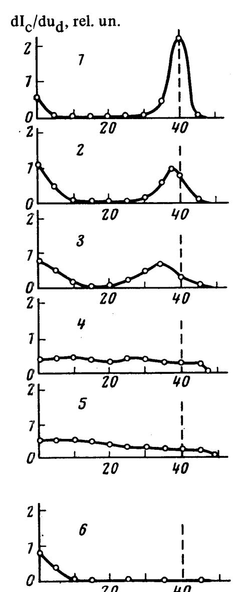

FIG. 3

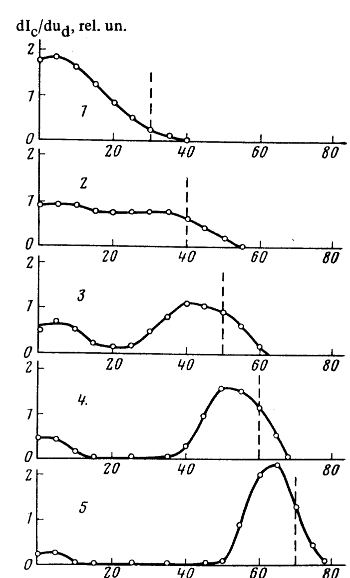

FIG. 4

FIG. 3. Ion-velocity distribution functions obtained at different flight distances of the beam in the plasma: 1–h = 4.3 cm, 2–h = 5.3 cm, 3–h = 6.1 cm, 4–h = 6.7 cm, 5, 6–h = 7.3 cm.

FIG. 4. Ion-velocity distribution functions obtained for different initial energies of the ion beam: 1–ϵ = 30 eV, 2–ϵ = 40 eV, 3–ϵ = 50 eV, 4–ϵ = 60 eV, 5–ϵ = 70 eV.

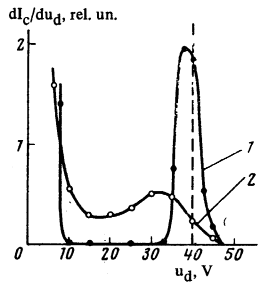

FIG. 5. Ion velocity distribution functions obtained at different plasma-electron temperatures.

sions of the beam ion with the neutral-gas atoms as a possible mechanism of scattering of the beam energy.

In the present experiments, the collective mechanism leading to thermalization of the ion beam in the plasma is the ion-acoustic instability. This was indicated by the region of frequencies of the excited oscillations and the characteristic connection between the effective interactions and the beam energy and the electron temperature (Figs. 4, 5). Excitation of linear ion-acoustic oscillations in a system consisting of a plasma and an ion beam was investigated experimentally in[6-8]. The frequency spectra obtained in the present investigation pertain to sufficiently low energies of the ion beam (see Fig. 2, frame 2) and have a nonlinear character (the oscillation energy is concentrated in the region of low frequency[5]). Under these conditions, the interaction of the beam with the oscillations leads to its effective deceleration (the loss of energy of a beam relaxing to a state with $dF/du \leq 0$, as is well known, exceeds 60%), i.e., to collisionless transfer of its energy to the plasma. It is of interest to determine the efficiency of the plasma-ion heating under the conditions of ion-acoustic instability.

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