# Investigation of the dynamics of formation of electron beams in a linear discharge

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It is shown that strong electron beams are generated in linear discharges, at a plasma concentration $n \sim 10^{12}$–$10^{13}$, in space charge layers that may arise near the electrodes, as well as in the plasma column. During the discharge they move with a velocity $v \sim 10^6$–$10^7$ cm/sec from the cathode to anode. The formation and movement of the layers are related to confinement of the carriers near the cathode or in the plasma owing to the inhomogeneity of the latter. The magnitude of the beam current produced in the space-charge layer is determined by the emissivities of the cathode and of the plasma, whereas its duration is determined by instabilities produced in the discharge.

## INTRODUCTION

Experiments with a linear plasma betatron[1], and also a number of experiments with direct discharges[2-5] have demonstrated the possibility of formation in a plasma of intense electron beams with current on the order of several kiloamperes. In spite of the great practical interest in the production and use of such beams, many problems of beam formation in a plasma have not been sufficiently well studied. Thus, the mechanism whereby the beams are formed is not clear. In a number of studies[4,5], the formation of the beam in a straight discharge is attributed to two-stream current instability, which appears in a plasma in electric fields exceeding the Dreicer field[6]. In this case the collective effects produce in the plasma a turbulent zone 5—20 cm long with an effective collision frequency $\nu_{\text{eff}} \sim v/l$, where v is the velocity of the beam electrons and $l$ is the length of the turbulent zone. This region of "anomalous" resistance of the plasma, in which the principal drop of the potential applied to the discharges is observed, is not connected with the layers next to the electrodes, and moves from discharge to discharge along the plasma column. The dissipation of the energy of the external circuit in the anomalous resistance causes the energy to be consumed not in heating of the plasma, but in translational motion of the beam of accelerated electrons.

This explanation of beam formation in a plasma does not yield any information on the energy-transfer mechanism itself, since the presence of the effective collisions $\nu_{\text{eff}}$ in the turbulent discharge zone, and hence in the region of anomalous resistance, should lead, one might think, to the dissipation of the energy in the turbulent discharge zone itself. Yet it is shown in[4] that more than 50% of the capacitor energy can be converted into the energy of translational motion of the fast electrons. In other papers[1-3], on the other hand, it is assumed that the principal role in the formation of the beams in the plasma is played by the layer next to the cathode, on which practically the entire voltage applied to the plasma is concentrated, owing to the limitation of the number of carriers. It is in this layer that the electric field reaches $10^5$—$10^6$ V/cm, where the intense electron beam is made up of the electrons emitted by the cold cathode. A diode of sorts is produced, in which the anode is the dense quasi-neutral plasma at the potential of the positive electrode, and the cathode is the negative electrode. The plasma plays in this case the role of the medium that contributes to the concentration of almost the entire voltage applied to the electrodes in the narrow near-cathode layer.

Closely connected with the beam-formation mechanism is a question of practical importance, that of the possible duration of high-power electron beams formed in the plasma. The duration of the electron beams obtained to date in discharges ranges from 0.3 to 1.0 μsec.

The present paper is aimed at a study of the conditions of beam formation in a plasma, as well as the possibility of obtaining in a plasma a large-current electron beam with large duration of the current. Therefore, instead of the solenoidal voltage of short duration (0.5 μsec) used by us earlier[1], we used a straight discharge of a capacitor bank through a plasma; this has made it possible to obtain, under certain conditions, a high-voltage pulse of several dozen microsecond duration.

Our results give grounds for assuming that the formation of strong-current electron beams occurs in space-charge layers. These electric layers can be produced not only near the electrodes, but also in parts of the plasma column that are far from the electrodes. The formation of these layers is due not to the development of plasma instabilities in electric fields $E > E_{\text{cr}}$ ($E_{\text{cr}}$ is the critical Dreicer field) and to the onset of anomalous resistance in the plasma, but to the limitation of the number of carriers in that part of the plasma column where the plasma density is minimal. Such an inhomogeneous longitudinal distribution of the plasma density takes place frequently in real experimental conditions.

## EXPERIMENTAL SETUP AND MEASUREMENTS METHODS

The experimental setup is shown in Fig. 1. A highly ionized plasma with density $n_0 \sim 5 \times 10^{11}$—$3 \times 10^{13}$ cm$^{-3}$ was produced at a pressure $p \sim (1$—$5) \times 10^{-5}$ mm Hg in a glass chamber (length 60 cm, diameter 8 cm) placed in a magnetic field of intensity up to 5 kOe. To ionize the residual gas, an electron beam was injected into the chamber with a current 4 A, an energy 8 keV, and a pulse duration 160 μsec; this beam was produced by electrons source 4. The initial plasma-column diameter in the chamber was 2 cm.

The discharge voltage was applied to stainless-steel reticular electrodes (2—cathode, 3—anode) of 5 cm diameter, with a delay 10—100 μsec after the end of the injection of the plasma-producing beam into the chamber. These delays have made it possible to operate with a decaying plasma with preselected concentration in the range $n_0 \sim 5 \times 10^{11}$—$3 \times 10^{13}$ cm$^{-3}$. The discharge voltage was applied from a 0.4-μF capacitor bank charged to 25 kV, through a vacuum discharge gap or through a thyratron. Connected in parallel with the discharge chamber was a resistor $R_{\text{sh}}$, which formed in the absence of plasma in the chamber together with the dis-

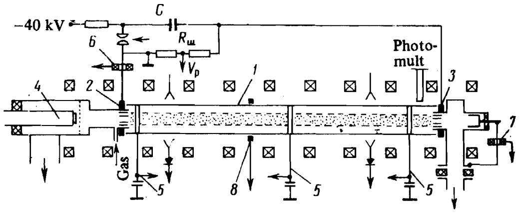

FIG. 1. Experimental setup. 1—Discharge chamber, 2—cathode, 3—anode, 4—electron source, 5—capacitive probes, 6—Rogowski loop to measure the total discharge current, 7—Rogowski loop to measure the beam current, 8—diamagnetic probe.

charge capacitance, a discharge circuit with time constant $R_{sh}C = 100\ \mu$sec.

The beam produced in the straight discharge passed through the reticular anode into a region with reduced gas pressure and was incident on a collector, where it was registered with a broadband (bandwidth 50 MHz) Rogowski loop 7 with a large dynamic output-voltage range, making it possible to feed the signal directly to the oscilloscope plates. A second Rogowski loop 6 registered the total discharge current. The voltage on the electrodes was measured with the aid of the voltage divider $R_{sh}$.

To measure the distribution of the potential along the plasma column as a function of the time, external capacitive probes 5 were placed in several spots along the chamber. The signals from the probes were fed to the plates of a two-beam oscilloscope. These probes registered the plasma potential relative to the cathode at the location of the probe.

The energy of the electrons of the beam produced in the straight discharge was estimated from the hardness of the x rays from the beam collector. The high-frequency radiation produced upon interaction of the beam with the plasma was registered with loop and horn antennas placed at three points along the setup.

The plasma concentration was estimated from the cutoff of microwave signals of wavelength $\lambda \sim 3$ cm and $\sim 8$ mm, and also with the aid of a microwave interferometer operating at 8 mm. To obtain the spatial distribution of the plasma concentration, the microwave apparatus was placed at three points along the setup. The concentrations were registered simultaneously.

## EXPERIMENTAL RESULTS

As shown by measurements of the time distribution of the potential along the plasma column, a straight discharge at a plasma concentration $n_0 \sim 10^{11}$—$10^{13}$ cm$^{-3}$ is initiated when the voltage applied to the cathode becomes concentrated in the near-cathode layer of the plasma, and the entire plasma column assumes the potential of the positive electrode. The redistribution of the potential proceeds at the same rate as the growth of the voltage, as is evidenced by the readings of the capacitive probe located in the immediate vicinity of the cathode, which registered the appearance of the positive potential equal to the electrode potential at the instant when the potential was applied to the electrodes. Depending on the initial concentration, the discharge can evolve in three ways that differ from one another both in the value of the discharge current and in the dependence of this current on the time. Figure 2a shows the dependence of the current on the plasma concentration during the initial stage of the discharge for a 20 kV voltage. It is possible to distinguish three regions in this dependence. At low concentration (region I), the current is very low ($I_d \sim 10$—$30$ A). At a concentration $n_0 \sim (1$—$2) \times 10^{12}$ cm$^{-3}$ (region II), the current increases jumpwise to 800—1000 A, after which it increases gradually. At $n_0 \sim (1$—$2) \times 10^{13}$ cm$^{-3}$, further increase of the discharge current takes place (region III). On going from one region to the other, the character of the discharge changes abruptly. Figures 2b—2d show discharge voltage and current oscillograms typical of these three regions ($V_0 \sim 15$ kV). The sweep duration is 60 $\mu$sec. As seen from the oscillograms, three types of discharge are possible (I, II, and III) in the straight discharge, depending on the plasma concentration. In many cases all three types are observed during one discharge of the capacitor, and gradually give way to one another. As shown by investigations, the generation of the electron beam takes place in discharges of type I and II.

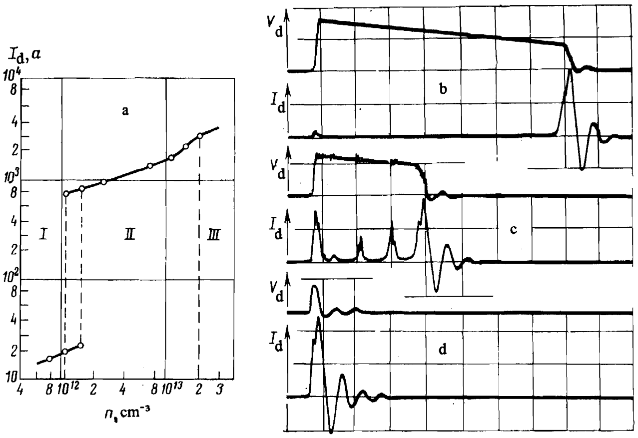

FIG. 2. Dependence of the current during the initial stage of the discharge of the plasma concentration (a); oscillograms of the discharge voltage and current in the first (b), second (c), and third (d) regions of the plasma concentration, V ≈ 15 kV, sweep 6 $\mu$sec/div.

A characteristic feature of the discharge of type I is the long lifetime of the near-cathode potential drop, the value of which is equal to the applied voltage. The entire plasma column, with the exception of the narrow region next to the cathode, has the potential of the anode. The maximum energy of the electrons participating in the transfer of the current during this stage of the discharge corresponds to the applied voltage. This indicates that a beam with $n_1 \ll n_0$ ($n_1$ is the beam-electron concentration) is produced in the near-cathode layer and carries the entire discharge current. A beam with current 10—30 A exists during the entire time, so long as there is a near-cathode voltage drop; this drop disappears at the instant when the oscillatory current is produced. During the entire lifetime of the beam, microwave radiation from the plasma is registered, at a frequency $\omega \sim \omega_{pe}$. The passage of the beam through the plasma column and its interaction with the plasma leads to a gradual increase of the concentration of the plasma and of the beam current. When a value $n \sim 2 \times 10^{12}$ cm$^{-3}$ is reached, the second type of discharge is produced, and goes over immediately into an oscillatory discharge, in which the plasma concentration and the discharge current increase rapidly and the voltage decreases. The near-cathode potential drop then vanishes and the beam formation is interrupted.

The discharge of type II is more complicated in form. Figure 3 shows the time dependences of the voltage (1)

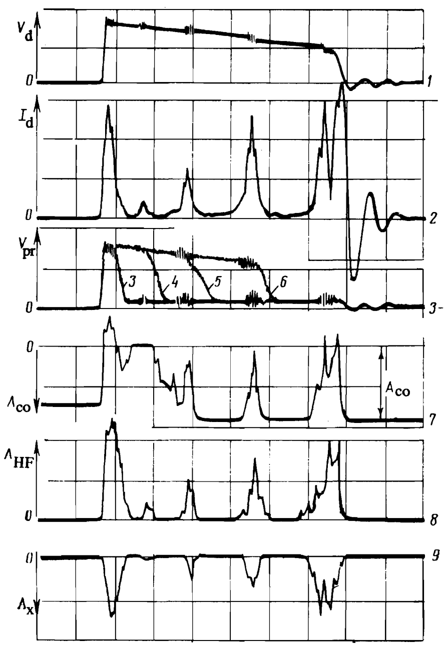

FIG. 3. Oscillograms of the voltage (1) and current (2) of the discharge, of the potentials of the capacitive probes (3–6), of the cutoff of the microwave signal (7), of the RF radiation (8), and of the x radiation (9) for a discharge of type II; $n_0 \sim 3 \times 10^{12}$ cm$^{-3}$, V ~ 15 kV, sweep 4 μsec/dov. A–signal amplitude.

and current (2) of the discharge, the signals from the capacitive probes (3–6) installed at distances 2, 47, 51, and 55 cm from the cathode, and the cutoff of a microwave signal of wavelength ~3 cm (7) that probes the plasma at the center of the chamber, the amplitudes of the RF oscillations (8) at frequency f ~ 500 MHz and of the x rays from the anode (9). Just as in the discharge of type I, the current in the discharge of type II is produced under conditions when the voltage drop becomes concentrated on the near-cathode layer of the plasma, as is evidenced by the signals from the capacitive probe. However, in contrast to the discharge of type I, the current reaches $I_d \sim 800$–$1000$ A. The existence of a near-cathode voltage drop layer and the presence of hard x rays from the anode, with energy equal to the applied voltage, indicate that a high-power electron beam is produced in the near-cathode layer in this type of discharge. This beam passes through the reticular anode and through the anode vacuum chamber, and strikes a collector, where it is registered with the Rogowski loop 7 (Fig. 1). The currents measured by loops 6 and 7 during the initial stage of the discharge are practically equal. Since the loop 6 registers simultaneously also the current of the fast electrons that move to the collector and are measured by loop 7, the equality of the currents registered by the loops 6 and 7 proves that the entire discharge current at the instant of generation of the strong-current beam is transported by the beam of fast electrons. Its duration amounts to 1–2 μsec, after which the beam current decreases sharply and the so-called pause in the current is produced. During the time of the pause, the current does not vanish completely, but is maintained at a level of 30–40 A, increasing gradually. A small resistor $R_{sh}$ (Fig. 1) connected in parallel with the plasma column prevents an overvoltage from being produced on the electrodes at the instant when the discharge-circuit current decreases abruptly. Current bursts, which sometimes reach 1000 A and more and have a duration ~1 μsec, are observed against the background of the pause. In one of the bursts, the current goes over into an oscillatory discharge regime, after which the voltage on the electrodes decreases rapidly.

To explain the factors that cause interruption of the strong-current beam and prevent the production of a beam of large duration, we investigated the temporal and spatial behavior of the plasma concentration, of the potential distribution, and of the x rays and the RF radiation. The experimental results show that the interruption of the current, which is observed 1–2 μsec after the production of the beam, is correlated in time with the rapid decrease of the plasma concentration ("unblocking" of the 3-cm signal takes place, Fig. 3, curve 7) and with a displacement of the potential-drop layer from the cathode into the plasma column (Fig. 3, curves 3–6, the signal from the probe placed near the cathode vanishes after 2 μsec, and the signals from the probes closer to the anode vanish with ever-increasing delay). The interruption of the beam current is also correlated in time with the vanishing of the x rays and the RF radiation (f ~ 200–10 000 MHz). As shown by measurements of the plasma diameter, at the instant of beam interruption, i.e., 2 μsec after the start of the discharge, the plasma column broadens and occupies the entire volume of the discharge chamber.

An investigation of the pause in the current has shown that at small electrode voltages ($V_0 < 10$ kV) the duration of the pause can reach 20–30 μsec without the appearance of current bursts. The current does not remain constant at the instant of the pause, but changes jumpwise all the time, in the range from 30 to 50 A, increasing on the average towards the end of the pause. The discharge current at that instant is carried by a small number ($n_1 < n$) fast electrons of the weak-current beam. This beam, in analogy with the beam in the type-I discharge, is formed in a potential-drop layer that becomes detached from the cathode and moves with variable velocity along the plasma column towards the anode. The rate of displacement of the potential-drop layer was estimated from the time required by it to cover the distance between neighboring capacitive probes. It is maximal ($v \sim 10^7$ cm/sec) at the initial instant of time after the interruption of the beam current and the formation of the pause in the current. The layer motion then slows down. Before the next burst of current, and also as the layer approaches the anode, the velocity decreases to ~$10^5$ cm/sec and lower. The spatial localization of the potential-drop layer in the current pause amounts to 2–5 cm. The motion of the layer at the instants when the secondary current bursts occur is more complicated in character and its study has not yet been completed. When the oscillatory discharge sets in, the potential-drop layer in the plasma disappears.

A study of the behavior of the plasma concentration in time and in space has shown that during the time of the pause, in addition to the displacement of the layer carrying the main potential drop, there is also motion of the front of a dense plasma ($n > 10^{13}$ cm$^{-3}$) in the current. The plasma-concentration drop moves from the cathode to the anode with an average velocity ~$5 \times 10^6$ cm/sec. As shown by an analysis of the "cutoff" of the microwave signals, immediately after the onset and interruption of the strong-current beam formed during the initial stage of development of the straight discharge, the plasma concentration decreases abruptly over the entire length of the chamber (the microwave signal becomes "unblocked" (Fig. 3, curve 7)), with the exception of the region near the cathode, where it increases. Subsequently, during the time of the current pause, the dense plasma propagating from the cathode first leads to a blocking of the microwave signal in the central part of the chamber, and finally at the anode. By the instant the oscillatory discharge sets in, the dense plasma fills the entire chamber. The concentration of the anode plasma (the plasma region located on the anode side of the potential-drop layer) increases gradually during the pause and by the instant when the secondary current bursts are produced it reaches values $8 \times 10^{11}$—$10^{12}$ cm$^{-3}$.

An appreciable contribution to the explanation of the mechanism producing the strong-current beams in straight discharges is made by a study of the current bursts. As shown by investigations, the current bursts produced after the pauses constitute strong-current beams of electrons with energy corresponding to the voltage applied to the electrodes, and with $n_1 \ll n$ particles that transport the entire discharge current. At the instant of beam generation, hard x rays are registered as well as HF noise (f ~ 100—10,000 MHz) (Fig. 3, oscillograms 8 and 9), in analogy with the situation that occurs when a strong-current beam is formed during the initial stage of the discharge. At the instant of formation of the secondary strong-current beams the electrode voltages decrease by 2—3 kV, thus indicating that part of the capacitor-bank energy is diverted to acceleration of the beam particles. The determination of the spatial localization of the generation region of the secondary-strong-current beams occurs in the potential-drop layer under conditions when this layer moves along the plasma column.

With increasing voltage, the current of the beam formed during the initial stage of the discharge increases (Fig. 4), and its duration decreases. At the same time, the secondary strong-current beams increase and the duration of the pauses between them decreases. At a voltage above 30 kV, the secondary strong-current beams merge with the primary beam and with one another, forming an electron beam of current exceeding 1000 A and total duration up to 5 μsec. The current of this beam experiences multiple abrupt oscillations in a range 300—400 A. The accompanying noise in the plasma is so intense, that the study of the dynamic characteristics of the beam and of the plasma becomes very difficult.

With increasing initial plasma concentration, the current increases in both the first beam and in the secondary beams. At a concentration above $n_0 \sim 5 \times 10^{12}$ cm$^{-3}$, the formation of a strong-current beam during the initial stage of development of the straight discharge, and its interaction with the plasma, lead not to a lowering of the plasma concentration along the discharge chamber and to a pause in the current, but to an increase in the plasma concentration and an increase of the discharge current. Under these conditions, the type-II discharge, which ensured generation of intense beams, goes over into a type-III discharge, which is characterized by the absence of conditions for beam generation.

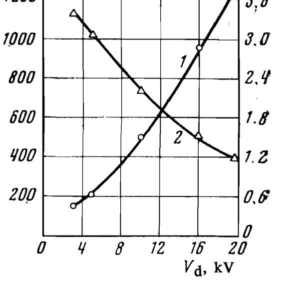

FIG. 4. Dependence of the current of the beam formed during the initial stage of the discharge (1) and of the beam duration (2) on the electrode voltage; $n_0 \sim 3 \times 10^{12}$ cm$^{-3}$.

The transition region of plasma concentration extends to $n_0 \sim 3 \times 10^{13}$ cm$^{-3}$. In the transition region, the total discharge current consists of two parts: an initial part, which is a strong-current electron beam with $n_1 \ll n_0$ and is formed in the layer next to the cathode, and the remainder, which is a beam of electrons with $n \sim n_0$ and with low energy. An increase of the plasma concentration above $n_0 \sim 5 \times 10^{12}$ cm$^{-3}$ leads to a gradual shortening of the beam-generation stage (type-II discharge) to fractions of a microsecond, and at a plasma concentration $n_0 \sim 3 \times 10^{13}$ cm$^{-3}$ practically no beam is formed, and the oscillatory discharge sets in immediately. The discharge current is carried in this case by all the plasma electrons, which have low energies. The current is determined by the wave resistance $(L/C)^{1/2}$ of the discharge circuit. With increasing voltage, the conditions for beam generation during the initial stage of discharge development remain in force for a denser plasma.

The magnetic field exerts no significant influence on the conditions of beam formation in the plasma. Changing the field from 2 to 5 kOe leads to a more stable onset of the type-II discharge, to a higher value of the current in the beam, and to an improvement in the reproducibility of the results. The value of the beam current produced during the initial discharge stage, and the probability of the appearance of any particular type of discharge, are greatly influenced by the degree of prior conditioning of the discharge by discharges and its outgassing. After prolonged operation, the emission of the electrons from the cathode decreases, and in place of a type-II discharge one obtains a type-I discharge at the same plasma concentration. It was therefore necessary to "restore" the cathode during the course of operation, by admitting a small amount of gas into the system for a certain time.

## DISCUSSION OF RESULTS AND CONCLUSIONS

Our results show that the formation of strong-current electron beams occurs both in the layer next to the electrode (just as in the experiments of [1-3]) and in the layer where the principle potential drop occurs in the plasma column (in analogy with the results of [4,5]).

The mechanism of beam formation in the near-electrode layers is well known. The dependence of the beam current on the cathode material and on the degree of its conditioning indicates that in discharges of type I and II the beam current is ensured by γ processes on the electrode [2,7]. The formation of strong-current beams (with current ~ 1000 A and more) is possible only at a plasma concentration $n_0 > 10^{12}$ cm$^{-3}$. In this case, an additional electron-emission mechanism appears and is apparently connected with the formation of cathode spots, as a result of which the beam current increases.

Let us examine the mechanism whereby strong-current electron beams are produced in a plasma column. As shown by the results, the formation of secondary strong-current beams occurs under conditions when the near-cathode space-charge layer, which takes the entire potential drop and in which the strong-current beam is produced during the initial stage of the discharge, moves in the plasma after becoming detached from the cathode. The movement of the layer in the plasma coincides in time with the appearance in the plasma column of concentration inhomogeneities, namely an increase of the concentration at the cathode and a sharp decrease along the chamber. The plasma-concentration drop moves in the same direction and at approximately the same velocity as the potential-drop layer. This is evidence that the existence and motion of a space-charge layer in the plasma is due to the inhomogeneity of its concentration. In this case the potential-drop layer itself is electric double layer, similar to that observed earlier in dc weak-current discharges[8,9] at places where the plasma concentration is decreased or where the diameter of the discharge changes; such a double layer separates two quasineutral plasmas (cathode and anode).

As shown by the simplest theory of the electric double layer (without allowance for its motion), the current density $j_e$ in a discharge with a double layer is given by

$$j_e = \frac{1.85}{9\pi}\left(2\frac{e}{m}\right)^{1/2}\frac{V^{3/2}}{d^2}. \tag{1}$$

Here V is the potential drop in the layer and d is the layer thickness. The density $j_e$ is connected with the flux of the ions moving to the double layer from the anode plasma by the relation

$$j_e = j_i (M/m)^{1/2}, \tag{2}$$

where $j_i = 0.4en(2kT_e/M)^{1/2}$ is the density of the ion current and is determined only by the plasma parameters.

It follows from (1) and (2) that the value of the current in a discharge with a double layer does not depend on the voltage, and is limited by the number of ions that move from the plasma into the double layer, i.e., by the plasma concentration. This property of a discharge with a double layer explains the singularity observed in our experiments, wherein an electron beam with a small current (during the pauses) and a large current (during the bursts) is produced at an almost constant electrode voltage in a discharge with a double layer (Fig. 3, curves 1 and 2). The small value of the beam current during the pause is explained by the limited number of the carriers in the anode plasma, owing to its low concentration during that time. The subsequent increase of the beam current to 1000 A and more during the time of the current bursts can be attributed to the rapid increase of the number of carriers with increasing anode-plasma concentration. It appears that the latter is due to ionization of the neutral gas that enters into the beam region from the chamber walls when the latter are bombarded by the particles of the expanding plasma and when the preceding strong-current beam is interrupted.

As shown in[9], motion of the double layer along the plasma column is due to the fact that the random electron flux $j_T = env_{Te}$ that enters the layer from the cathode side exceeds the discharge current $j_e$ that passes through the double layer. Recognizing that the production of the space-charge layer is connected with a limitation of the carriers, it can be assumed that these layers can be produced directly in an inhomogeneous plasma without their being formed at the electrode. It appears that the formation of such layers can explain the onset of turbulent regions of the principal potential drop, which were observed in some experiments on plasma heating in straight discharges[4,5], and which have not found sufficient explanation. This is indicated by the formation of the pause in the current, observed in[5], and by the experimentally obtained[10] dependence of the beam current on the voltage, which is characteristic of discharges with double layers.

In order to produce in a straight discharge a strong-current beam with large duration (more than 2 μsec) it is necessary to ensure stationary formation conditions during the duration of the voltage pulse. It follows from the experimental results that strong-current beams can be formed either in the near-cathode space-charge layer which is produced as a result of limitation of the carriers by their small emission from the electrode, or in an electric double layer located in the plasma column itself and produced as a result of the limitation of the carriers by the section of the column with the reduced plasma concentration. For a strong-current beam to be formed in the first case, it is necessary to ensure sufficient emission of the electrons from the cathode and this emission, as follows from Fig. 2a, depends critically on the plasma concentration. At plasma concentrations above $n_0 \sim 2 \times 10^{12}$ cm$^{-3}$ one observes an abrupt increase of the electron emission from the cathode (apparently as a result of the onset of cathode spots), so that it becomes sufficient for the formation of a strong-current beam. For a strong-current beam to be formed in the second case, the plasma concentration should also be large enough to ensure, according to relations (1) and (2), the required value of the beam current.

An analysis of the results shows that the phenomena accompanying the formation of strong-current beams are identical in both cases. The formation conditions are maintained for a short time, and vanishing is due to the fast disintegration of the plasma through which the strong-current beam passes. The intense microwave and x radiation from the plasma at the instant when the strong-current beam passes through it indicates that the cause of the plasma disintegration, and hence the disruption of the beam may be the low-frequency instabilities investigated in[11]. The dependence of the critical current of the beam and the time of its disruption on the electrode voltage (Fig. 4) is similar to that obtained in[11]. It should be noted that the instability has a threshold and develops in the plasma when the beam current exceeds I ~ 50–100 A. At currents below the threshold (10–20 A), electron beams that last a long time (up to 10 microseconds) can be formed (type I discharge, pause in the current).

To explain the cause of prolonged generation of a strong-current beam in a straight discharge it is necessary to investigate further the instabilities that lead to the disintegration of the plasma, in order to reveal the conditions for their stabilization. It must be emphasized that the conditions for the formation of a strong-current beam in a direct-discharge plasma disappear also when the anode plasma concentration greatly exceeds the cathode concentration, as is the case when a considerable amount of gas is released from the walls of the chamber or when working with an insufficiently ionized plasma (transition to the type-III discharge (Fig. 2d)). In this case a rapid increase of the plasma concentration as a result of the additional ionization of the neutral gas in the case of beam-plasma interaction leads to a vanishing of the layers and to a transition to a discharge in which the value of the current is determined by the wave resistance of the discharge circuit.

The results of the present set of experiments lead to the following conclusions.

1. When a large potential is applied to a highly ionized plasma (bounded or inhomogeneous in length) with concentration $10^{11}$–$10^{13}$ cm$^{-3}$, the potential is not distributed

over the entire plasma column, but is concentrated in the space-charge layer that is produced at the electrode or in the plasma column as a result of the limitation of the carriers in the given place.

2. At sufficient plasma concentration ($10^{12} < n < 10^{13}$ cm$^{-3}$) a strong-current electron beam is produced in the space-charge layer and carries the entire discharge current. A definite relation is automatically established in this case between the beam current and the plasma concentration.

3. The duration of the strong-current beam in the straight discharge is determined by the time during which a plasma with enough carriers exists. The beam duration is limited by the development of instabilities when the beam passes through the plasma. The disruption of the beam is due not to the onset of an anomalous resistance of the plasma following development of the instabilities, but to the decrease in the number of carriers as a result of the decrease of the plasma concentration.

Further investigation of the dynamics of electric layer production in a straight discharge should yield an answer to many unsolved problems. In particular, it may determine the values of the electric field and plasma-concentration drop needed for the formation of space-charge layers.

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[1] E. I. Lutsenko, Ya. B. Faĭnberg, V. A. Vasil'chuk, and N. P. Shepelev, Zh. Eksp. Teor. Fiz. **57**, 1575 (1969) [Sov. Phys.-JETP **30**, 853 (1970)].

[2] V. A. Simonov, V. V. Abozovik, and V. V. Ignat'ev, Proc. Internat. Conf. on Plasma Physics and Controlled Thermonuclear Fusion Research, Vol. 2, Vienna, IAEA (1966), p. 93.

[3] C. L. Hsien and A. J. Lichtenberg, Phys. Fluids **13**, 2317, 1970.

[4] A. I. Karchevskiĭ, V. G. Averin, and V. N. Bezmel'nitsyn, Zh. Eksp. Teor. Fiz. **58**, 1131 (1970) [Sov. Phys.-JETP **31**, 605 (1970)].

[5] N. K. Berger, V. S. Koĭdan, A. N. Papyrin, A. G. Ponomarenko, V. S. Stibunov, and B. A. Yablochnikov, Zh. Eksp. Teor. Fiz. **56**, 1463 (1969) [Sov. Phys.-JETP **29**, 784 (1969)].

[6] H. Dreicer, Phys. Rev. **115**, 238 (1959).

[7] V. L. Granovskiĭ, Élektricheskiĭ tok v raze (Electric Current in Gas), Nauka (1971).

[8] J. Langmuir, Phys. Rev. **33**, 954, 1929.

[9] M. J. Schönhuber, Zs. angew. Phys. **15**, 454, 1963.

[10] A. I. Karchevskiĭ and Yu. I. Strakhov, ZhETF Pis. Red. **13**, 595 (1971) [JETP Lett. **13**, 424 (1971)].

[11] E. I. Lutsenko, L. M. Kontsevoĭ, V. A. Bondarenko, and N. D. Sereda, Zh. Eksp. Teor. Fiz. **64**, 833 (1973) [Sov. Phys.-JETP **37**, 424 (1973)].

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