Investigation of current limitation in a strong-current discharge

E. I. Lutsenko, N. D. Sereda, and L. M. Kontsevoĭ

Kharkov State University
(Submitted July 2, 1975)
Zh. Eksp. Teor. Fiz. **69**, 2067–2078 (December 1975)

Results are presented of an investigation of current limitation in a straight discharge with a plasma density $n \gtrsim 10^{13}$ cm^{-3} in a longitudinal magnetic field. It is shown by measuring the spatial and temporal characteristics of the discharge that the current limitation in a strong-current high-voltage discharge is due to production of a double space-charge layer under conditions when the plasma density is longitudinally inhomogeneous, owing to local rarefaction of the gas during the course of the discharge. By producing conditions under which the charged particles can be removed from the discharge, it is possible to control the location and the time of the onset of the current limitation.

PACS numbers: 52.80.Pi

INTRODUCTION

Many experiments have by now been performed with direct discharges in a plasma with concentration $n > 10^{13}$ cm^{-3},[1-4] in which the onset of a large active resistance was observed during the course of the discharge. The resistance set in with a delay 0.5–1 μsec following the start of an inductive ($R < 2\rho$) discharge when the current exceeded a certain critical value that increased with increasing plasma concentration. The appearance of the resistance was revealed by the abrupt increase of the voltage across the electrodes, accompanied by a decrease of the discharge current, by the heating of the plasma, and by the appearance of intense high-frequency and x-ray emission. The cause of the appearance of the active resistance was assumed in[1-4] to be the production of anomalous resistance in the current-carrying plasma as a result of the plasma turbulence due to instabilities that develop in the plasma, namely ion-sound instability when the current velocity of the electrons v_e exceeds the ion sound velocity v_s, or electron-ion instability when v_e exceeds the thermal velocity v_{Te} of the plasma electrons.

This explanation of the onset of a large active resistance in the plasma cannot, however, explain a number of phenomena observed in the experiments. Thus, for example, from the assumption that the resistance is due to the development of current instabilities it follows that it must be distributed over the discharge gap. The electric field in the plasma should similarly be distributed over the discharge length. Yet the results obtained in[1,2] indicate that the main potential drop and acceleration of the charged particle are localized in a narrow discharge-gap region that can furthermore have different positions from discharge to discharge. This forces us to assume that some other mechanism is responsible for the appearance in the discharge of a large active resistance accompanied by the acceleration of the charged particles and by heating of the plasma.

Such a mechanism that limits the discharge current may be the formation of a double space-charge layer, such as observed in[5], in the discharge gap. The double layer is produced in a plasma that is longitudinally inhomogeneous because there are not enough carriers at the point where its density is decreased. The current is restricted in this case by the plasma parameters to the level

$$I \sim e n_m v_{Te} S \qquad (1)$$

regardless of the applied voltage, where n_m is the minimal plasma concentration in the discharge gap and S is the transverse cross section area of the plasma filament. The active resistance of the discharge is determined in this case by the resistance of the double layer

$$R_{\text{layer}} \sim V_p / e n_m v_{Te} S. \qquad (2)$$

The entire voltage applied to the electrodes is concentrated in the double layer, where intense electron and ion beams are produced with particle density $n_1 \ll n_0$, and carry the entire discharge current. The interaction of these beams with the plasma leads to development of two-stream instability and to plasma heating, i.e., a discharge with a double layer is outwardly accompanied by the same characteristic phenomena as the discharges described in[1-4].

The experiments described below are continuations of previously initiated[5] investigations of the dynamics of current limitation in strong-current discharges as a result of space-charge layer production. In contrast to[5], where the plasma concentration was so low ($n < 10^{13}$ cm^{-3}) that the limitation of the discharge current by the appearance of the space-charge layer was observed at the very start of the discharge, the present investigations were made at $n \gtrsim 10^{13}$ cm^{-3}, when conditions are realized for the flow of a strong-current discharge, in which the entire current is transported by all the plasma electrons with small directional velocity before it reaches a definite value that depends on the plasma parameters. In this case the value of the discharge current prior to its limitation depends on the applied voltage and is given by $I = V_0\sqrt{C/L}$.

EXPERIMENTAL PROCEDURE AND RESULTS

The experiments were performed with the apparatus described in[5] but modified as follows: the glass chamber placed in a longitudinal magnetic field $H_0 \sim 5$ kOe had a diameter 10 cm, the distance between the reticular electrodes was 70 cm, and the high-voltage electrode was the cathode. A voltage $V_0 \sim 2$–20 kV was applied from a capacitor bank rated $C = 0.4\ \mu$F to a discharge gap filled with a highly-ionized plasma with concentration $n_0 \gtrsim 1 \times 10^{13}$ cm^{-3} and temperature $T_e \sim 3$–5 eV, produced by a beam-plasma discharge at a gas pressure $p = 5 \times 10^{-5}$ mm Hg in the chamber with constant inflow of gas (air into the cathode region of the discharge. The initial diameter of the plasma filament was $d_0 \sim 2$ cm. The experiments were performed in a homogeneous magnetic field and in a magnetic field of mirror configuration.

To identify the mechanism that limits the discharge current, it was necessary to carry out a variety of experiments, including measurement of time dependence of the distribution of the potential along the discharge length, study of the behavior of the plasma concentration and the plasma-filament diameter, measurements of the fast-particle streams produced in the course of the discharge, and measurements of the RF and x-ray emission.

The distribution of the potential along the gap was measured simultaneously with several external capacitive probes that measured the plasma potential relative to the grounded anode. The temporal variation of the plasma concentration was estimated from the cutoff of microwave signals with frequencies 10–75 GHz simultaneously at three points along the chamber. The time variation of the plasma filament diameter was determined with the aid of three photomultipliers that received simultaneously light signals from points located in the chamber at different distances from its axis. A multigrid probe located behind the reticular anode was used to register the beam of fast electrons produced during the course of the discharge. The high-frequency emission produced by the interaction of the beam with the plasma was registered with loop and horn antennas.

We consider first the case of a homogeneous magnetic field. Figure 1a shows the following oscillograms: of the electrode voltage (V_d) of the discharge current (I_d), of the x-rays from the anode (A_X) and of the RF radiation from the plasma (A_{RF}); all these characterize the limitation of the discharge current and the accompanying processes. At the instant when the discharge is produced, the electrode voltage V_d decreases abruptly and amounts to approximately two-thirds of the capacitor voltage V_0, owing to the voltage drop across

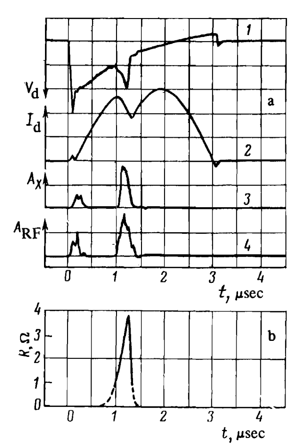

FIG. 1

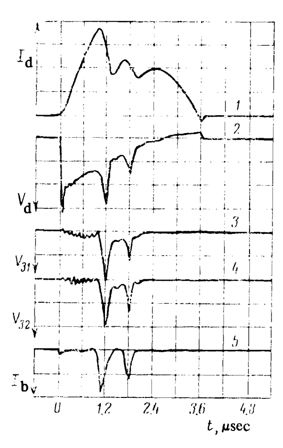

FIG. 2

FIG. 1. a) Oscillograms of the electrode voltages (V_d; 4000 V/div), of the discharge current (I_d, 1000 A/div), of the x rays (A_X) and of the RF emission (A_{RF}) (relative units). b) Time variation of the active resistance of the discharge.

FIG. 2. Oscillograms of the discharge current (1000 A/div), of the electrode voltage (4000 V/div), of the signals from the capacitive probes (V_{31}, V_{32}; 4 kV/div), and of the fast-electron beam current (I_b; 1000 A/div).

the conducting leads and the switching apparatus. Just as in[1-4], at a time $t \sim 1.2$ after the start of the discharge, during which the discharge current increased sinusoidally, the current stops growing and then decreases, and at the same time the voltage on the electrodes increases abruptly, indicating that a large active resistance has been produced in the discharge gap (Fig. 1b). At the same time that the current is limited, RF emission is observed from the discharge region adjacent to the anode, in a wide frequency band (50–30 GHz), as well as hard x rays from the anode. During the initial stage of the discharge there appeared also RF emission and x rays over the entire length of the discharge gap, but of much lower intensity. The current limitation due to the active resistance produced in the plasma can appear several times during the discharge and can occur both on the rising and on the dropping sections of the sinusoidal current.

Measurements of the distribution of the potential over the length of the discharge gap show that under the conditions when an inductive discharge exists (up to the instant when the current is limited) there is no electric field of noticeable magnitude in the plasma (capacitive probes reveal no presence of an active potential drop along the discharge gap). The active voltage drop appears in the discharge only at the instant when the active resistance is produced in it. Figure 2 shows oscillograms of the discharge current I_d, the electrode voltage V_d, signals V_{31} and V_{32} from capacitive probes placed 3 and 67 cm away from the current, and the fast-electron beam current I_b registered by a multigrid probe ($n_0 \sim 1 \times 10^{13}$ cm^{-3}). In this experiment, conditions were realized for double limitation of the beam in the discharge. At the instant of the appearance of the current limitation, all the probes placed along the chamber register the same potential, corresponding to the cathode potential. This indicates that the entire plasma filament acquires at that time the potential of the cathode and the entire potential drop occurs in a narrow (2–3 cm) region next to the anode, where the active resistance of the discharge is also concentrated. At the instant of discharge-current limitation, a beam of fast electrons passes through the reticular anode and strikes a multigrid probe, which serves as the collector for the entire beam. The maximum beam energy corresponded to the active voltage drop in the discharge, which sometimes exceeded the initial capacitor voltage. An estimate of the value of the beam current shows that the entire discharge current at the instant of current limitation is carried by the beam of fast electrons. A low-intensity beam of fast particles is registered also during the initial stage of the discharge.

An investigation of the time variation of the discharge current has shown that at a low given voltage ($V_0 < 4$ kV) and at large plasma densities ($n_0 > 3 \times 10^{13}$ cm^{-3}) the discharge has a sinusoidal character, and its current does not depend on the plasma parameters but is determined only by the charging voltage V_0 and the wave resistance of the circuit, $\rho = 1.5\ \Omega$. With increasing voltage and decreasing plasma density, the current deviates from that given by $I_d = V_0\sqrt{C/L}$, and its shape deviates from sinusoidal, and they begin to depend on the plasma parameters n_0 and v_{Te}. For each set of chosen plasma parameters there is a definite current I_{cr} at which the dependence on these parameters sets in. Figure 3 shows the dependence of the limitation current I_M on the capacitor voltage V_0 at three values of the plasma density (at high plasma density, the value of I_M is limited by the parameters of the external circuit ($I_M = V_0/\rho$), and at low density it is limited by the plasma parameters n_0 and v_{Te}). At a discharge current $I_M < I_{cr}$, the current waveform is sinusoidal. After the current reaches the value I_{cr}, its waveform is no longer sinusoidal, and I_M ceases to vary—the discharge current becomes limited. With increasing plasma density, I_{cr} increased and no current limitation occurred in our experiment at a plasma density $n_0 > 2 \times 10^{13}$ cm^{-3}. The magnitude and lifetime of the resistance, at equal initial plasma parameters, are subject to a considerable scatter that does not lend itself readily to systematization, indicating that all the quantities depend on the phenomena that occur during the course of the discharge.

Measurement of the diameter of the plasma filament as a function of time has shown that during the course of the discharge the plasma diameter increases rapidly over the entire length of the discharge gap, from an initial diameter $d_0 \sim 2$ cm to the inside diameter of the chamber $d \sim 9$ cm within a time $t \sim 0.5$–0.8 μsec. The rate of expansion of the filament diameter increases with increasing discharge current, reaching a value $v \sim 10^6$ cm/sec.

Measurements of the plasma density as a function of length show that after the discharge is initiated the plasma density decreases somewhat during the time of expansion of the plasma filament, and then during the time of existence of the current limitation, the plasma concentration increases over the entire length of the discharge, except for the region adjacent to the anode, where the density decreases. At the end of the current-limitation time, the plasma density over the entire length of the discharge gap reaches $n \gtrsim 6 \times 10^{13}$ cm^{-3}, with the exception of the near-anode region of the discharge gap, where it is somewhat lower.

If the experimental conditions are altered by eliminating the inhomogeneity of the gas pressure in the chamber (this inhomogeneity is due to the inflow of the gas in the cathode region of the discharge and the pumping-off conditions), and by using a magnetic field of mirror geometry, then a situation arises in which the decrease of the plasma density occurs during the discharge at the center of the discharge gap. In this case, when the current became limited, the active potential drop was concentrated in a narrow layer at the point of minimum density, as revealed by the capacitive probes placed along the discharge gap. The potential-drop layer could be produced in this case at various points of the central part of the discharge gap. During the current-limitation time, the plasma was divided by the potential-drop layer into two quasi-neutral plasma-column regions—cathode and anode regions—having the potentials of the corresponding electrodes. The main measured parameters of a discharge with a potential-drop layer at the discharge-gap center were of the same form as shown in Fig. 1. Conditions were realized sometimes for a repeated appearance of a potential drop, but now at the anode, in which case the waveform of the discharge current was similar to that shown in Fig. 2. The dependence of the critical current I_{cr} on the plasma density at the center of the discharge gap, for the case of mirror configuration of the magnetic field, is shown in Fig. 4. It was impossible to estimate the width of the potential-drop layer because the spatial resolution of

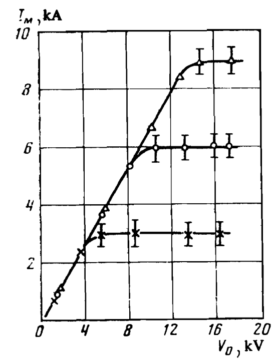

FIG. 3

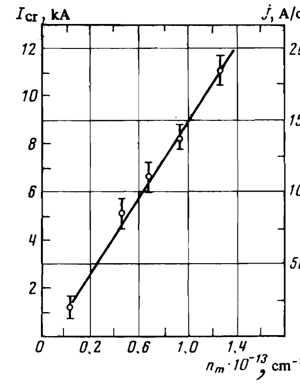

FIG. 4

FIG. 3. Dependence of the limited current on the capacitor voltage at various initial plasma concentrations: ×—$n_0 = 1\cdot 10^{13}$ cm^{-3}, ○—$n_0 = 1.5\cdot 10^{13}$ cm^{-3}, △—$n_0 = 2\cdot 10^{13}$ cm^{-3}.

FIG. 4. Dependence of the critical current on the plasma density at the center of the discharge gap.

the capacitive probes ($l \sim 1.5$ cm) exceeded the width of the layer.

It follows from the experiments described above that the current limitation is due to the onset of a large resistance in a narrow layer, on ehich the entire voltage applied to the plasma is concentrated. The large resistance is due to the lowering of the plasma density in this place during the course of the discharge. As an additional check on the current-limitation mechanism, and also to assess the possibility of controlling the place and time of formation of the current limitation, an experiment was performed wherein a density inhomogeneity was artifically produced in a strong-current discharge of duration $t \sim 60$ μsec under conditions of a homogeneous field and at a gas pressure $p \sim 1 \times 10^{-4}$ mm Hg, when no spontaneous discharge-current limitation was observed. Under the conditions of such a discharge, a local decrease of the plasma density in the discharge gap was produced artificially with the aid of an additional coil that produced a pulsed magnetic field with the following parameters: magnetic-field pulse period $T \sim 30$ μsec and a field intensity $\tilde{H} \sim 5$ kOe. The local decrease of the average plasma density at the location of the coil was observed in the first and third half-cycles of the pulsed magnetic field.

The results of the experiments are shown in Fig. 5 in the form of oscillograms of the pulsed perturbing field $\tilde{H}$, the electrode voltage V_d, the discharge current I_d, the signals of external capacitive probes located 1 cm away from the perturbing coil on the cathode and anode sides, respectively, V_{31} and V_{32}, and the fast-particle beam current I_b. As seen from the V_d and I_d oscillograms, the strong-current inductive discharge started in this case 10 μsec after application of the voltage to the electrodes. The delay time of the inductive discharge relative to the time of voltage application could vary in a range of several dozen microseconds and was determined by the initial plasma density in the discharge gap and by the gas pressure. The perturbing magnetic field was applied with a delay of 10 μsec relative to the start of the discharge. It is seen that when the perturbing magnetic field is applied to the plasma the voltage on the electrodes increases, the discharge current is limited and this limitation is accompanied by a signal on the capacitive probe located near the addi-

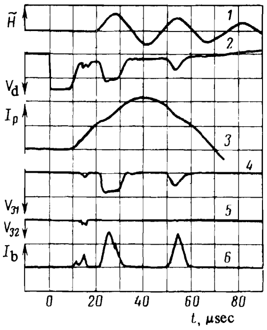

FIG. 5. Oscillograms of perturbing magnetic field H̃, electrode voltage (2000 V/div), discharge current (1000 A/div), signals from the capacitive probes V_{31} and V_{32} (2000 V/div), and fast-electron beam current I_b (800 A/div).

tional coil on the cathode side, whereas the probe on the anode side registers nothing.

Just as in the case of spontaneous formation of a large active resistance during the course of the discharge, a discharge in which conditions are artificially created to produce an active resistance was characterized by the appearance, during the time of current limitation, of a beam of fast electrons, by RF emission from the discharge region adjacent to the coil on the anode side, and x rays from the anode. It should be noted that when the discharge voltage was increased or when the gas pressure in the chamber was decreased, the current in the chamber could be limited without applying the perturbing magnetic field. The voltage drop occurred in this case in the discharge region next to the anode.

During the experiments it was observed that the discharge is strongly influenced by the residual gas pressure in the chamber and by the presence of films of adsorbed gas on the chamber walls and the electrodes. The onset of electron emission from the cathode is most strongly influenced by the presence of adsorbed gases on the cathode itself. This is confirmed by the dependence of the duration of the startup process on the gas pressure in the chamber, on the time interval between succeeding discharges, on the cathode temperature, and on the magnitude of the discharge voltage. Thus, in the case of a low discharge voltage ($V_0 < 4$ kV) it was necessary to raise the pressure in the chamber to $p \sim 3 \times 10^{-4}$ mm Hg in order to reduce to a minimum the duration of the startup process ($\sim 0.1-0.2$ μsec), and with increasing voltage ($V_0 \sim 10$ kV), a discharge with a startup time $\sim 0.1-0.2$ μsec is formed already at a pressure $p \sim 5 \times 10^{-4}$ mm Hg. If the adsorbed-gas films are removed from the cathode by heating the latter to $T = 500°C$, then at the gas pressures and discharge voltages used by us we were unable to obtain a strong-current inductive discharge.

The influence of the gas pressure in the chamber on the course of the discharge is evidenced by the fact that at a relatively low density of the preliminary plasma, $n_0 \sim 5 \times 10^{13}$ cm^{-3}, but at an increased gas pressure ($p \sim 10^4$ mm Hg), a discharge without current limitation can take place, thus indicating that in the course of the discharge there occurs gas ionization and an increase of the plasma density above the level that leads to the limitation of the current. Thus, in final analysis the presence or shortage of neutral particles in the discharge gap leads to formation of a discharge with and without current limitation.

DISCUSSION OF RESULTS AND CONCLUSION

An analysis of the results obtained in the experiments points to a number of conditions under which current limitation takes place in a strong-current direct discharge.

1. Prior to the instant of the appearance of current limitation and after the cessation of the current limitation the investigated discharge is a strong-current vacuum arc, the current in which is determined by the discharge-circuit parameters (V_0 and ρ). This is evidenced by the sinusoidal character of the discharge ($R < 2\rho$) and by the small value of the active voltage drop IR on it. Thus measurement of the distribution of the plasma potential shows (Fig. 2, oscillograms V_{31} and V_{32}) that the active voltage drop on the plasma prior to the onset of the current limitation and after the current limitation is very small, and there is no noticeable electric field in the plasma. The voltage $V_0 = IR + d(IL)/dt$ applied from the capacitor is almost completely balanced by the self-induction counter emf $d(IL)/dt$. The gaseous phase needed for the existance of such an arc is released from the electrodes and the chamber walls under the influence of arc itself.

The limitation of the discharge current arises under conditions when the cathode processes that lead to establishment of the arc current have in the main already been completed. This is evidenced by the vanishing of the "startup" electron beam observed at the initial stage of the discharge ($t \sim 0.1-0.2$ μsec after the onset of the discharge, Figs. 1 and 2) and the vanishing of the RF and x radiation produced by it. A characteristic feature of the investigated current limitation is that it can arise both when the discharge current increases and when it decreases. The current limitation can occur several times during the discharge.

2. The current limitation is accompanied by an abrupt increase of the active voltage drop on the discharge; this drop is concentrated in a narrow discharge-gap layer either in the near-anode region or in the central part of the discharge; in either case, the plasma density in these regions is lower than in the remaining parts of the discharge. The active voltage drop is proportional to the rate of change of the discharge current.

3. During the time of current limitation, the entire discharge current is transported by the beam of fast particles ($n_1 \ll n_0$) with maximum energy corresponding to the potential drop V_d in the layer. The discharge current ceases to depend at that time on the voltage (Figs. 1 and 2). The duration of the current limitation time, at the same plasma parameters, decreases with increasing charging voltage. During the limitation time, the current I_M does not depend on the external parameters of the circuit, but is determined by the parameters of the plasma. The critical limitation current is proportional to the minimum plasma concentration in the discharge gap (Fig. 4). The directional velocity of the electron reaches at the instant of limitation the value $v_e \sim 10^8$ cm/sec, which is close to the value of the thermal velocity of the plasma electrons.

4. The place and time of current limitation can be controlled by producing, at a definite time, a local plasma-density inhomogeneity in any part of the discharge gap.

5. The current limitation depends essentially on the gas pressure in the chamber and on the degree of outgassing of the electrodes.

On the basis of the foregoing conditions, let us attempt to ascertain the current-limiting mechanism in our case and explain the phenomena that take place during the course of the discharge. It follows first from these conditions that the observed current limitation is not due to the onset of current instabilities. Indeed, the current limitation begins in our case under conditions of an inductive arc discharge with small longitudinal electric field in the plasma, and the current limitation can occur several times during the discharge, both when the current rises and when it falls. These data indicate that the observed current limitation is not connected with the external parameters (i.e., with the external electric field E necessary for the plasma turbulence to develop), but the phenomena that cause it appear during the course of the discharge. In our case, these phenomena are the longitudinal redistribution of the plasma density during the discharge and the formation of space-charge layers at locations where the plasma density is decreased, as observed in[5]. This is evidenced by the fact that the potential-drop layer is produced every time in that part of the discharge gap where a decrease of the plasma density is registered.

The onset of the anode potential drop, which is observed in experiments with homogeneous magnetic fields, can apparently be explained by resorting to the ideas developed in[6] concerning the anode potential drop. Under the conditions of the experiment with a homogeneous field, a longitudinal pressure drop amounting to half an order of magnitude was produced. This pressure drop was the result of the inflow of gas into the cathode region of the discharge and the evacuation of the volume on the anode side. This pressure drop exerted no significant influence on the formation of the preliminary plasma, since there was time for the density to become equalized under conditions when the time of formation of the preliminary plasma was long ($\sim 200\ \mu$sec). Under strong-current discharge conditions, however ($T/2 = 3\ \mu$sec), when expansion of the plasma column and ionization of the residual gas filling the discharge chamber took place during the current flow, an anode-region gas pressure lower than in the remainder of the discharge could decrease the generation of positive ions from the anodes, and these are needed to maintain the discharge. In this case an anode potential drop is produced and is capable of enhancing the gas-ionization processes at the anode and of increasing the number of produced ions. However, under the conditions of low gas pressure ($p \sim 5 \times 10^{-5}$ mm Hg) the increase of the electric field at the anode leads (owing to the large electron mean free path) to a faster escape of the electrons from the discharge and to an additional decrease of the rate of ion production, so that the discharge current decreases (current limitation sets in), and the potential drop at the anode increases rapidly to the value of the voltage corresponding to the active voltage drop of the discharge. Since the ion production rate is proportional to the plasma density, the critical current I_{cr} also depends on the plasma density (Fig. 3). From the instant when the limitation sets in, conditions are produced in the anode part of the region such that the intense beam of ions flowing into the plasma from the anode side is accelerated, as does the electron beam flowing from the plasma to the anode. The latter beam, with an energy corresponding to the proportional drop in the layer, bombards the anode, causes gas to be released from it, and delivers neutral gas to the anode region of the discharge, where it leads to an increase of pressure. As a result, the ion generation rate increases, and this stops the limitation of the discharge current.

By starting from these ideas concerning the current-limitation mechanism, we find that the value of the active resistance produced at the instant of limitation, as well as its lifetime, depend essentially on the degree of rarefaction of the gas and on the rate at which the gas flows into the volume from the surface of the anode. The degree of rarefaction of the gas seems to depend on the current, while the lifetime depends on the energy of the electron beam that causes gasification of the bombarded ion. With increasing beam energy, the rate of delivery of gas increases and the duration of the current limitation decreases. In addition, the rarefaction of the gas at the anode and the associated large anode drop at the potential can be the result of the departure of gas molecules in the form of ions from the space next to the anode,[7] and this apparently can take place also if the initial gas pressure in the chamber is uniform.

We consider now the discharge-current limitation in a magnetic field of mirror geometry under conditions of a homogeneous pressure along the discharge tube. In this case, flow of large current can cause rarefaction of the gas in the central part of the discharge gap, at the place where the departure of the particles from the discharge is facilitated, and the balance of the number of carriers can be upset as a result.[8,9] The local rarefaction of the gas leads to an uneven distribution of the plasma density along the discharge gap. Under these conditions, a double electric layer is produced at the point where the concentration is decreased, and the current is limited to a level determined by relation (1). The mechanism that produces the double layer can be understood from the following physical considerations:

If plasma inhomogeneities are present along the discharge gap, then to satisfy the condition of the current continuity the directional velocity of the electrons in the section with the lower density must be larger than in the section with the higher density. Therefore the flow of current in the inhomogeneity section produces a negative space charge, the magnitude of which depends on the value of the current and on the degree of inhomogeneity; this space charge produces an electric field $E(z)$ that accelerates the electrons to the required velocity. So long as the current $j = env$ is small, the energy acquired by the electrons in this field over the inhomogeneity section is equal to

$$E(z)\,dz \ll kT_e$$

($z_1 - z_2 = l$ is the length of the inhomogeneity region). In this case the presence of the field will not affect significantly the motion of the thermal-particle currents $env_{Te}/4$, which moves through the inhomogeneity both towards the cathode and towards the anode.

When the current is increased, $E(z)$ increases and this leads to acceleration of the electron flow through the inhomogeneity region towards the anode, and to deceleration of the flow towards the cathode. At the same time, the ions entering the inhomogeneity region from the anode side are accelerated, and those from the cathode are decelerated. When the energy acquired by the electrons on the inhomogeneity section reaches the value

$$e\int_{z_1}^{z_2} E(z)\,dz \geqslant kT_e, \qquad (3)$$

i.e., when the directional velocity v_e of the electrons passing through the inhomogeneity region towards the anode reaches v_{Te}, the flux of thermal electrons entering the inhomogeneity region from the anode side stops completely. At the same time, the energy of the ions entering the inhomogeneity region from the anode side reaches the value needed for the production of the ion space-charge layer[10]:

$$W_i > {}^1/_2 kT_e,$$

where W_i is the energy acquired by the ions in the electric field. The resultant double electric layer leads to a limitation of the current at a level defined by relation (1).

If the directional electron velocity v_e at the instant of occurrence of the current limitation is estimated on the basis of the experimental values of I_{cr} and n_m (Fig. 4), then we obtain $v_e \sim 9 \times 10^7$ cm/sec. The plasma-electron temperature T_e was not measured during the course of the discharge, but if it is assumed that in the time from the start of the discharge to the instant when the current limitation sets in the temperature changes little from its initial value ($T_e \sim 3-5$ eV), then the obtained directional velocity of the electrons at the instant when the current limitation sets in is close to the thermal velocity of the plasma electrons $v_{Te} \sim 1 \times 10^8$ cm/sec. This confirms the assumption made above, that the formation of a double space-charge layer in a plasma and the resultant limitation of the discharge current occur under conditions when the directional velocity of the electrons on the plasma inhomogeneity section reaches a value equal to the thermal velocity of the plasma electrons. From the condition $v_e \sim v_{Te}$ of the double-layer formation it follows that the formation of a space-charge double layer in a plasma that is not longitudinally uniform should hinder the development of the electron-ion instability,[11] instead of which a two-stream instability develops when the intense beam of electrons produced in the layer interacts with the plasma.

From an examination of the phenomena preceding and accompanying the current limitation, we can therefore draw the following approximate picture of the dynamics of the processes in a strong-current discharge. A discharge with a previously-prepared highly-ionized plasma $n_0 \gtrsim 1 \times 10^{13}$ cm^{-3} begins with the onset of processes next to the cathode, lasting $\sim$0.1–0.2 μsec, during which the entire voltage applied from the capacitor is concentrated in the cathode potential-drop layer. The electron and ion beams generated in the layer during that time lead to a local excess of plasma density at the cathode and to production of an arc discharge. At the instant when the discharge is produced, an abrupt decrease of the electrode voltage is observed (Figs. 1 and 2) as a result of its distribution over the discharge inductance L_1 and the inductance L_2 of the supply leads. The active resistance of the discharge is small in this case. The voltage applied from the capacitors is balanced by the self-inductance counter-emf of the circuit $d(IL)/dt$, with the exception of a small active component IR. With further increase of the current, the plasma column begins to expand. During this expansion time, the discharge current increases on account of the increase of the number of particles by ionization of the gas surrounding the plasma column. After the discharge fills the entire cross section of the discharge tube, the subsequent increase of the current is due to the increased electron velocity, and by that time effects of the gas rarefaction and of the redistribution of the plasma density, due to mass transport by the ions, begin to come into play. As a result, the plasma density becomes inhomogeneous along the discharge.

With increasing discharge current, the directional velocity of the electrons on the inhomogeneity section increases rapidly. At a certain value of the current I_{cr} the electron velocity v_e reaches a value v_{Te} and a double space-charge layer is produced in the plasma, and limits the discharge current to a level determined by the plasma parameters n_m and v_{Te}. The active resistance of the discharge then increases sharply (Fig. 1b) because of the large resistance of the double layer, as given by (2), and as a result the active component IR_{layer} of the voltage increases. Added to the active component of the voltage is the voltage produced in the circuit as a result of the decrease of the discharge current $d(IL)/dt$, so that the voltage drop in the layer may exceed the power-supply voltage. The entire discharge current is transported during the limitation time by electron and ion beams formed in the layer and having an energy corresponding to the voltage drop in the layer. Interaction of these beams with the plasma gives rise to two-stream instabilities, which lead to turbulization of the plasma, accompanied by gas release from the walls and subsequent ionization of the neutral gas. This equalizes or increases the plasma density along the discharge to a level exceeding the critical value, to a vanishing of the space-charge layer, and to the establishment of conditions under which a strong-current arc with small active resistance flows.

It follows from the results that the current limitation observed in our experiments is due apparently to the same processes as take place when the current is limited in dc discharges.[8,12,13] Many details of the general picture of the high-voltage discharge, however, have not been sufficiently well studied and require additional research.

Let us compare our results with those of[1,14]. There, too, they obtained the dependences of the instability-development critical current I_{cr} on the plasma density n_0. These dependences are in good agreement with Fig. 4 and show that the discharge-current limitation is produced in the plasma in the same manner as in our experiments, at a directional electron velocity $v_e \sim v_{Te}$. It is therefore not excluded that the discharge-current limitation observed in[1,14], as well as in[2-4], is due to the formation of space-charge layers in the discharge on account of the longitudinal plasma inhomogeneity that is produced during the course of the discharge. Nor is it excluded that the formation of intense electron and-ion beams, observed in[15-17] during the time when the total discharge current is interrupted and a gap was produced in the plasma, occurred for the same reason. Obviously, a similar phenomenon takes place also in strong-current toroidal discharges.[18,19]

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Translated by J. G. Adashko
222