TWO-STREAM INSTABILITY IN A SYSTEM OF INTERACTING ION BEAMS

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Submitted to JETP editor November 26, 1965

J. Exptl. Theoret. Phys. (U.S.S.R.) 50, 1183–1186 (May, 1966)

It is shown that a two-stream ion instability can arise in a system containing two ion beams that move in the same direction, but with different velocities, if the energy difference in the beams is smaller than some threshold value. This instability leads to an effective exchange of energy between the beams; the energy exchange increases with increasing beam currents.

EARLIER investigations of the present authors concerned with the interaction of an ion beam with a plasma[1, 2] have verified the basic theory of the two-stream ion instability[3, 4] and have shown, in particular, the possibility of thermalization of an intense ion beam in a plasma characterized by a high electron temperature. The two-stream instability can also be realized in a fast ion beam and a low electron temperature if the single beam is replaced by two ion beams which move in the same direction, but with different velocities (below these will be called interpenetrating beams). A system consisting of interpenetrating cold beams moving in a plasma can be described by the dispersion relation

$$\frac{\omega_{p1}^2}{(\omega/k)^2}+\frac{\omega_{p2}^2}{(\omega/k-v_0)^2}+\frac{\omega_{p3}^2}{(\omega/k-v)^2}+\frac{\omega_e^2}{(\omega/k-v)^2-c_e^2}=k^2, \qquad (1)$$

where v_0 is the relative velocity of the two fast ion beams, v is the relative velocity of the beams in the plasma, ω_{p1}, ω_{p2}, ω_{p3} and ω_e are the plasma frequencies of the ions in the first beam, the ions in the second beam, the plasma ions, and the plasma electrons and c_e is the thermal velocity of the plasma electrons.

Analysis of this equation shows that the system is unstable against excitation of longitudinal waves for values of v_0 that are below some threshold value

$$v_{0,\mathrm{thr}}^2=\frac{\omega_{p1}^2}{(\omega_e/c_e)^2-(\omega_{p3}/v)^2}\left\{1+\left(\frac{\omega_{p2}}{\omega_{p1}}\right)^{2/3}\right\}^3; \qquad (2)$$

the expression in (2) is obtained for the condition $\omega/k \ll v$.

By substituting in (2), $\omega_{p3}=0$ and $\omega_e^2 m/M = 2\omega_{p1}^2$ it is possible to determine the relative threshold velocity for the particular case in which an interaction occurs between two ion beams with different ion density and space charge, compensated by electrons at temperature T_e. Going from the beam velocities to the corresponding potentials we write

$$(U_1-U_2)_{\mathrm{thr}}^2/U_1=8\gamma kT_e/e. \qquad (3)$$

It follows from these expressions, for example, that for ion beams with energies of the order of several kiloelectron volts with $\gamma = 3$ and $T_e = 1$ eV the quantity $\Delta U_{\mathrm{thr}} = (U_1-U_2)_{\mathrm{thr}}$ amounts to several hundred volts. It should be noted that the interaction considered here differs from the interaction between electrons streams in a two-beam tube[5] in the fact that the interaction of the compensated ion beams is such that the width of the instability region ΔU_{thr} is determined to a large extent by the temperature of the electron gas.

In the present work we have investigated the instability of interpenetrating potassium ion beams with energies up to 4 keV in a plasma formed by the ionization of a gas (krypton or neon) at a pressure $3\times10^{-6}-10^{-4}$ mm Hg) by these fast ions.

A diagram of the experimental arrangement is shown in Fig. 1. The beams of potassium ions with different velocities are obtained by ionization of

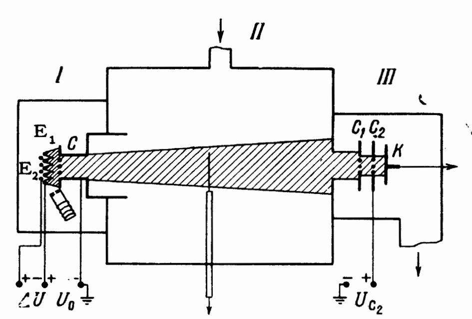

FIG. 1. Diagram of the experimental arrangement.

an atomic beam on the surfaces of two heated ionizers (E_1 and E_2) which consist of a series of tungsten wires located in approximately the same plane; (the individual wires of the ionizers alternate). The ions are accelerated (I) by the field of a grid C (grid diameter 7 mm); thus, the chamber marked II contains interpenetrating ion beams with a controlled energy difference $e\Delta U$. The intensity of the beams is controlled by the temperature of the ionizers and the atomic beam source. It is possible to produce ion currents of approximately 1 mA at energies up to 4 keV. The oscillations that are excited are observed by means of a movable probe and by means of a three-electrode electrostatic analyzer (III). The latter consists of a grid C_1 to reflect the electrons, a grid C_2 which can be used to retard the ion beams, and a collector K. A typical retardation characteristic showing the dependence of the collector current I_k on grid potential (C_2) is given in Fig. 2 (U_0 = 2.0 kV, ΔU = 170 V). It is evident that the beam actually consists of two components with an energy difference (the lower plateau is related to the emission of electrons from the collector produced by the fast neutral particles that arise in charge exchange).

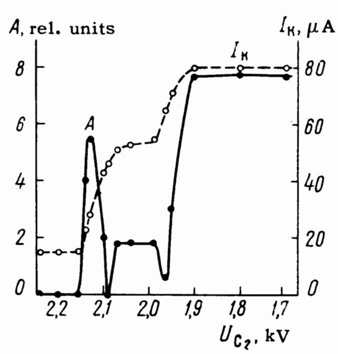

FIG. 2. The constant component of the current I_k and the ac signal in the collector circuit of the energy analyzer (A) as functions of the potential on the ion retarding grid.

In accordance with the predictions of the theory, the interaction of the interpenetrating ion beams characterized by a small energy difference ΔU leads to the excitation of oscillations. In Fig. 3 (1–4) we show the oscillation spectra observed in the probe circuit as seen with a spectrum analyzer (ASSh-4) with different energy differences between the ion beams $e\Delta U(U_0$ = 2.2 kV). The oscillations are usually harmonic; at higher levels, however, in addition to the basic peaks there are lines that form continuous or discrete spectra. (5). Under certain conditions the oscillation spectrum ex-

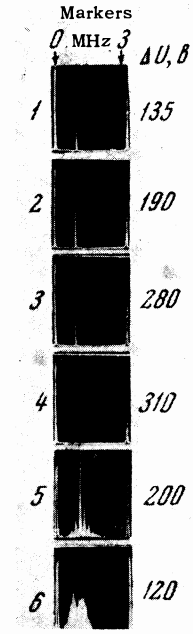

FIG. 3. Spectrum of the oscillations excited in interpenetrating beams for various values of the quantity ΔU (1 – 4); details of the spectrum observed with high gain (5); example of a spectrum of noiselike nature (6).

hibits a noise structure (6). The dependence of oscillation amplitude on the quantity ΔU is shown in Fig. 4 (curve 1, U_0 = 1.9 kV). In this case the threshold energy is approximately 270 eV and is found to be of the same order of magnitude as that computed from (3). In this same figure we show curve 2, which is obtained at a higher ion energy (U_0 = 18 kV) and which is taken from a preliminary brief communication on the existence of collective interactions in interpenetrating ion beams.[6] In accordance with (3), decreasing the beam energy leads to an increase in the threshold energy.

The excitation of oscillation in the system of interpenetrating ion beams must obviously lead to modulation of the density and velocity, that is to say, there must be a modulation of the current. By using the electrostatic analyzer it is possible to isolate the velocity modulation against the background of current modulation (in the region of ion retardation). In Fig. 2 we show the dependence of the ac signal in the collector circuit of the analyzer (A) as a function of U_{C_2}, the potential on the retarding grid. The plateau near U_{C_2} = 2.0 kV characterizes the current modulation of the fast

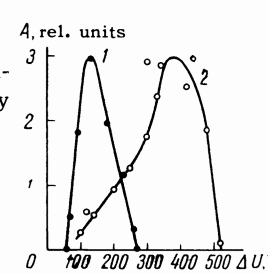

FIG. 4. Amplitude of the oscillations as a function of the energy difference of the interpenetrating (curve 1, U_0 = 1.9 kV; curve 2, U_0 = 18 kV).

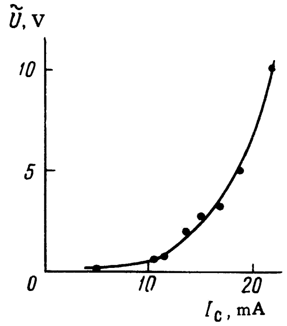

FIG. 5. The amplitude of the velocity modulation of the interacting ion beams as a function of the current I_c which is proportional to the total beam current.

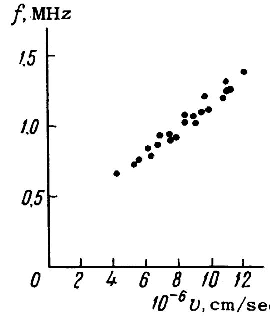

FIG. 6. The frequency of the observed oscillations as a function of the velocity of the interpretating ion beams.

beam (the slow beam does not reach the collector). The constant amplitude of the signal at $U_{C_2} < 1.9$ kV corresponds to modulation of the total current in both beams reaching the collector. In regions of ion retardation ($U_{C_2} \gtrsim 2.1$ kV and $1.9 \text{ kV} < U_{C_2} < 2.0$ kV) one sees signals caused by modulation of the ion energy and additional signals due to modulation of the current. In interpreting these results it should be noted that appreciable phase differences can exist between the signals, a feature that has been verified in independent experiments.

By measuring the amplitude of the ac current at the collector due to modulation of the ion beam energy and by measuring the slope of the retardation characteristic one can estimate the depth of modulation $\tilde{U}$, that is to say, it is possible to estimate the energy exchange between the beams due to the collective interaction. The strong growth in $\tilde{U}$ with increasing current in the ion beams is especially interesting. In Fig. 5 we show the dependence of the quantity $\tilde{U}$ on I_{C_2} the current to the grid electrode C (Fig. 1) which is proportional to the total current. This dependence indicates the possibility of achieving an effective exchange of energy in unstable interpenetrating beams that carry high currents.

In conclusion we wish to note the dependence of the frequency of these oscillations on the velocity of the ion beams (6). The proportionality established between these quantities is related to the Doppler effect which is observed in the coordinate system fixed in the plasma.

It should be noted (as shown by special experiments) that because of the high angular divergence of the ion beams the effective interaction length is relatively short (2–3 cm). Hence, it would be of interest to investigate the instability of interpenetrating ion beams in a situation in which the divergence is limited, for example by a strong magnetic field.

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Translated by H. Lashinsky
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