Nonlinear Effects in a Synthesized Plasma Consisting of Positive and Negative Ion Beams

M. D. Gabovich and A. P. Naĭda

Physics Institute, Ukrainian Academy of Sciences

Submitted July 14, 1971

Zh. Eksp. Teor. Fiz. **62**, 183–188 (January, 1972)

Alteration of the individual velocity distribution functions due to collective interaction of positive and negative ion beams is investigated experimentally. It is shown that phase focusing of the particles during development of beam instability results in strong nonlinear interaction between the beams and in intense energy exchange between them.

We have investigated experimentally the nonlinear effects resulting from the development of two-beam instability in a system of mutually penetrating beams of positive and negative ions of equal mass and concentration, moving with a certain velocity relative to each other. Unlike a system of two beams of equal sign, in which the neutralization of the space charge is ensured by introducing a third component, the system considered here is an example of a two-component quasineutral plasma. Such a system is different because the theoretical analysis of the collective nonlinear effects is relatively simple.[1] In addition, the difference of the signs of the interacting particles makes it possible to determine separately the velocity distribution functions of each beam in the same velocity interval, something that cannot be done in the case of charged particles having the same sign. Such individual distribution functions contain essential information concerning the mechanism of the nonlinear interaction, and their experimental determination is of fundamental interest.

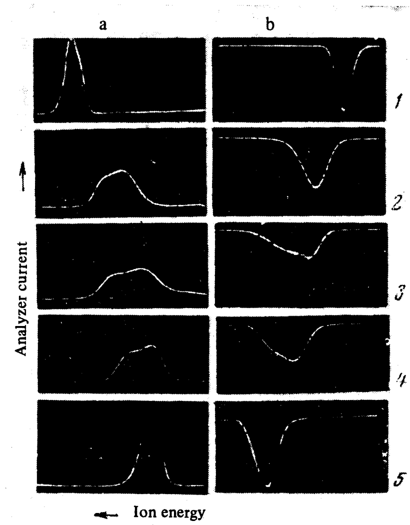

FIG. 1. Distribution functions in a beam of positive (a) and negative (b) ions at different values of the relative velocity (f = 54 MHz, $\tilde{W}_0$ = 50 eV, L = 220 cm): 1–ΔW = 950 eV; 2–ΔW = 700 eV; 3–ΔW = 350 eV; 4–ΔW = 250 eV; 5–ΔW = 0.

EXPERIMENTAL RESULTS

Interpenetrating beams of positive and negative hydrogen ions, with current up to 2 mA and energy $W_0 \approx 13$ keV each, were obtained with a setup whose diagram and description are given in [2]. In the present study, to obtain a nonlinear oscillation regime at a limited length (which could be increased to 220 cm), the beams were energy-modulated at the entrance to the interaction chamber with the aid of three grids, the two outer ones being grounded and the central one supplied with an alternating potential of adjustable amplitude. After passing through the grids, the energy variations of the beams were opposite in sign. Independently of the modulation, the beams could be imparted a relative velocity $2\Delta v$ without changing their average velocity v_0 (the beam velocities were $v_1 = v_0 \pm \Delta v$ and $v_2 = v_0 \mp \Delta v$, and their energies were $W_1 = W_0 \pm \Delta W$ and $W_2 = W_0 \mp \Delta W$; since $\Delta v \ll v_0$ in the experiments, it follows that $2\Delta v/v_0 = \Delta W/W_0$).

A Hughes-Rojansky analyzer was used to determine the energy-distribution function of each of the beams. The corresponding circuitry has made it possible to observe the distribution function of any of the beams (averaged over a time much longer than the modulation period) on an oscilloscope screen.

Figure 1 shows typical particle energy distribution functions for each of the beams, obtained at different values of their relative velocity; the initial energy-modulation amplitude $\tilde{W}_0$ was kept constant and satisfied the condition $\tilde{W}_0 \ll \Delta W$. This figure shows that when the velocity is varied, a significant change takes place in the distribution function of each of the beams. The maximum energy spread of the distribution functions is obtained at a certain optimal relative velocity. An analysis of similar oscillograms at a large number of relative-velocity values has shown that the velocity interval $0 < \Delta v < \Delta v_{cr}$ coincides with the interval in which the oscillation enhancement observed in [2] takes place, and the optimum relative velocity is equal to the velocity at which the oscillation increment is maximal. It is important to note that the maximum energy spread greatly exceeds the initial modulation amplitude $\tilde{W}_0$.

Figure 2 shows the change of the distribution function of each of the beams with increasing initial-modulation amplitude (modulation frequency f = 112 MHz; the relative beam velocity was optimal in this case). The data of Fig. 2a were obtained at an interaction length L = 120 cm (the negative-ion beam was faster in this case); the data of Fig. 2b were obtained at L = 220 cm (the positive-ion beam was chosen to be faster here). We see that with increasing initial-modulation amplitude, the beam distribution functions become asymmetrical, and the av-

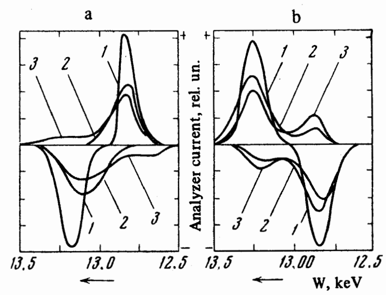

FIG. 2

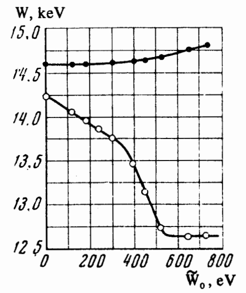

FIG. 3

FIG. 2. Variation of the particle energy distribution functions in beams of positive and negative ions with increasing modulation amplitude (f = 112 MHz, a–L = 120 cm, b–L = 220 cm): 1–$\tilde{W}_0/\Delta W = 0$; 2–$\tilde{W}_0/\Delta W = 0.15$; 3–$\tilde{W}_0/\Delta W = 0.3$.

FIG. 3. Dependence of the energy corresponding to the limits of the region of smearing of the distribution function on the modulation amplitude. f = 28 MHz, $\Delta W = \Delta W_{opt} = 800$ eV, L = 120 cm.

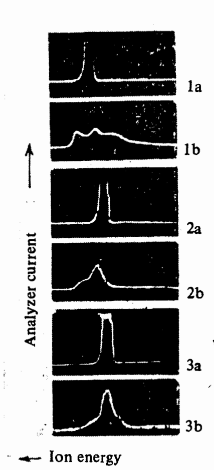

FIG. 4. Distribution function of beam of positive ions for different values of the relative velocity (f = 28 MHz, a–$\tilde{W}_0 = 0$, b–$\tilde{W}_0 = 600$ eV): 1–$\Delta W = -800$ eV; 2–$\Delta W = -200$ eV; 3–$\Delta W = 0$.

erage particle energy of the fast beam decreases while that of the slow one increases, i.e., energy exchange between the beams takes place. The energy exchange effect was briefly reported in [3].

A comparison of the distribution functions obtained at different interaction lengths shows that an additional maximum is formed on the distribution function of each of the beams at sufficiently large initial-modulation amplitudes and interaction lengths; the position of the additional maximum corresponds approximately to the energy of the second beam. With increasing interaction length, the energy spread decreases somewhat.

Analogous changes in the distribution functions are also obtained at other modulation frequencies. At f = 28 MHz, the optimal relative energy ($2\Delta W_{opt} = 1600$ eV) greatly exceeds the energy resolution of the analyzer, making it possible to trace in greater detail the change of the distribution function with increasing amplitude of the initial modulation.

Figure 3 shows how the energy corresponding to the limits of the region of smearing of the energy distribution function depends on the amplitude of the initial modulation. We see that the energy of the upper limit changes little with changing initial-modulation amplitudes, whereas the energy of the lower limit is considerably decreased.

Finally, Fig. 4 shows the distribution functions of a beam of positive ions, corresponding to different values of the relative velocity $2\Delta v$ in the absence (a) and presence (b) of modulation. Attention should be called to the existence of two different cases where the distribution function changes with changing Δv. In the case corresponding to the frames in Figs. 1a and 1b ($\Delta v \approx \Delta v_{opt}$; $\tilde{v}_0 < v$), just as in the case of Fig. 2, a deceleration of the fast beam is observed (accompanied by acceleration of the slow one). In the case corresponding to the frames in Figs. 2a and 2b ($\Delta v \ll \Delta v_{opt}$; $\tilde{v} \gg v$), to the contrary, the fast beam becomes accelerated and the slow one is correspondingly decelerated. The energy spread in the second case is noticeably smaller than in the first.

DISCUSSION OF RESULTS

From the linear theory of collective oscillations in a system of mutually penetrating beams we can obtain an expression for the alternating component of their velocity. In the case of $\Delta v = \Delta v_{opt}$ and $\cosh(0.5\omega_p z/v_0) \gg 1$, it takes the form

$$\tilde{v} = {}^1/_4 \tilde{v}_0 \exp\{0.5\omega_p z / v_0\} \sin\{\omega t - kz\}, \tag{1}$$

where $\tilde{v}_0$ is the amplitude of the initial velocity modulation, ω_p is the plasma frequency of the ions, and z is the distance from the modulator along the beam propagation direction.

It follows from this expression that an increase of the distance or of the amplitude of the initial modulation leads to a symmetrical increase of the velocity interval of the averaged distribution function, and the change in the velocities of both boundaries of this interval is proportional to the amplitude of the initial modulation. Relation (1) and the statements made above are valid so long as the condition for the applicability of the linear approximation is satisfied, which in this case takes the form

$$\tilde{v} \ll \Delta v. \tag{2}$$

However, the observed effects are characterized, first, by a particle-velocity spread comparable with the relative beam velocity $2\Delta v$ and, second, by the fact that when the amplitude of the initial modulation is increased the smearing of the distribution function of each of the beams takes place in asymmetric fashion. This indicates that the observed interaction is nonlinear.

Figure 3 shows that the entire range of variation of the lower limit W_{min} as a function of the initial-modulation amplitude can be broken up into three characteristic regions.

In region I (corresponding to variation of $\tilde{W}_0$ from 0 to 350 eV), in spite of the nonlinear character of the interaction, a linear relation $W_{min} = f(\tilde{W}_0)$ is observed. It is important to note that the velocity corresponding to the energy W_{min} in the vicinity of the region of transition into region II is close to the average beam velocity, which in our case determines the phase velocity of the wave, i.e., the following relation is satisfied:

$$v = v_0 = \omega / k. \tag{3}$$

Condition (3) coincides with the condition given in [1] for phase bunching in the waves. This circumstance and the fact that the slope of the $W_{min} = f(\tilde{W}_0)$ dependence changes at this point, thus evidencing a change in the character of the interaction, give grounds for identifying it with the formation of a phase focus.

Region II (corresponding to the variation of W_0 from 350 to 550 eV) is characterized by a sharper change of the limiting energy, corresponding to an enhancement of the collective interaction of the beams. A considerable decrease of the average beam energy also takes place in this region. The mechanism of the observed nonlinear enhancement can be connected with the interaction of the plasmoids produced as a result of phase focusing. In the plasmoid region, the particles of the slow beam are mainly accelerated, while the particles of the fast beam are decelerated by the summary field of the beams.

Finally, in region III ($\tilde{W}_0 > 550$ eV) W_{min} remains practically unchanged and is somewhat smaller than the specified energy of the second beam. The form of the distribution function, however, continues to change, and it acquires an additional maximum whose height increases with increasing $\tilde{W}_0$. The appearance of additional maxima (besides the maximum corresponding to the unperturbed distribution function) indicates that a developed multistream motion is produced in each beam. This leads to saturation of the relation

$$W_{min} = f(\tilde{W}_0).$$

The problem of nonlinear interaction of two electron beams was solved by numerical methods in [4]. In spite of the fact that our system is not identical with that considered in [4], the change we observed in the energy spectrum of the beams is in qualitative agreement with the change predicted in [4] for the beam-velocity profile. This agreement is observed both for $\Delta v \approx \Delta v_{opt}$ and $\tilde{v}_0 \ll \Delta v$ and in the case $\Delta v \ll \Delta v_{opt}$ and $\tilde{v}_0 \gg \Delta v$ (Fig. 4, frame 2b).

Thus, an analysis of the experimental data shows that the phase focusing of the particles during the development of two-stream instability leads to a strong nonlinear interaction of the beams and to intense exchange of energy between them.

The results may be useful, in particular, in the development of the nonlinear theory of two-beam instability.

The authors are grateful to É. A. Pashitskiĭ for a discussion of the results.

[1]I. P. Freidberg, Phys. Fluids **8**, 1031 (1965).

[2]M. D. Gabovich and A. P. Naĭda, Zh. Eksp. Teor. Fiz. **60**, 965 (1971) [Sov. Phys. JETP **33**, 522 (1971)].

[3]M. D. Gabovich and A. P. Naĭda, Zh. Eksp. Teor. Fiz., Pis'ma Red. **14**, 3 (1971) [JETP Lett. **14**, 1 (1971)].

[4]I. M. Gel'fand, N. M. Zueva, V. S. Imshennik, O. V. Lokutsievskiĭ, V. S. Ryaben'kiĭ, and L. G. Khazin, Zh. Vychisl. Mat. Mat. Fiz. **7**, 322 (1967).

Translated by J. G. Adashko
25