Collisionless relaxation of an ion beam in a plasma with a high-frequency electric field

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Effective collisionless energy loss of a fast ion beam, $\epsilon_o >> T_e$, in a plasma with a high-frequency ($\omega_{pi} << \omega_o << \omega_{pe}$) electric field ($\epsilon_o$—initial beam energy; T_e—plasma electron temperature; ω_{pi}, ω_{pe}—ion and electron plasma frequencies, respectively; ω_o—field frequency) was experimentally identified.

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Thermalization of externally injected ion beams may be attained by other than collisional mechanisms. It is known that an ion beam is effectively relaxed in a plasma in the case of excitation by the beam of an ionic-acoustic turbulence.[1–4] However, this occurs at relatively low beam energies, $\epsilon_0 \sim T_e$ (provided beam ion and plasma masses are identical). In this work we show that superposition of a high-frequency (HF) electric field on a plasma leads to rapid thermalization of an ion beam at considerably higher initial energies of that beam.

An argon plasma was produced by low-pressure discharge, $(1-2)\times 10^{-4}$ mm Hg, with a heated cathode in a metallic vacuum chamber 10 cm in diameter. The

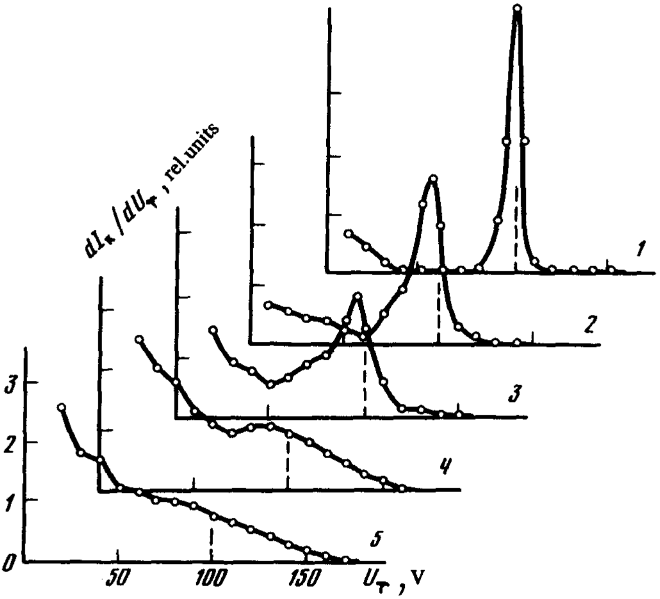

FIG. 1. Beam ion velocity distribution function at different values of HF field intensity $H = 80$ Oe, $\epsilon_0 = 100$ eV, $I_0 = 3$ mA; 1—$\tilde{U} = 0$; 2—$\tilde{U} = 60$ V; 3—$\tilde{U} = 90$ V; 4—$\tilde{U} = 120$ V; 5—$\tilde{U} = 135$ V.

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cathode and anode were spaced 25 cm apart. A monoenergetic potassium ion beam—obtained by means of a porous plane tungsten emitter 16 mm in diameter—was injected into a plasma across the discharge column, at its middle section. The plasma parameters were determined by single Langmuir probes and the beam characteristics, by a moving multiscreen electrostatic analyzer. The experimental conditions were: plasma density $n_e = (2\text{–}5)\times 10^9$ cm^{-3}, $\epsilon_0 = 50\text{–}300$ eV, beam current $I_0 = 0\text{–}4$ mA, transit distance in a plasma 10 cm, ion beam to plasma density ratio $n_0/n_e \approx 0.1 - 0.5$. An HF field ($\omega_0/2\pi = 15$ MHz) was generated in the beam propagation region by means of two plane-parallel screen electrodes (10×6.5 cm^2 each, 8 cm apart) immersed in a plasma. Penetration of the electric field into the plasma volume between the screens was accomplished by the application along the plasma column of a relatively weak ($H\sim 100$ Oe) magnetic field that was parallel to the screen electrodes. The magnitude of the variable electric field in the plasma ($\widetilde{E}$) was evaluated from results of probe measurements at different points of the described plasma condenser. The maximum attainable values of $\widetilde{E}$ in our work were 10 V/cm. Under typical conditions the ratios

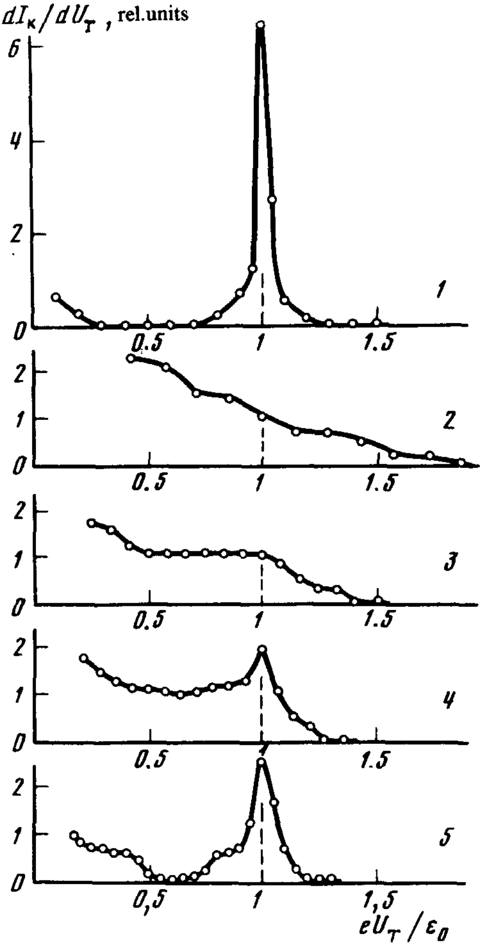

FIG. 2. Beam ion velocity distribution function at different energies: 1—$\widetilde{U} = 0$, $\epsilon_0 = 100$ eV; curves 2,3,4 and 5 correspond to $\epsilon_0 = 70$, 120, 140 and 200 eV, respectively, at $\widetilde{U} = 120$ V.

of characteristic frequencies were: $\omega_{pe}/\omega_{He} \approx 3$, $\omega_{He}/\omega_0 \approx 15$, $\omega_0/\omega_{pi} \approx 6$ (ω_{He} is the electron cyclotron frequency).

Experiments were carried out under conditions whereby an ion beam was injected into a plasma at right angles to the magnetic field direction, and an HF field was directed either along the direction of beam injection or perpendicular to it. In both cases identical beam-plasma interaction effects were obtained.

Experiments showed that superposition of an HF field on a plasma leads to a rapid (over the given transit distance) scattering of energy of the injected ion beam. Figure 1 shows the velocity distribution functions of the beam ion $f(v)$ measured at the end of the transit distance. The curve parameter is the HF voltage amplitude, $\widetilde{U}$, applied to the electrodes of the plasma condenser. The derivative dI_k/dU_T—proportional to the ion velocity distribution function—was obtained by graphical differenti-

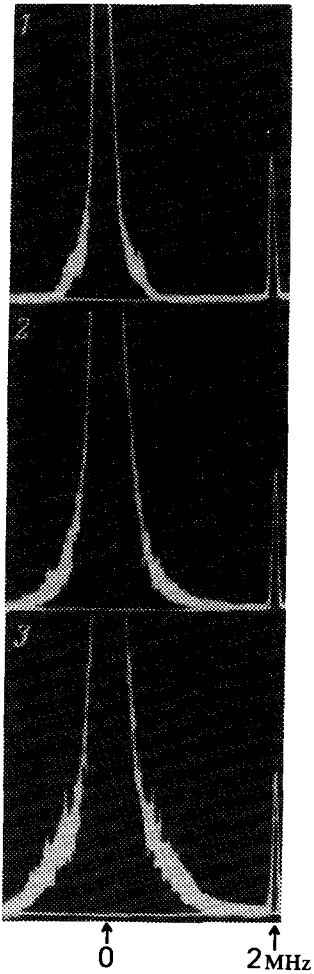

FIG. 3. Low-frequency spectra of ion beam current oscillations: $H = 80$ Oe, $I_0 = 3$ mA, $\epsilon_0 = 240$ eV, $n_e \approx 3\times 10^9$ cm^{-3}; 1—$\widetilde{U} = 0$; 2—$\widetilde{U} = 60$ V; 3—$\widetilde{U} = 60$ V; 3—$\widetilde{U} = 150$ V.

ation of the analyzer delay curves and the dependence of collector current I_k on decelerating potential U_T. In the region of small values of U_T, the analyzer fixes the presence of the plasma ions. Curve 1 shows that under given conditions in the absence of an HF field, the ion beam passes through the plasma volume practically without interacting. As U increases, the ion velocity spectrum broadens and the beam is decelerated. At high field values a velocity distribution is formed which is close to equilibrium ($\delta f(v)/\delta v<0$), i.e., thermalization of the beam in a plasma occurs with a 70–80% loss of initial energy. Investigations with a movable miniature analyzer showed that the process of beam retardation develops along its path in the plasma. The beam nature of the interaction is confirmed by the fact that a reduction in the beam current ($I_0 \leqslant 0.3$ mA) leads to restoration of the unperturbed velocity distribution in the ion flow.

Figure 2 shows the variation in the ion velocity distribution function for different initial energies of the injected beam (the abscissa represents the potential on the analyzer retarding screen U_T in normalized units eU_T/ϵ_0). Curve 1 represents the velocity distribution function of a beam that fails to interact with the plasma $\widetilde{U}=0$. It is evident from subsequent curves that a plateau-like—(or one with a negative derivative)—distribution function is formed at $\epsilon_0 \leqslant 120$ eV under the described experimental conditions. However, effective retardation of a beam in a plasma is observed up to its initial energies of 150–160 eV.

The investigations showed that the low-frequency noise level in a plasma increases when an HF field is applied. Under these conditions, modulation of the ion beam current is observed as a result of passage through the plasma volume in the HF field frequency region and $\omega<\omega_{pi}$. The low-frequency spectra of ion beam current oscillations—obtained in the collector network of the ion velocity analyzer at different values of $\widetilde{U}$—are shown in Fig. 3.

A direct influence of the applied HF field on the ion beam velocity distribution was either excluded by the experimental conditions (when $\widetilde{E}\perp \mathbf{V}_0$, where $\mathbf{V}_0$ is ion beam velocity) or was negligibly small (for $\widetilde{E}\parallel \mathbf{V}_0$ the maximum variation in the ion velocity was $\Delta\tilde{v}=(e\widetilde{E}/M\omega_0)\approx 2\times 10^3$ cm/sec$\ll V_0$, where M and e are the mass and charge of an ion). Thus, retardation of beam particles evidently depends on their resonant interaction with the plasma oscillations.

Excitation of waves in a plasma which are resonant with an ion beam may take place under the assumption of increased velocity of ion sound, i.e., the occurrence of an "effective" electron temperature constrained by the HF field. This effect was predicted by theory in the frequency interval of interest ($\omega_0 \ll \omega_{pe}$) and for a given formulation of the problem.[5] Oscillations that are resonant with a beam may, evidently, also be excited as a result of disintegration of the "pumping wave", i.e., high-frequency electric field.

The observed effects of a strong ion beam-plasma interaction may take place in the plasma systems with injection of fast particles and a simultaneous high-frequency heating of the plasma.

[1] A.G. Borisenko and G.S. Kirichenko, Zh. Eksp. Teor. Fiz. **60**, 384 (1971) [Sov. Phys. JETP **33**, 207 (1971)].

[2] R.J. Taylor and F.V. Coroniti, Phys. Rev. Lett. **29**, 34 (1972).

[3] Y. Kiwamoto, J. Phys. Soc. Jap. **37**, 466 (1974).

[4] A.A. Ivanov, Fizika sil'noneravnovesnoĭ plazmy (Physics of a Strongly Imbalanced Plasma), M., Atomizdat, 1977.

[5] K. Papadopoulos and J.B. McBride, Phys. Fluids **16**, 711 (1973).