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FORMATION OF A VIRTUAL CATHODE IN AN ELECTRON BEAM PASSING THROUGH A PLASMA

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The nature of a previously observed [1] instability of an intense plasma beam in a strong magnetic field, which causes effective ion acceleration transverse to the magnetic field,[2] is analyzed. It is shown by direct experiment that this instability is manifest in the formation of a virtual cathode in the beam of fast electrons passing through the plasma column.

We have already investigated experimentally[1,2] some properties of an intense beam of fast electrons passing through the plasma column which they produce in a strong longitudinal magnetic field. It is shown in [1] that under certain conditions, namely when the current density in the electron exceeds a certain critical value, the beam displays a unique instability. Upon occurrence of this instability, the character of the passage of the fast-electron beam through the plasma column changes radically. When the beam is stable, all the electrons emitted from the cathode and accelerated in the cathode layer by the discharge potential difference V_d (Fig. 1) move along the magnetic field and reach the beam collector (anode). When the beam becomes unstable, the current of the electrons from the cathode layer (discharge current) remains practically constant, but the anode current (I_a) decreases sharply. Simultaneously, a large flux of electrons is produced transversely to the strong magnetic field and goes to the walls of the discharge chamber of the plasma source ($I_{d.c}$); the sum of the electron currents parallel and perpendicular to the magnetic field remains approximately constant, $I_a + I_{d.c} \approx I_d$. Such a sharp redistribution of the electron currents parallel and perpendicular to the magnetic field is accompanied by the occurrence of intense oscillations in the currents I_a and $I_{d.c}$; the phases of these oscillations are in opposition and the period of the oscillation amounts to fractions of a microsecond.

This instability imposes a limitation on the current density of the fast-electron beam which can pass freely through the plasma [1]. It also causes effective acceleration of the ions transverse to the magnetic field [2].

As to the nature of this instability, it was suggested in [1] that it is connected with the formation of a virtual cathode in the fast-electron current (henceforth, when speaking of the unstable plasma beam, we shall have in mind precisely this type of instability, characterized by the outward symptoms indicated above).

According to this point of view, the indicated outward manifestation of the instability of the beam is explained by the fact that only part of the beam electrons pass through the plasma column, and the remainder are reflected by the virtual cathode and move under the influence of the resultant strong electric fields transversely to the magnetic field to the walls of the discharge chamber of the plasma source.

The main purpose of the present investigation was to check this point of view by performing an experiment on the direct observation of the virtual cathode in the unstable plasma beam.

In this experiment (Fig. 1), two insulated plane tantalum rings were placed around the plasma beam so that they could be moved along the beam axis both inside and outside the discharge chamber. The gap between the rings was 2 mm and the ring thickness was 1 mm. The internal diameters of the rings were equal in one series of measurements (2 cm) and different in the other series; in the latter case the diameter of ring number 1, facing the cathode of the plasma source was 1.6

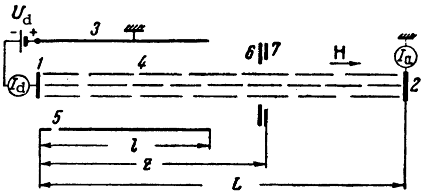

FIG. 1. Geometry of experiment with rings: 1–plasma source cathode, 2–anode (plasma beam receiver), 3–discharge chamber, 4–plasma beam, 5–gas inlet to the source, 6–ring No. 1, 7–ring No. 2; l = 15 cm, L = 170 cm, z–distance from the cathode to the ring.

cm, while the diameter of ring number 2, facing the anode was 2 cm. The discharge chamber had a 4 cm diameter and a length l = 15 cm, the cathode diameter was 1 cm, the plasma beam length (distance from cathode to anode) was L = 170 cm, and the anode diameter was 15 cm. The discharge chamber, vacuum chamber, and the anode were at ground potential (assumed in the following to be zero). The gas (hydrogen) pressure in the discharge pressure was of the order of 10^{-3} mm Hg while that in the vacuum chamber was $\sim 10^{-5}$ mm Hg.

The object of the experiment was as follows: if the decrease of the electron current to the anode, which is observed in the unstable beam mode, is actually due to the reflection of fast electrons from the virtual cathode produced in the beam, then some of these reflected electrons (moving in the resultant electric field transversely to the magnetic field) should arrive at ring number 2. In other words, the virtual cathode (if it is really produced) can be observed by comparing the energy spectrum of the reflected electrons (reaching ring number 2) with the energy spectrum of the beam electrons moving in the forward direction (from the cathode to the anode).

The experiment was carried out with the experimental set-up described in [2]. The energy spectrum of the plasma-beam fast electrons moving in the forward direction was measured by the method of the retarding field with an analyzer (Fig. 2) consisting of an anode, intermediate electrode (grid) and collector. Holes 0.5 and 2 mm in diameter were provided in the anode and in the intermediate electrode, respectively; the thickness of each of these electrodes was 6 mm. The intermediate electrode was used to eliminate interference on the part of the secondary electrons knocked out by the beam electrons from the collector; to this end, a potential $V_g = -25$ V relative to the collector was applied to it. The measurements have shown that prior to formation of the dense plasma the electron beam is monoenergetic. This is illustrated by curve c of Fig. 2, plotted without feeding gas to the source ($p = 3.5 \times 10^{-6}$ mm Hg) at a sufficiently low beam current (I_a = 7.5 mA). Following the formation of the stable plasma beam, the energy spectrum of the fast electrons becomes smeared out and is characterized at any distance from the source and for any beam current ($2\text{ mA} \leq I_a \leq 1.5\text{ A}$) by the deceleration curves a and b of Fig. 2. It is seen from Fig. 2 that the fast electrons of the stable plasma beam have a continuous energy spectrum.

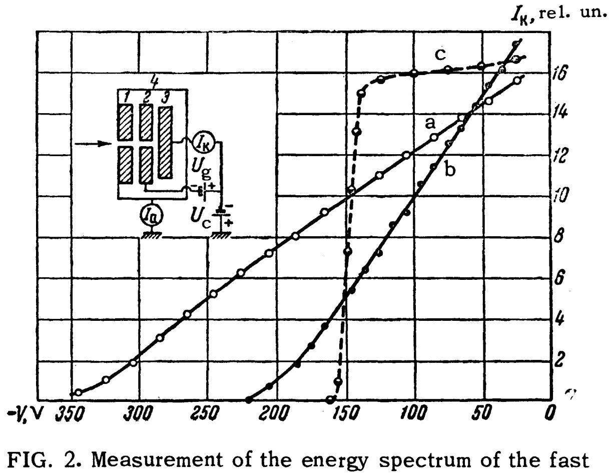

FIG. 2. Measurement of the energy spectrum of the fast electrons of the plasma beam: 1—anode, 2—"grid," 3—collector, 4—screen (the arrow shows the beam direction), right—deceleration characteristics of the collector with $V_g = -25$ V, H = 2400 Oe, L = 26 cm: a—V_d = 300 V, $I_d = I_a$ = 300 mA, b—V_d = 160 V, $I_d = I_a$ = 1000 mA, c—V_d = 160 V, I_a = 7.5 mA, no gas fed to the source; $V = V_c + V_g$.

The energy spectrum of the unstable plasma beam is also continuous and contains a relatively large number of "anomalous" electrons (whose energies exceed eV_d). Such a strong smearing of an initially monoenergetic fast-electron beam, as shown by simple estimates, cannot be attributed to collisions between the electrons and atoms or ions. It is well known that a monoenergetic beam of fast electrons entering into a low pressure plasma acquires a continuous energy spectrum as a result of effective loss of electron energy to the excitation of electronic plasma oscillations (see, for example, [3,4]). From the fact that such a character of the energy spectrum of fast electrons is observed also in the stable plasma-beam mode, it follows that the investigated instability of the beam is not connected directly with the excitation of electronic plasma oscillations by the beam.

In connection with such a character of the energy spectrum of the fast beam electrons, we must again agree on the definition of the term "virtual cathode." In the case of a monoenergetic electron spectrum, this term is used, as is well known (see, for example, [5]), to denote the region from which part of the beam electrons is reflected and which has a negative potential equal to the electron energy. By virtual cathode in the case of a beam with a smeared energy spectrum we understand here (as also in [1,2]) the region of the beam with negative potential of the order of the mean energy of this spectrum.

After measuring the energy spectrum of the beam electrons moving in the forward direction, we investigated the character of the energy spectrum of the electrons moving in the opposite direction (from the anode to the cathode). Initially, in order to estimate the energy of the electrons arriving at the rings (Fig. 1), we measured the floating potential of each of the rings (i.e., the potential at which the total current of the electrons and ions to the ring is equal to zero) as a function of the distance from the rings to the cathode. During the measurement of the floating potential of one of the rings, the neighboring ring was grounded. The measurements have shown that for a stable beam ($I_a \gtrsim I_d$) the floating potential of each of the rings does not exceed several volts; the currents to the grounded rings are in this mode also small (not exceeding several milliamperes). The results of the measurements made in the unstable beam mode ($I_a < I_d$) are shown in Fig. 3, in which curves a pertain to rings of equal diameter and curves b to unequal rings.

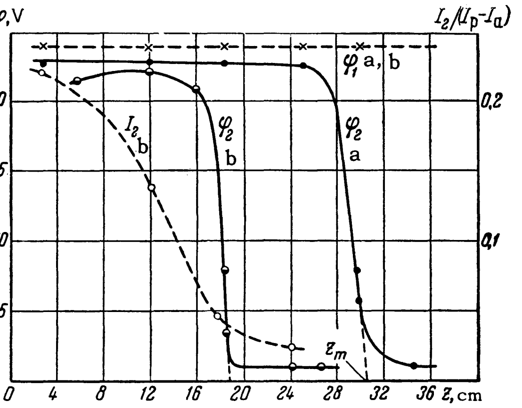

FIG. 3. Floating potentials of the first ring (φ_1) and of the second ring (φ_2) as functions of the distances from the cathode to the rings: a–both rings 2 cm in diameter; b–first ring diameter 1.7 cm, second 2 cm. I_2–current to second ring at zero ring potential. Diameter of discharge chamber 4 cm; length 15 cm; H = 2700 Oe, V_d = 250 V, I_d = 1.5 A, I_a = 0.6 A.

Let us discuss first case a. We see that in this case ring No. 2 is charged to a high negative potential if the distance z from this ring to the cathode does not exceed some maximum value ($z_{max} \approx 31$ cm), and at $z > z_{max}$ the floating potential of ring No. 2 is close to zero. Ring No. 1 is charged to a high negative potential at any distance from the cathode (this fact will be explained below).

It follows from Fig. 3 that the unstable plasma beam is divided in length into two regions which differ greatly in the character of motion of the fast electrons. In the first region, from the cathode to the plane $z = z_{max}$, the fast electrons move in both the forward direction (from the cathode to the anode) and in the opposite direction. In the second region, from the plane $z = z_{max}$ to the anode, the fast electrons move only in the forward direction.

Figure 4 shows the volt-ampere characteristics of ring No. 2, plotted in the unstable beam mode at $z < z_{max}$ and at $z > z_{max}$.

Attention must be called to the fact that the energy spectrum of the electrons moving in the reverse direction changes abruptly on passing through the plane $z = z_{max}$. In fact, whereas for $z > z_{max}$ this spectrum has an average energy ~ 5 eV and is cut off at an energy ~ 30 eV, when $z < z_{max}$ it contains a large number of fast electrons, the energies of which extend to the value of the accelerating (discharge) voltage V_d. In other words, whereas for $z > z_{max}$ the energy spectrum of the electrons moving in the reverse direction does not contain any fast electrons, when $z < z_{max}$ this spectrum is close to the energy spectrum of the fast electrons moving in the forward direction, i.e., to the energy spectrum of the electrons with energy eV_d, which smears out as a result of their interaction with the plasma (compare Fig. 4 with Fig. 2).

The volt-ampere characteristic of ring No. 1 for arbitrary z has the same form as curve a of Fig. 4.

Thus, the change in the energy spectrum of the electrons that move in the reverse direction on going through the plane $z = z_{max}$ leads to the conclusion that a virtual cathode is produced in the fast-electron current in the unstable plasma beam, and that this occurs in the region of the plane $z = z_{max}$.

This conclusion is confirmed also by the fact that with decreasing plasma beam length L, the

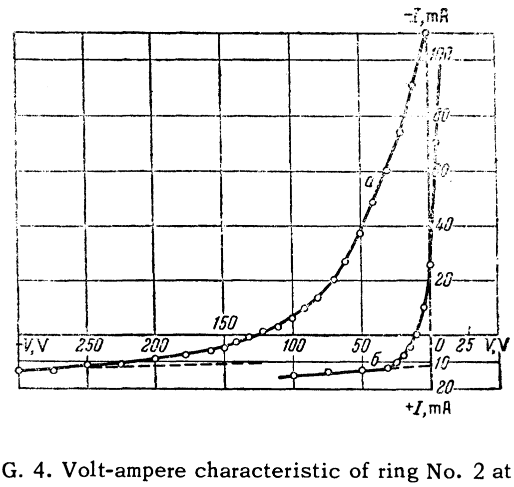

FIG. 4. Volt-ampere characteristic of ring No. 2 at two ring positions: a–$z < z_{max}$, b–$z > z_{max}$. H = 2700 Oe, V_d = 300 V, I_d = 1.5 A, I_a = 0.6 A.

beam becomes stable when $L \lesssim L_{max} \approx z_{max}$. The latter is illustrated by Fig. 5, which shows the dependence of the floating potential of stationary ring No. 1 on the distance between the cathode and the anode. The abrupt increase of the potential $|\varphi_1|$ from 0 to 120–140 V with increase in L from 30 to 35 cm is explained by the fact that when $L \leq 30$ cm the beam is stable, but when $L \gtrsim 35$ cm a virtual cathode is produced in the beam. The formation of the virtual cathode in the beam explains also the fact that all the manifestations of beam instability considered here remain when the anode with zero potential is replaced with a reflector having the cathode potential (see below).

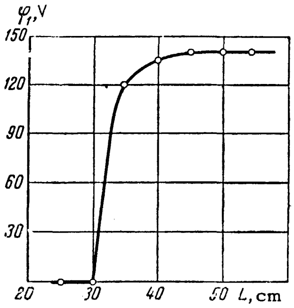

FIG. 5. Dependence of the floating potential of ring No. 1 on the distance between the cathode and the anode. Experimental conditions the same as for Fig. 2.

As was already noted, in a beam which is unstable with respect to the formation of the virtual cathode, intense currents of fast electrons transverse to the magnetic field are observed, and the electron current to the discharge chamber becomes comparable with the total current of the electrons leaving the cathode. It follows from this that large azimuthal electric fields are produced in the unstable beam and these lead to a rapid drift of the electrons in a radial direction. The occurrence of azimuthal fields is due apparently to the spatial inhomogeneities in the beam, and also possibly to the fact that the virtual cathode is produced not simultaneously over the entire cross section of the beam, but alternately, in individual "jets." The magnitude of these fields can be estimated roughly from the results of the experiment with the unequal rings. Figure 3 shows that in case b we obtain qualitatively the same results as in case a, except that ring No. 2 is no longer charged to a high negative floating potential when the distance to the cathode is ~12 cm shorter than in case a. This enables us to estimate the azimuthal component E_φ of the electric field in the plasma beam. In fact, if the rings are shifted towards the cathode by an amount Δz from the plane $z = z_{max}$, then the fast electrons reflected from the virtual cathode at $z \approx z_{max}$ can strike ring No. 2 only if in twice the time necessary to transverse the distance Δz under the influence of fields E_φ and H they can drift in a radial direction by an amount ΔR equal to the difference in the radii of the rings. This condition has the form

$$2c\frac{E_\varphi}{H}\frac{\Delta z}{v} \geqslant \Delta R, \qquad (1)$$

where v is the electron velocity and c the velocity of light. For H = 2700 Oe, $v = 10^9$ cm/sec, $\Delta z = 12$ cm and $\Delta R = 0.2$ cm we get from (1)

$$E_\varphi \geqslant 200 \text{ V/cm}. \qquad (2)$$

Such electric fields exist over the entire section of the beam between the plane $z = z_{max}$ and the cathode. This follows from the fact (Fig. 3) that the current I_2 of the electrons flowing to ring No. 2 increases monotonically with increasing distance from the ring to the plane $z = z_{max}$.

The data obtained lead to some conclusions concerning the character of the time variation of the electric fields in the beam. Thus, from the oscillograms of [1] we see that in the case of the unstable beam intense oscillations are produced in the electron currents to the anode and to the discharge chamber, with opposite phases and with periods of the order of a fraction of a microsecond1). In accordance with the data presented here, this means that the virtual cathode (and the electric fields associated with it), once produced, does not remain constant but vanishes and reappears, with a period of the order of a fraction of a microsecond. Thus, the experimental data considered lead to the following notion concerning the character of the motion of fast beam electrons. At those instants of time when a virtual cathode exists in the beam, a considerable portion of the fast electrons oscillates between the cathode and the virtual cathode and drifts under the influence of the electric fields transversely to the magnetic field.

It is easy to see that in such strong electric fields, determined by (1) and (2), the fast electrons have time to drift several centimeters in a radial direction during the time of the existence of the virtual cathode (tenths of a microsecond), i.e., they have time to strike the wall of the plasma source discharge chamber. In those time intervals when the virtual cathode vanishes, the fast electrons pass freely through the plane $z = z_{max}$ and move towards the anode. The latter circumstance explains (Fig. 3) why ring No. 1 is charged to a high negative potential for any distance from the source. With such a character of the electron

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1) Some annoying misprints have crept into [1]. Figure 6 must be reversed and the captions of Figs. 8 and 9 interchanged.

motion, the time-averaged electron current to the anode is, naturally, considerably smaller than the total discharge current ($I_a < I_d$).

In conclusion we present a few experimental data pertaining to the properties of the so-called ''oscillating arc.'' The latter differs from the ''dc arc'' described above in that the anode, which has the same potential as the discharge chamber, is replaced by an electron-beam reflector having the cathode potential. Our observations have shown that the oscillating arc can also be either stable or unstable. In the latter case, as in the case of the unstable dc arc, not only are fast ions emitted from the arc [2], but electric fields of the order of 200 V/cm are also produced. The fact that these attributes of an unstable beam are qualitatively the same in the dc and oscillating arcs favors the assumption that the instability has the same nature in both modes. The volt-ampere characteristic of ring No. 2 in the unstable mode of the oscillating arc is very similar to curve a of Fig. 4, which pertains to the unstable mode of the dc arc for $z < z_{max}$, differing from the latter only in the value of the floating ring potential (−220 in place of −125 V, with $V_d = 300$ V), and the somewhat larger number of electrons with energies of order eV_d. In the stable oscillating arc mode, the characteristic of ring No. 2 is practically the same as curve b of Fig. 4 and thus shows that the energy of the electrons arriving at the ring does not exceed 20—30 eV. The latter signifies that in the stable beam mode the fast electrons which oscillate between the cathode and the anode and which drift slowly in a radial direction have time to lose (by interaction with the plasma and the neutral gas) an overwhelming part of their energy prior to reaching any of the rings. This does not occur in the unstable beam mode because of the considerably larger radial drift velocity, and the beam electrons arrive at the rings with higher energies.

The question of the mechanism of the instability of the plasma beam with relation to the formation of a virtual cathode still remains open.

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