tron beam. The calculated R_e and $\overline{R}$ for $E_0=0.1$, 0.3, 0.5, 0.7, and 1.0 keV (curves 1-5, respectively) as functions of the initial pitch angles are presented in Fig. 2, a and b, from which it is seen that R_e and $\overline{R}$ undergo a smooth decrease with an increase in the initial angle of entry of the beam into the absorber at all initial energies. The numerical values of the calculated normal and average ranges are presented in Tables 1 and 2 (the values are given in grams per square centimeter).

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INFLUENCE OF THE CATHODE LAYER ON THE VOLT–AMPERE CHARACTERISTICS OF A DISCHARGE EXCITED BY AN ELECTRON BEAM

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UDC 533.915

The volumetric discharge with preionization of the gas by an electron beam has found wide application in the creation of powerful laser systems, since it can provide the excitation of large volumes of gas at a pressure $p\approx 1$ atm [1, 2]. However, the physical processes determining the basic laws of energy absorption have clearly been inadequately investigated, and this pertains especially to the electrode layers of the discharge. The importance of studying the cathode and anode potential drops is due to their decisive role in maintaining the current in the discharge at the level assigned by the external source and by the conductivity of the gas of the discharge gap [3], as well as by the influence on the stability of the volumetric discharge [4].

Numerical modeling of the cathode layer (see [5-7]) has been limited to the drift approximation and does not allow for many processes – photoionization, a change in the rate of impact ionization at a high density of absorbed energy, cascade processes, etc. – which can significantly affect its actual parameters.

In the present report the electron concentration n is measured for the first time by the interferometric method, the volt–ampere characteristics (VAC) of the discharge are investigated, and the cathode potential drop is determined as a function of j_c/p^2 in a powerful volumetric discharge at $p=0.25$-1 atm of nitrogen (j_c is the discharge current density at the cathode).

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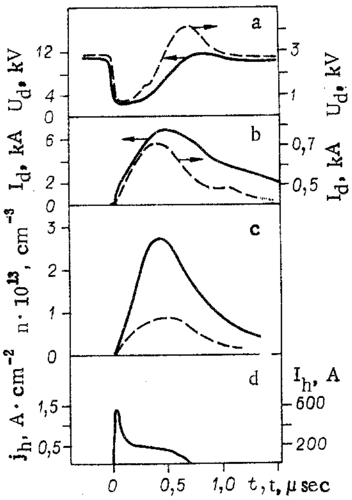

Fig. 1

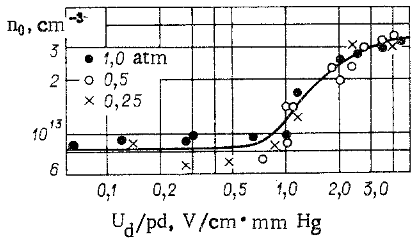

Fig. 2

A volumetric discharge in nitrogen containing $\leqslant 0.2\%$ impurities was ignited in the chamber of an electroionization CO_2 laser, a detailed description of which is given in [2]. The gas was ionized by an electron beam with a cross section $S_0 = 100 \cdot 4\ cm^2$ at the entry to the discharge chamber and an average energy $W_0 = 120$ keV. The distance between the electrodes was d = 3.7 cm. A battery of KMK-50-4 capacitors with a capacitance of 30 μF and a maximum voltage of 50 kV, connected to the discharge gap through a commutator, was used as the source of the energy absorbed in the discharge. The inductance of the supply system was L = 0.7 μH. In the experiment the total discharge current and the voltage on the discharge gap were monitored with a Rogowski loop and an ohmic divider.

To measure the electron concentration n we used a two-longwave interferometer of the Mach–Zehnder type (λ = 0.63 and 10.6 μm) with photoelectric recording. A description of the diagnostic system and the results of an investigation of the possibility of its application in powerful pulsed discharges at a pressure p ≈ 1 atm and a degree of ionization $n/N \leqslant 10^{-5}$ are presented in [8]. Probing of the plasma with the interferometer was performed along the maximum dimension $l = 100$ cm at the center of the discharge gap. Special measurements showed that the values of n are constant with an accuracy of 10% along the direction of current flow. Consequently, the magnitude of the electric field in the discharge, excluding the electrode regions, does not depend on the distance to the electrodes. A detailed investigation of the transverse distribution of n was not made, although control measurements at a distance h = 3.5 cm from the axis of the discharge, outside the region of direct passage of the electron beam, showed the presence of an electron concentration comparable with the value at the center of the discharge, which is evidently due to scattering of the high-energy beam on the electrodes of the discharge gap.

Typical oscillograms are presented in Fig. 1: *a* is the voltage on the discharge gap, b is the discharge current, c is the time variation of the electron concentration, and d is the current of the beam of high-energy electrons. The initial voltage on the discharge is $U_d = 10.3$ and 2.8 kV (solid and dashed lines in Fig. 1a, respectively) and p = 1 atm.

The energy source was connected to the discharge gap 2 μsec before the electron accelerator was turned on. The decrease in the voltage on the discharge when the external ionizer is turned on (Fig. 1a) is connected with a redistribution of the voltage between the created resistance of the discharge and the internal resistance of the energy source.

We note the following important features of the discharge. With a high voltage on the discharge gap ($E_d/p > 2$ V/cm · mm Hg) the current and the electron concentration reached the maximum at t ≈ 0.5 μsec after the start of the discharge initiation and then decreased in accordance with the recombination law of loss of free electrons in N_2. With a decrease in U_d below a critical value, however, a faster decrease in the discharge current was observed, which led to an additional increase in the voltage on the discharge gap, $U' \approx -L(\partial I_d/\partial t)$. We note that no changes in the behavior of the electron concentration were observed in this discharge mode.

Let us consider the basic laws determining the volt–ampere characteristics of a discharge in nitrogen. The values of the current I_d and the electron concentration n in the steady-state case, i.e., when dn/dt = 0, can be determined from the simple expressions

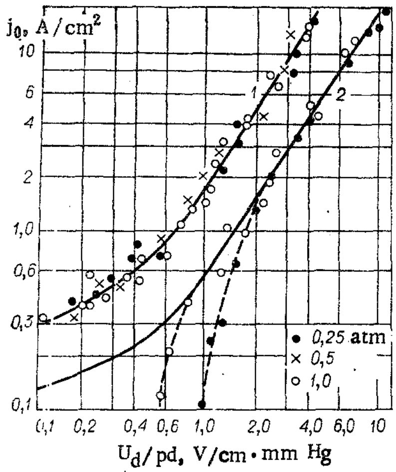

Fig. 3

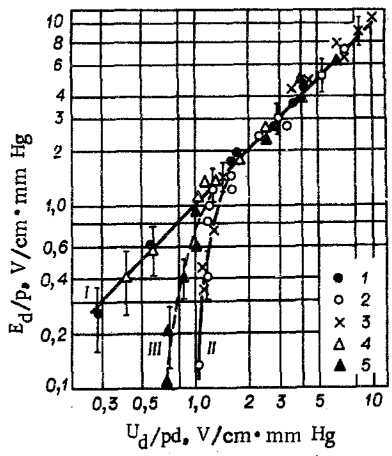

Fig. 4

$$j_0 \approx e\psi_0^{1/2} F(E_d/p); \quad (1)$$

$$n_0 \approx (\psi_0/\beta)^{1/2}, \quad (2)$$

where $j_0 = (I_d/S)(p_0/p)^{1/2}$, $n_0 = n(p_0/p)^{1/2}$, and ψ_0 are the current density of the discharge, the electron concentration, and the intensity of external ionization, respectively, reduced to a pressure $p_0 = 1$ atm; $F(E_d/p) = v/\beta^{1/2}$; v is the electron drift velocity; β is the recombination rate; S is the average cross section of the discharge. With δ_c, $\delta_a \ll d$ and uniform ionization of the gas, the electric field in the gap is

$$E_d \approx (U_d - U_a - U_c)/d, \quad (3)$$

where U_c and U_a are the cathode and anode potential drops; δ_c and δ_a are the characteristic sizes of the cathode and anode layers. With allowance for the fact that $U_a \ll U_c$, the quantity U_a usually does not affect the value of E_d. When $U_c \ll U_d$ we obtain $E_d/p \approx U_d/pd$ from (3), and Eq. (1) determines the parametric law of similarity of volt–ampere characteristics in the presence of external ionization.

After the electron beam is turned off the discharge current with β = const is determined by the expression

$$j_0(t) = j_0(t_0)/[1 + (\psi_0\beta)^{1/2}(p/p_0)^{1/2}(t - t_0)], \quad (4)$$

where $j_0(t_0)$ is the discharge current normalized to the time t_0, the end of the action of the ionizer. In this case with $\psi_0 \approx$ const an additional condition for similarity of the volt–ampere characteristics is

$$(p/p_0)^{1/2}(t - t_0) \approx \text{const}.$$

The experimental confirmation of the fulfillment of the similarity laws (1), (2), and (4) in a powerful volumetric discharge in N_2 is shown in Figs. 2 and 3. We present the electron concentration n_0 (Fig. 2) and the current density j_0 (Fig. 3) as functions of U_d/pd in the presence and absence of external ionization (curves 1 and 2, respectively). Curve 1 in Fig. 3 and the values of n_0 in Fig. 2 are plotted for the time 0.5 μsec, i.e., when $dn/dt \approx 0$; curve 2 corresponds to a value of the parameter $(p/p_0)^{1/2}(t - t_0)$ of $1.25 \cdot 10^{-7}$ sec. The results of the corresponding calculations of j_0 from Eqs. (1) and (4) are shown by solid lines. We used values of $v = f(E/p)$ in N_2 from the data of [9] and of $\beta = \varphi(E/p)$ measured under experimental conditions analogous to ours [10]. The quantity $\psi_0 = (3 \pm 0.5) \cdot 10^{20}$ cm^{-3} • sec^{-1} in the discharge gap for t = 0.5 μsec (i.e., when $dn/dt \approx 0$) was determined in two ways: by the method described in [11] and from the expression $\psi_0 = \beta n_0^2$ with independently measured n_0 and β.

The average cross section S of the discharge was found from the relation $S = I_d/env$ at a high voltage on the discharge gap, $U_d \approx$ 8–28 kV, for which it was assumed that the conditions $U_c \ll U_d$ and $E_d/p \approx U_d/pd$ are satisfied. The value of S was 880 cm² at p ≈ 1 atm, S = 1250 cm² at p ≈ 0.5 atm, and S = 1350 cm² at p ≈ 0.25 atm, and it did not depend on the electric field when $E_d/p \leqslant 10$ V/cm • mm Hg. The inaccuracy in the determination of the values of S did not exceed 4%. It is seen from Fig. 3 that in the presence of external ionization the quantity j_0 grows monotonically with an increase in the parameter U_d/pd. Within the limits of the experimental scatter of ± 15% the similarity law (1), $j_0 = e\psi_0^{1/2}F(E_d/p)$, is satisfied in a wide range of variation of the quantity $U_d/pd \approx$ 0.1–5.0 V/cm • mm Hg, with the voltage on the discharge gap varying in the range of 150–4000 V with p = 0.25 atm. In a decaying plasma Eq. (4) determines the discharge current only for $U_d/pd \gtrsim 2$ V/cm • mm Hg. A decrease in $U_d/pd \leqslant 2.0$ V/cm • mm Hg leads to a sharp decrease in j_0 and to the breakdown of the similarity of the volt–ampere characteristics.

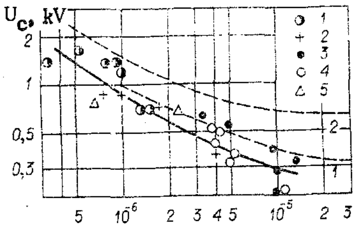

Fig. 5

We note that the value of the discharge current density, as seen from Eqs. (1) and (4), is determined by the actual electric field in the plasma, i.e., by the parameter E_d/p. In Fig. 4 we present typical dependences of the electric field in the discharge, excluding the electrode layers, on the voltage on the discharge gap for different times from the start of the discharge initiation: $t = 0.5$ μsec: 1) $p \approx 0.25$ atm; 4) $p \approx 1$ atm; $t = 0.75$ μsec: 2) $p \approx 0.25$ atm; 5) $p \approx 1$ atm; $t = 1.0$ μsec: 3) $p \approx 0.25$ atm. The vertical lines show the inaccuracy in the determination of the field. The quantity E_d/p was found from the known dependence $v = f(E_d/p)$ [9] through the preliminarily determined electron drift velocity. The values of v were calculated from the relation $v = j_0/n_0e$ through the experimentally measured I_d/S and n (see Figs. 2 and 3).

The data presented in Fig. 4 show that in the presence of external ionization of the gas, the field in the discharge is entirely determined, within the limits of the measurement error, by the voltage on the discharge gap, i.e., $E_d/p \approx U_d/pd$ (curve I) in the entire investigated range of $U_d/pd \approx 0.2$–10 V/cm · mm Hg. A distinctive feature on the dynamics of the discharge after the ionizer is turned off is the sharp decrease in the field strength in the plasma with a decrease in the voltage on the discharge gap, i.e., $E_d/p \ll U_d/pd$ when $U_d/pd \lesssim 2$ V/cm · mm Hg Hg (curves II and III in Fig. 4). The observed effect is evidently connected with strong screening of the field near the electrodes, which makes it possible to determine the cathode potential drop U_c from the relation

$$U_c \approx U_d - E_d d.$$

Values of U_c measured at different times as a function of the parameter j_c/p^2 are presented in Fig. 5. The current density j_c at the cathode was determined from the average current density of the discharge with allowance for the transparency of the cathode grid.

Two principal modes of maintenance of the current in the cathode layer of a powerful volumetric discharge at a high gas pressure $p \approx 1$ atm can be distinguished which are characterized by the parameter $\delta = \alpha j_e/e\psi$, where α is the Townsend coefficient of ionization in the cathode layer and j_e is the electron current density. When $\delta \ll 1$ the cathode layer is formed through the generation of charged particles under the action of the beam, while the process of impact ionization is unimportant. With a decrease in ψ or an increase in j_e, i.e., when $\delta > 1$, the parameters of the cathode layer are entirely determined by impact ionization and should hardly differ from those obtained from the theory of a glow discharge [12]. It is evident that this mode occurs in the experiment when the external ionizer is turned off. We note that the values of $U_c = 200$–300 V obtained with large $j_c/p^2 \approx 2 \cdot 10^{-5}$ A/cm² · mm Hg² are in good agreement with the classical normal cathode potential drop at low pressures [12].

As already mentioned, under the conditions of our experiment screening of the field by the cathode layer is absent within the limits of the measurement accuracy in the entire investigated range of $U_d/pd \approx 0.2$–10 V/cm · mm Hg when an electron beam is present. The greatest interest is offered by the region of low currents, i.e., low U_d/pd, in which the influence of the cathode potential drop on the VAC should be greatest.

Let us estimate the possible value of the upper limit of U_c in the presence of an electron beam. The inaccuracy in the determination of E_d/p at small values of $U_d/pd < 0.5$ V/cm · mm Hg (see Fig. 4) was ~40%, which is connected with the weak dependence of the drift velocity on E/p. Thus, with $p \approx 0.25$ atm, $U_d/pd \approx 0.3$ V/cm · mm Hg, and $j_c \approx 0.2$ A/cm² ($j_c/p^2 \approx 8 \cdot 10^{-6}$ A/(mm Hg)² · cm²) the value of the cathode potential drop should not exceed $U_c \lesssim 85$ V under the conditions of our experiment.

Simple estimates show that such a low value of U_c cannot be explained by the formation of a cathode layer either under the action of impact ionization by discharge electrons ($\delta > 1$) or by external ionization (in accordance with the Thomson theory) with an average rate $\psi_0 \approx 3 \cdot 10^{20}$ cm⁻³ · sec⁻¹ over the discharge gap.

Evidently, the properties of the electrode layer in the initial stage of the discharge are due to the influence of a whole complex of processes. In particular, the establishment of a steady cathode potential drop, which can lead to a decrease in the actual value of U_c [11] observed in the experiment, does not occur during the formation of the discharge, i.e., during the rise in n and I_d.

It must be noted that the ionization processes near the cathode cannot be analyzed without allowance for the interaction of the electron beam with the surface of the electrode. In our experiment the cathode was made in the form of a brass grid through which the beam was injected into the discharge gap. The bombardment of the cathode by fast electrons leads to inelastic reflection of the beam with an efficiency of ~ 0.3 and an average energy $W \approx 0.5W_0$, as well as to secondary emission of electrons with an energy $W_e \approx 50$ eV [13]. One can assume that the low-energy component of the scattered electrons and the secondary electrons can significantly increase the rate of ionization of the gas near the cathode and lead to a decrease in U_c. Additional experiments are needed for a detailed investigation of the mechanism of formation of the cathode layer in the presence of an electron beam interacting with the surface of the cathode.

Scattering of the beam on structural elements of the discharge gap evidently also has a significant effect on the dimensions of the volume of ionized gas, and hence on the volt–ampere characteristics of the discharge. A decrease in pressure, i.e., a reduction in ionization losses, leads to an increase in the energy of electrons scattered on the anode, an increase in their range, and hence an increase in the cross section of the discharge, and this was observed in the experiment.

We note that at a low pressure $p \approx 0.25$ atm the value of $S = 1350$ cm^2 was limited by the size of the anode.

Data of a measurement of U_c in the presence of weak external ionization [14] (curve 1) and typical results of numerical modeling (curve 2) [7] are given with dashed lines in Fig. 5 for comparison. At a low beam current density the formation of the cathode layer is due to impact ionization and the value of U_c coincides with our data obtained after stopping the injection of the electron beam. The values determined by numerical modeling exceed the experimental data by more than twofold, which indicates the need for more complete allowance for ionization processes in the cathode layer when making model calculations.

In conclusion, we note that the influence of the cathode layer on the volt–ampere characteristics of a discharge was investigated in the work. The electron concentration in a powerful volumetric discharge of N_2 at atmospheric pressure was measured for the first time. Universal VACs of the discharge were obtained. The cathode potential drop was determined in the absence of an external ionizer in a powerful volumetric discharge at a pressure $p = 0.25$–1.0 atm in the range of $j_c/p^2 = 10^{-7}$–10^{-5} A/cm$^2\cdot$(mm Hg)^2. The possibility of a significant decrease in U_c in the presence of external ionization was shown experimentally, which is evidently achieved by intense ionization of the gas in the cathode layer by secondary electrons produced in the interaction of the high-energy beam with the surface of the electrode.

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DYNAMICS OF THE DEVELOPMENT AND STRUCTURE OF A BARRIER DISCHARGE IN A LARGE GAP

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UDC 533.09

The barrier discharge (BD) has been used in the past mainly in ozonizers and has been investigated under the optimum conditions for these devices: $U = 3$–10 kV, $f \simeq 10$ kHz, a gas gap of 0.1–0.4 cm, and with barriers of glass [1]. Spectroscopic investigations of BD have been made in recent years under similar conditions [2, 3]. In all the reports the multichannel nature of its structure was noted as a specific feature, which permitted its use in [4] for the synchronous initiation of 20 high-current autonomous discharges and in [5–7] for the formation of multichannel high-current discharges.

However, the nature of the multichannel structure and the mechanism of its development have been studied inadequately up to now. This circumstance, as well as the fact that in [4, 5] the BD was generated in a larger gas gap and at a higher magnitude and frequency of the supply voltage, served as a basis for the formulation of the present work. In it we investigated the dynamics of the development of a BD, its structure, the influence of the parameters of the discharge and supply circuits and of the gas composition on its properties, and the dependence of the delay time of the discharge initiated by it on the voltage on the barrier electrode.

Description of Experimental Installation

A diagram of the experimental installation is presented in Fig. 1. Inside the chamber, through which argon could be blown, the two plane primary electrodes 1 and 2 having a cross section of 4.5×0.8 cm were placed with a gap of 0.8–3 cm. The ends of the electrodes had a wedge shape ($\measuredangle = 90°$). Between them there was a trigger electrode 3 in the form of a wire 0.15 cm in diameter or an aluminum cylinder 1 cm in diameter and 4.5 cm long, enclosed in a quartz tube sealed at one end and having an inner diameter of 0.15 and 1 cm, respectively, and a wall thickness of 0.15–0.2 cm. The voltage was supplied to it from a step-up transformer constructed on three F 1000 ferrite rings with dimensions of $110 \times 60 \times 15$ mm. A capacitor $C_1 = 0.01$ or 0.1 μF was discharged through the first winding ($w = 2$). A high-voltage pulse with a frequency of 1.3 and 0.45 mHz, respectively, was transformed in the second winding ($w = 20$); its amplitude depended on the initial voltage on C_1 and was varied from 20 to 60 kV. The BD grew from the surface of the quartz tube 3 to each of the primary electrodes 1 and 2 (Figs. 1-3). Their wedge shape predetermined the formation of all the channels in the same plane, which made it possible, by placing the photographic apparatus 4 normal to it, to focus the images of all the channels on the film. The voltage U on the BD was measured with a capacitive divider, $C_3 = 16$ pF and $C_4 = 0.015$ pF (1 : 1000). To measure the current I of the BD and the delay time of the initiated discharge of the capacitor $C_2 = 2200$ pF we used $R_s = 5.1\ \Omega$, common to the two discharge circuits. The voltage from R_s was applied to the plates of the tube of an S1-42 oscillograph while the voltage from C_4 was applied to its amplifier through a delay line ($t = 0.3\ \mu$sec).

Description of Experiments

The low brightness and small transverse size of the BD channels hinder the use of streak-camera photography in its investigation, and therefore the dynamics of its development was obtained from the compari-

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