SOVIET PHYSICS JETP VOLUME 21, NUMBER 5 NOVEMBER, 1965

UNSTABLE PLASMA BEAM

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Submitted to JETP editor December 18, 1964

J. Exptl. Theoret. Phys. (U.S.S.R.) 48, 1237-1247 (May, 1965)

The turbulent state of a plasma beam in which a virtual cathode is formed [1-3] is studied experimentally. It is shown that the state is characterized by: a) a broad electric field oscillation spectrum, which includes the ion Larmor frequency and which permits one to carry out multiple (stochastic) acceleration of the ions up to kilovolt energies, b) the formation of a strongly eccentric plasma "torch" rotating in the "ion" direction with a frequency corresponding to several tens of kilocycles per second, and c) acceleration of the ions not only in the transverse but also in the longitudinal direction. The conditions are determined for the transition of the beam to a stable state in which the particle acceleration does not occur.

I. INTRODUCTION

In speaking of a plasma beam, we have in mind a plasma column generated by a beam of fast (primary) electrons. Such a system of charged particles is, under certain conditions, a singular instability.[1-3] The difference of this instability from the well-known varieties of "two-stream" instability of a current of fast electrons in a plasma [4-6] is easy to trace out by observing the change in the state of the beam for a gradual increase in the current density of the primary electrons j_e for an unchanged plasma density. Here, as is shown in many experiments (see, for example, [7]), when j_e reaches some value j_1 (which can be called the first critical current), the state of the beam changes sharply; the initially "monoenergetic" beam spreads out widely over the velocities, which testifies to the growing instability of the beam. However, in spite of such an essential change in the state of the beam, its potential (relative to the surrounding walls) remains negligibly small in comparison with the mean energy of the electron beam.[3] This state of the beam persists until j_e reaches a much larger value j_2, which we shall call the second critical current. There a new, sharp change takes place in the state of the beam, characterized by the fact that the amplitude of the potential oscillations reaches a value of the order of the mean energy of the fast electrons. The beam and, consequently, the state of the beam for $j_e < j_2$ will (tentatively) be called stable. Under experimental conditions [1-3], the quantity j_2 exceeds j_1 by a factor of 100.

The unstable plasma beam possesses a number of interesting properties; of these we should first mention the effective acceleration of the ions in a direction perpendicular to the magnetic field up to energies of hundreds and thousands of electron volts, and the resultant possibility of using such a beam as a plasma injector for magnetic traps.

The systematic study of the properties of an unstable plasma beam was begun by us earlier.[1-3] In the present work, we have considered: 1) the determination of the conditions under which the plasma beam transforms to an unstable state, as functions of such parameters as the energy of the fast electrons and the mass of the ions; 2) the study of the electric fields and the character of the motion of the charged particles in a plasma with fast ions, created by the unstable plasma beam in a trap with magnetic mirrors.

2. EXPERIMENTAL SETUP AND METHODS OF MEASUREMENT

All the experiments were carried out on the apparatus described in [2] which represented a trap with magnetic mirrors. The magnetic field intensity H in the center of the trap was varied in the range from 1000 to 5000 Oe, the mirror ratio amounted to 1.3, the distance between the mirrors was 100 cm, the diameter of the vacuum chamber was 30 cm, the residual gas pressure was $p \sim 10^{-6} - 10^{-5}$ mm Hg. To create the plasma beam, a gas discharge was used with an incandescent cathode in a strong longitudinal magnetic field; the diameter of the cathode was 1 cm. The experiments were carried out in two discharge modes, continuous and pulsed. The plasma source used in the experiments with continuous discharge is shown schematically in Fig. 1a.[8] The pulsed mode (with

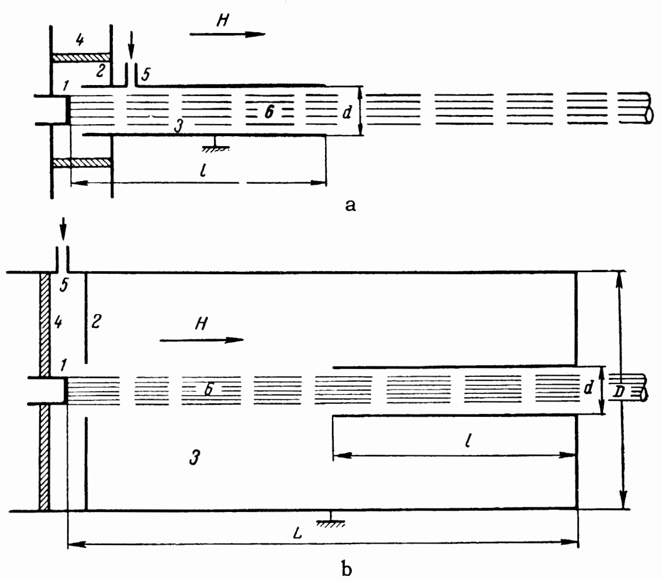

FIG. 1. Diagram of the plasma source: a) for continuous discharge; b) for pulsed discharge. 1 – cathode, 2 – diaphragm, 3 – discharge chamber, 4 – insulator, 5 – aperture for pumping the gas, 6 – plasma beam. Diameter of the cathode – 1 cm, d = 2 cm, D = 15 cm, l = 15 cm, L = 35 cm.

current strength $I_p = 10–20$ A) differed from the continuous in that, as a consequence of the intense "ion pumping" of the gas from the discharge chamber, the ion current which enters the beam from the source could appreciably exceed (for example, by one order of magnitude) the flow of gas to the source. In order that this circumstance not lead to a rapid quenching of the discharge, the volume of the discharge chamber of the source was greatly increased (Fig. 1b). This made it possible to obtain rectangular pulses of discharge current ($I_p \approx 20$ A) with a duration T_p up to several tens of milliseconds at a hydrogen flow $Q \approx 100–150$ cm^3/hour. This same source was used in [2] in experiments on the accumulation of the plasma in a magnetic trap.

The beam emitted from the source was received by a watercooled anode of 15-cm diameter. The distance between the source and the anode amounted to 140 cm.

Measurement of the densities of the charged particles inside the beam of primary electrons was carried out by the same method as in [1], that is, by measurement of the flow of charged particles to a collector placed behind a small aperture in the anode bored in a cone. The diameter of the aperture amounted to 1 mm.

Measurement of the energies and currents of ions accelerated in the unstable plasma beam perpendicular to the magnetic field was carried out by the method of a retarding potential with the help of the two-electrode radial probes, described in [2]. Three such probes were located at different azimuths in the central plane of the trap.

Measurement of the energies and currents of ions accelerated along the magnetic field was also carried out by the method of a retarding potential, but with multigrid probes rather than diodes. The latter circumstance was due to the obvious necessity of separating the currents of ions and electrons moving along the magnetic field. Two such end-type probes were placed in the magnetic mirrors, one against the other and could be shifted along the radius of the apparatus. The arrangement of end-type probes and grid potentials is shown in Fig. 2. The grids were made of molybdenum wire of 0.1-mm diameter. The first three grids had rectangular cells with mesh 0.4 mm, while the mesh of the fourth was 1 mm. The ion energies were determined from the dependence of the ion current at the collector on the positive potential V_3 of a third (control) grid. Two Langmuir probes were also used in the experiments. These were placed along the radius in the central plane of the trap. One of these was spherical, with a diameter of 3 mm. The other was cylindrical with a diameter of 0.5 mm and length 2 mm.

3. CONDITION FOR THE INSTABILITY OF A PLASMA BEAM

As was shown earlier,[1] the transition of a beam from the stable state to an unstable one takes place when the ratio of the density of plasma electrons n_2 to the density of fast primary electrons n_1 becomes less than some critical value α_c, which is of the order of several times ten. The purpose of the measurements reported in this paper was the determination of the dependence of α_c on such beam parameters as the energy of the primary electrons, (determined from the value of the discharge voltage) and the mass of the ions. A change in the value of α is brought about by the

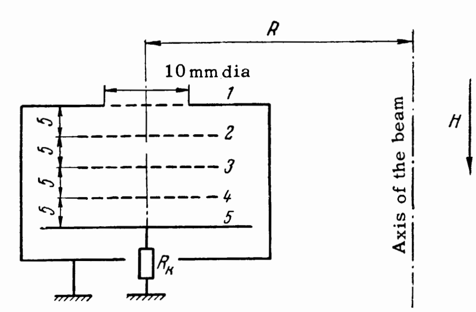

FIG. 2. End-type probe: 1 – screen with grid, 2, 3, 4, – grids, 5 – collector. Grid potentials: $V_1 = 0$, $V_2 = -200$, $V_4 = -500$ V. Third grid – "control." The collector resistance $R_c = 2000$ ohms. Distance between electrons – 5 mm.

regulation of the gas flow Q: increase in Q leads to an increase in α.

Figure 3 shows the dependence of α_c on the energy of the primary electrons of the beam (eV_p). It is seen that the relation $\alpha_c \sim (V_p)^{1/2}$ is satisfied with great accuracy. If one takes the temperature of the plasma electrons in the stable beam to be equal to 2 eV (on the basis of probe measurements), and also assumes that the velocity scatter of the primary electrons is equal to the mean velocity,[3] then it follows from the data shown in Fig. 3 that

$$\alpha_c = (n_2/n_1)_c \approx 4v_1/v_2 \qquad (1)$$

and the condition of instability of the plasma beam is

$$n_1v_1 > n_2v_2/4, \qquad (2)$$

where v_1 and v_2 are the mean velocities of the primary and plasma electrons, respectively:

$$v_1 = {}^1/_2(2eV_p/m)^{1/2}, \qquad v_2 = (8kT_e/\pi m)^{1/2}. \qquad (3)$$

The experimental data given in Fig. 3 refer to a discharge in hydrogen (beam length L_b = 140 cm, H = 3000 Oe). Similar data, obtained in experiments with discharges in heavier gases (nitrogen, argon, krypton, xenon), show that a change in the ion masses by two orders of magnitude has no appreciable effect either on the value of α_c or on the character of its dependence on the energy of the primary electrons.

It is of interest to note that the transverse dimention (diameter) of the plasma column in the stable system of the beam amounts to 1–1.5 cm, that is, it corresponds to the diameter of the cathode, while in the unstable state it increases to 12–15 cm.

The obtaining of the unstable beam presents no difficulties. For this purpose, it is only necessary that the gas pressure in the discharge chamber of plasma source of the type of Fig. 1 not greatly exceed the threshold of plasma ignition.[1]

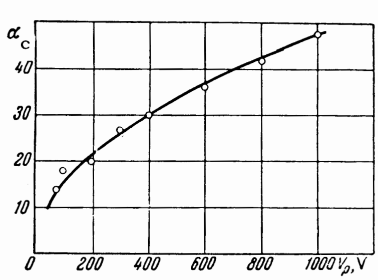

FIG. 3. Dependence of α_c on the discharge voltage (in hydrogen). H = 3000 Oe, I_p = 1 A.

4. ROTATION OF THE PLASMA

Elizarov and Zharinov [9] have shown clearly that under definite conditions there erupt from a plasma column generated by a beam of fast electrons "protuberances" or "torehes" which rotate about the beam axis. A similar phenomenon was observed by Neidigh and Weaver.[10]

To study the rotation of a plasma created by an unstable beam, oscillograms were taken of the currents of accelerated ions to the three radial probes mentioned above. These are distributed in the central plane of the apparatus at equal distances from the axis of the beam (R = 10 cm). The second and third probes were displaced in azimuth relative to the first by 180° and 300°, respectively, on the ion side, that is, in the direction of Larmor rotation of positive ions in the magnetic field. The experiments were conducted in the pulsed discharge made in hydrogen. Oscillograms of the currents to the radial probes are shown in Fig. 4 a, b. These oscillograms, and also the similar oscillograms taken at different radii of the probe, show that in the unstable regime of the beam, the distribution of the density of the plasma in azimuth is strongly inhomogeneous, and has the shape of a strongly eccentric "tongue," which turns about the axis of the beam in the ion direction. In transverse cross section, this tongue is restricted to a circular sector with an angle of ~120°, covering the axis of the beam of primary

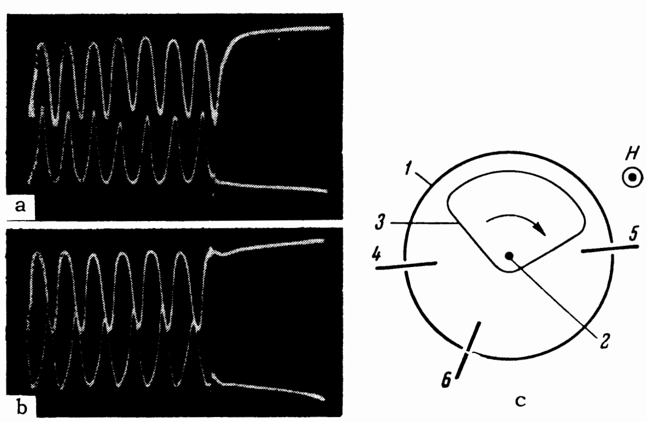

FIG. 4. Oscillograms of the current of accelerated ions on three radial probes 4–6. Time scale – left to right. a – upper trace – current at the first probe 4, lower trace – current at the second probe 5; b – upper trace – current at the first probe 4, lower trace, current at the third probe 6. The second and third probes are displaced relative to the first in the direction of the ions by 180 and 300°, respectively. The duration of the time interval was 500 microseconds, V_p = 1 kV, H = 2000 Oe, R = 10 cm, I_p = 8 A, p = 2 × 10^{-6} mm Hg, c – 1 – wall of the vacuum chamber, 2 – axis of the beam, 3 "boundary" of the tongue. The arrow indicates the rotation of the plasma, 4–6 – radial probles.

electrons (Fig. 4). A similar result was obtained in [10].

An experiment with longitudinal displacement of one of the probes showed that the current oscillations at the probe located in different places on the same magnetic tube of force are identical in shape and phase. Oscillograms of the end-type probes, separated from one another by a distance of 100 cm (see Fig. 9), give the same evidence. This means that the plasma "tongue" is extended along the magnetic field over the whole length of the apparatus and has the same shape in each cross section.

The rotation frequency f of the tongue lies in the range of tens of kilocycles and depends on the plasma regime and the magnetic field intensity. Under the conditions of Fig. 4, for $H = 2000$ Oe, $f = 21$ kc. The entire plasma in the trap—up to the walls of the vacuum chamber—rotates at this frequency. The density distribution of the plasma over the radius is given in [2]. It corresponds to a mean "diameter" of the region occupied by the plasma with fast ions of $\sim 12-15$ cm.

5. POTENTIAL OF THE PLASMA

The formation of a rotating plasma tongue can be naturally regarded as the consequences of the centrifugal flute instability of the plasma, rotating in the magnetic field under the action of a radial electric field (centrifugal instability of the first mode: $m = 1$). The direction of this rotation—in the ion side—corresponds to a field directed toward the walls. It must therefore be assumed that the plasma beam is charged and has a positive potential relative to the walls of the vacuum chamber. A special experiment was carried out for the purpose of estimating this potential on the axis of the beam of primary electrons. The conditions of the experiment were so chosen that the Larmor radius of the accelerated ions greatly exceeded the radius of the apparatus (15 cm), while the radial probe recording these ions was so oriented that the ions fell on it perpendicularly to the surface of the collector. A discharge in xenon (in the continuous mode) was used to obtain the plasma beam for this purpose.

Under these conditions, the maximum energy (W_m) of the xenon ions accelerated perpendicularly to the magnetic field was obviously close to the amplitude of the oscillations of the potential (φ_m) on the axis of the beam. Figure 5 shows the dependence of W_m on the discharge voltage V. It is seen that $W \approx eV_p$, whence it follows that $\varphi_m \approx + V_p$. For comparison, it should be noted that the potential in the stable state of the beam is $\approx +5-15$ V.

To find the distribution of the potential in the cross section of the rotating tongue, outside the primary beam, a spherical Langmuir probe was used which could be shifted along the radius in the central plane of the apparatus. The volt-ampere characteristics of this probe were plotted for different instants of time, corresponding to the successive passage along the motionless probe of parts of the tongue with different density. Thus, for example, one characteristic was constructed for the "crest" of the tongue (corresponding to the maximum density), another, for its "sides." This allowed one to estimate the character of the potential variation inside the tongue. It was shown that the potential of the tongue was maximal near the crest and fell off almost to zero for a displacement of about $\pm 60°$ in azimuth. The potential of the tongue in the plane of the crest decreases monotonically toward that edge from 300-400 V at $R = 3$-4 cm to 100-150 V at $R \approx 12$ cm. These measurements show that radial and azimuthal electric fields with an intensity of several tens of V/cm exist inside the tongue. It must be noted that the measurements were carried out on a low-frequency oscillograph OK-24 and therefore incorporate an appropriate time averaging. Such fields produce a drift motion of the charged particles with velocity $\sim 10^6$ cm/sec.

6. ELECTRIC FIELD OSCILLATION SPECTRUM

The fundamental properties of an unstable plasma beam are determined by the size, the spatial distribution, and the frequency spectrum of this variable bucking electric field which arises in a certain region of the beam (the virtual cathode [3]) and leads to deep current pulses of the primary electrons. A direct indicator of the oscillations of this field are the oscillations in the flow of fast primary electrons, which are reflected

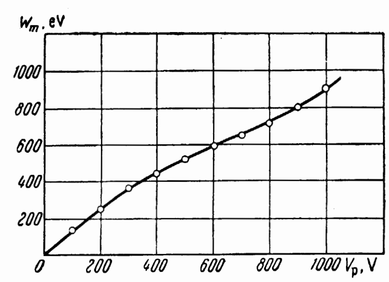

FIG. 5. Dependence of the maximal energy of Xe^+ ions on the discharge voltage. $H = 1000$ Oe, $I_p = 1$ A, anode current $I_a = 0.4$ A, $p = 3 \times 10^{-6}$ mm Hg, $Q = 13$ cm³/hour.

from the region of the virtual cathode and which move in the direction of the source. The measurement of the current of these reflected electrons (I_2) was carried out as in [3], with the help of a ring surrounding the beam [1)] with an inside diameter of 2 cm, screened from the side of the source by a diaphragm of smaller diameter (1.6 cm). The ring and the diaphragm were placed at a distance of 5 cm from the source; in the experiment, a source of the type of Fig. 1a was used, operating in the continuous mode. The measurement (oscillography) of the spectrum of current oscillations I_2 was carried out by means of a panoramic spectrum analyzer S4-8. The result of the measurement is shown in Fig. 6. It is seen that the spectrum of oscillations of the current of reflected electrons is continuous and extends from the tens of kilocycles up to several megacycles and includes the Larmor frequency of the ions.

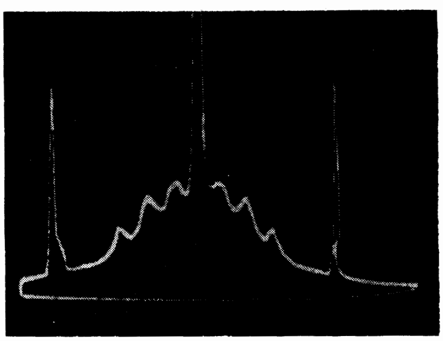

FIG. 6. Oscillogram of the oscillation spectrum of the current at ring No. 2. The high, narrow peaks are frequency markers at f = 0 and f = 2 Mc. The Larmor frequency of the protons f_p = 1.5 Mc, H = 1000 Oe, V_p = 250 V, I_p = 0.5 A, T_a = 0.2 A, p = 2 × 10^{-5} mm Hg. Amplitudes of oscillations ($I_\sim$) in relative units. (For displacement of the trace of the oscillograph from the left edge position to the right edge, the oscillation spectrum is recorded twice.)

The spectrum of Fig. 6 is obtained for a zero potential of the measurement ring. The imposition of a negative regarding potential on the ring does not change the character of the spectrum, but leads to a similar decrease in the amplitudes of all the spectral components. The dependence of the amplitude of oscillation ($I_\sim$) of any harmonic on the negative potential of the ring (V_2) is shown in Fig. 7. The fact that $I_\sim$ vanishes for a retarding potential V_2 approximately equal to the discharge voltage indicates that the quantities actually measured in the experiment are the oscilla-

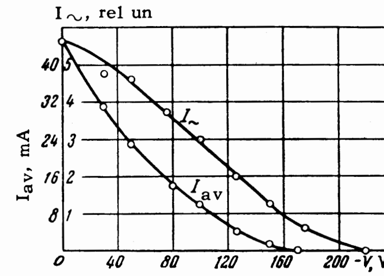

FIG. 7. Dependence of the amplitude of the current oscillations in ring No. 2 ($I_\sim$) on the negative potential of the ring. I_{av} is the constant component of the current at the ring. H = 1000 Oe, V_p = 250 V, I_p = 0.5 A, I_a = 0.2 A, p = 2 × 10^{-5} mm Hg.

tions of a current of fast primary electrons reflected from the virtual cathode. Therefore, it can be assumed that Fig. 6 characterizes the spectrum of oscillations of the electric field in the unstable plasma beam. The oscillogram of the current I_2 is similar to the oscillogram of the current at the anode. (see [1,2]).

7. ON THE MECHANISM OF THE TRANSVERSE ACCELERATION OF THE IONS

The set of experimental data that have been obtained make it possible to express the following point of view in connection with the possible mechanism of acceleration of the ions perpendicular to the magnetic field in the unstable beam. The virtual cathode divides the beam into two regions. Let us consider the region that extends from the virtual cathode to the anode (the beam collector). At the moment directly following the formation of the virtual cathode, the current of fast electrons emerging from the region under consideration, toward the anode, exceeds the current of fast electrons coming into this region from the source (by the value of the current of reflected electrons). Therefore, the potential of the considered region is increased to a value of the order of the energy of the primary electrons, i.e., of the order of the discharge voltage (the formation of the electrons in the considered region can be neglected). The generation of such a potential, as was shown above, is an experimental fact. When the virtual cathode disappears, the positive potential disappears along with it. A virtual cathode is formed again within a certain time interval, and a positive potential again appears ($\varphi_m \approx + V_p$), and so forth. Inasmuch as the beam is cylindrical, the generated electric field has an essentially radial direction. The oscillation spectrum of this field is characterized qualitatively by Fig. 6 and, what is important in principle, includes within it the Larmor frequency of the ions. In such an electric field,

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1)In the previous paper,[3] this ring was denoted as ring No. 2.

multiple acceleration of the ions can take place, similarly to what happens in a cyclic stochastic accelerator of charged particles.[11] The maximum energy acquired by the "correct phase" ion in a single act of acceleration is close to eV_p, as was shown above.

It is not difficult to see that the oscillations of the potential with amplitude $\varphi_m \approx + V_p$ can arise in the plasma beam in an arbitrary case in which the current strength of the primary electrons is subjected to a sufficiently rapid modulation, if only the amplitude ΔI of the variable component of the current satisfies the approximate relation: $\Delta I \gtrsim 7 \times 10^{-5} V_p^{3/2}$, where ΔI is in amperes and V_p is in volts (for example, for $V_p = 250$ V, $\Delta I \gtrsim 0.25$ A). In the special case considered in the present work, this modulation of the beam is associated with the formation of a virtual cathode, but in principle, it can have a different nature.

8. LONGITUDINAL ACCELERATION OF THE IONS

Experiments show that in an unstable beam, in addition to the transverse acceleration of the ions ($\perp H$) described above and in [2], longitudinal acceleration of the ions ($\parallel H$) can also take place in the direction of motion of the primary beam. This can be verified by comparison of the volt-ampere characteristics of two oppositely-directed end-type probes, one of which (No. 1) is placed on the anode side and records ions moving along the beam, while the other (No. 2) is located on the source side and records ions moving against the path of the beam (the distance between the probes is 100 cm). The retardation curves of both probes are shown in Fig. 8. In Fig. 9 are plotted the current oscillograms on the two probes for zero potential and for a retarding potential $V_3 = +500$ V (the probes are set on the same magnetic force tube). It is evident that the energy of the ions incident on the probe No. 1 appreciably exceeds the energy of the ions impinging on probe No. 2. (The ion current at probe No. 1 for $V_3 = 0$ exceeds by about a factor of two the ion current at probe No. 2). It is seen here that upon application of a retarding potential on probe No. 2, the ion current at the probe during the entire discharge pulse decreases in approximately the same fashion, i.e., all the ions reaching probe No. 2 belong to the same group (the curve a in Fig. 8); the maximal energy of these ions corresponds to the plasma potential measured by the Langmuir probe. In contrast with this, upon application of a retarding potential on probe No. 1, the group of ions arriving at the probe during the first 100 microseconds from the moment of generation of the discharge current has a much higher energy than the ions arriving during the rest of the time of the discharge pulse. The retardation of these two groups of ions by the potential of the central grid is shown in Fig. 8 by the separate curves b and c.

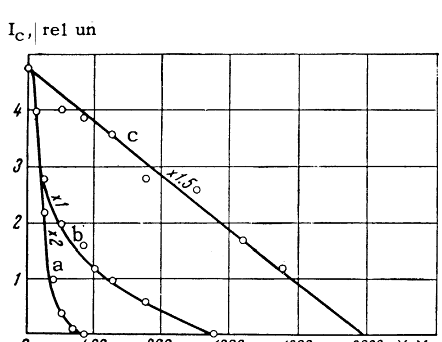

FIG. 8. Dependence of the ion current at the collector on the positive potential of the control grid for two end-type probes: curve a – probe on the side of the plasma source (No. 2), curves b and c, probe on the side of the receiver of the beam (No. 1). H = 2000 Oe, $I_p = 10$ A, $V_p = 1$ kV, $T_p = 0.6$ microsec, R = 7 cm, $p = 1.5 \times 10^{-6}$ mm Hg.

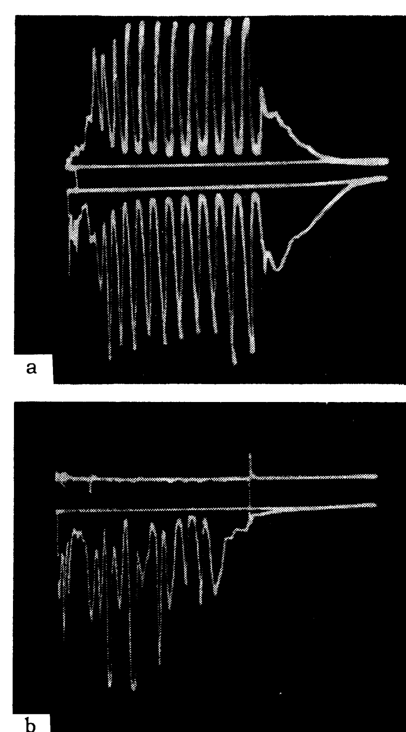

FIG. 9. Oscillograms of the ion currents at the end-type probes No. 1 (lower trace) and No. 2 (upper trace) for two values of the potential of the control grid: a – $V_3 = 0$ and b – $V_3 = +500$ V; H = 2000 Oe, R = 7 cm, sweep length – 1 microsec, $T_p = 0.6$ microsec, $V_p = 1$ kV, $I_p = 10$ A, p = 3 × 10 mm Hg.

It is important to note that the ions of group c are observed only during that interval of time in which the plasma beam propagates from the cathode to the anode. These ions cease to be observed again at the moment (~ 100 microseconds from the beginning of the discharge) at which the current at the anode reaches a maximum (up to this moment, the discharge current is essentially perpendicular to **H**, on the sides of the discharge chamber of the source). Thus, the acceleration of the ions of this group is directly connected with the appearance of the virtual cathode in the plasma beam, which always (independently of the degree of stability of the beam) takes place at the moment of start of the powerful discharge, because of the different velocities of the ions and the primary electrons (and is easily recorded experimentally with the aid of the rings described above). Inasmuch as the virtual cathode also pulsates during the remaining part of the discharge pulse in the beam, the acceleration of the ions of groups b and c is evidently connected with the same mechanism of ambipolar acceleration of the ions by the electrons.[2)] It is possible that a similar phenomenon lies behind the longitudinal acceleration of the ions at the source with a high voltage pulse discharge between the hydrogen-saturated titanium washers, used in experiments on the adiabatic compression in the laboratory of Post.[13] We note that the "diameter" of the region in which the longitudinal acceleration of the ions is observed is equal to 10-12 cm, while the total current of these ions under the conditions described in the experiments amounts to ~ 100 mA, i.e., it is of the order of 5-10% of the ion current accelerated by the perpendicular magnetic field and arriving at the walls of the vacuum chamber.

9. COMPARISON OF THE RESULTANT EXPERIMENTAL DATA WITH THE RESULTS OF OTHER RESEARCHES

In the works of Alexeff, Neidigh, and Weaver,[10,14] the stability of a plasma beam is similar in its composition and method of obtaining the beam to that investigated in the present work. The basic differences of the experimental conditions in [10,14] from ours are the much smaller beam length, which did not exceed 23 cm, and the smaller cross sectional dimensions of the beam (6 mm). These differences can be important, since in our experiments, the transition of the beam from the stable state to the unstable was observed only when the length of the beam exceeded some minimal length. Thus, for example, in the conditions of [3], this minimal length amounted to approximately 35 cm, and it is not eliminated a priori that it depends on the diameter of the beam. It was shown in [10,14] that the plasma beam can be found in two states: "mode I," and "mode II." The first of these states corresponds to the stable beam in our terminology. The second state is characterized by four fundamental signs: 1) diffusion of the boundaries of the beam; 2) by the generation of a tongue which rotates in the ion direction with a frequency of the order of tens of kilocycles; 3) acceleration of part of the ions perpendicular to the magnetic field up to energies in the hundreds of eV; 4) by the excitation of ion-sound waves at the ion Larmor frequency.

Judging by the first three of these signs, it would seem that mode II corresponds to the unstable beam in our terminology. However, as Alexeff and Neidigh emphasize,[14] the transition of the beam from the state of mode I to the state of mode II comes about under the condition of equality of the frequency of the ion-sound wave with the Larmor ion frequency:

$$\frac{1}{2L_b}\left(\gamma\frac{kT_e}{M}\right)^{1/2}=\frac{eH}{2\pi Mc}, \tag{4}$$

where L_b is the beam length, $\gamma = 3$. Comparison of (4) and (2) shows that the condition for the generation of the state of mode II has nothing in common with the condition for the appearance of the instability considered in the present work. In fact, in the first place, condition (4), in contrast with (2), includes neither the velocity of the primary electrons nor their density, nor the density of the plasma. In the second place, in our experiments ($L_b \approx 150$ cm, $H = (2-3) \times 10^3$ Oe, hydrogen) condition (4) cannot be satisfied, since its left side is two orders of magnitude smaller than the right. It therefore must be concluded that mode II is not at all identical to what is called the unstable plasma beam in our research. In the opinion of Alexeff, Neidigh, and Weaver, mode I is a specific state of the beam which arises as a consequence of the presence of a longitudinal pressure gradient of the neutral gas: when the pressure gradient is large mode II exists; for a small one, it does not. This also does not correspond to the transition of the beam from the unstable state to the stable under the conditions of our experiments. In fact, under the conditions of operation of the plasma source of the type of Fig. 1, the transition of the beam from the unstable

[2)]Outwardly, this phenomenon resembles the process observed in[12].

state to the stable takes place upon an increase in the discharge of gas at the source, which corresponds not to a decrease, but to an increase in the longitudinal pressure gradient.

Thus a comparison of the results of our experiments with the results of [10,14] once more shows that the diversity of states of the plasma beam is of course not limited to those two states which in the present work are provisionally named "stable" and "unstable." On the other hand, it is not excluded that there lies a single general physical mechanism behind these two instabilities which, under different conditions of experiment, leads to different consequences: either to the "unstable plasma beam" under the conditions [13], or to mode II under the conditions [10,14].

In conclusion, the authors express their gratitude to M. S. Ioffe and Ya. B. Faĭnberg for useful discussions, and also thank E. K. Eroshchenkov who took part in some experiments.

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Translated by R. T. Beyer
187