DISCHARGE IN A HIGH-PRESSURE GAS, INITIATED BY A BEAM OF FAST ELECTRONS*

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It was shown in [1] that, to avoid forming a discharge channel in a high pressure gas, one must have many initiating electrons before the start of the discharge, distributed over the cathode or through the discharge gap volume. To achieve this Koval'chuk et al. [2] proposed using a beam of fast electrons. The present paper presents results of investigation of a discharge in nitrogen at pressures up to 16 atm, initiated by a beam of electrons with an average energy of 100 to 350 keV. A channel-less type of discharge was obtained for voltages above 10^5 V and for switched currents of tens of kiloamperes. This type of discharge has typically a specific absorbed power in the gas of the order of 10^7 to 10^9 W/cm^3 or more for a time of the order of 10^{-8} sec.

1. Experimental Method. The experiments were conducted on the equipment shown schematically in Fig. 1 (a – using discharge of a long line, and b – discharge of a capacitor). The electron beam was formed by direct acceleration from a high-voltage nanosecond pulse generator using a multispike cathode as load. The high-voltage pulse was formed by means of coaxial line system 9, connected in the Blumlein manner [3], charged from the pulse transformer 10, through the primary winding of which a battery of low-inductance capacitors C_1 was discharged via the multigap spark-gap 13 [4]. The pulse front was formed by the spark-gap 8, whose action is to attain the maximum charge voltage. The pulse of amplitude 300 kV and duration 10^{-8} sec is applied to the multispike cathode 7, producing emission of electrons. The duration of the electron beam formed by the accelerator is 10^{-8} sec; the rise time of the electron current is $3 \cdot 10^{-9}$ sec (Fig. 2a); the maximum electron energy is $W_* = 300$ keV. The energy distribution of the electrons in the beam after it passed through the collimator 2 with titanium foil of thickness 50 μ was evaluated by passing the beam through a set of calibrated Al foils of thickness 20 μ. The maximum energy of the electrons that had traversed the Ti foil was $W_* = 180$ keV; the most probable electron energy was $W_0 \approx 70$ keV. The electron current behind the foil was controlled to be in the range 20 to 100 A, by varying either the accelerating voltage or the anode–cathode distance in the accelerating gap. The electron current was measured by means of a Faraday cylinder. The beam area at its exit from the foil was 20 cm^2. The current density distribution across the beam was of Gaussian type.

After passing the collimator 2 the beam was led out into the discharge test gap 1 (Fig. 1a), through which was discharged the long line 11, charged synchronously with the accelerator from the pulse transformer 12, through whose primary winding the low-inductance capacitor C_2 was discharged via the multigap switch 14.

The line 11 (the dielectric is glycerin, the characteristic impedance R = 10 ohm) formed voltage pulses of duration $8 \cdot 10^{-8}$ sec with amplitude up to 250 kV. The charging time of the shaping line from the pulse transformer, equal to $0.5 \cdot 10^{-6}$ sec, gave a voltage at the test gap U_0, which exceeded the static breakdown voltage U_* by a factor of 2 ($\beta = U_0/U_* \leq 2$). The charge voltage was measured by means of the resistive divider R_q; the discharge current was recorded as the signal at the points 15 from the low-ohm, noninductive shunt R_* in the I-2-7 oscilloscope.

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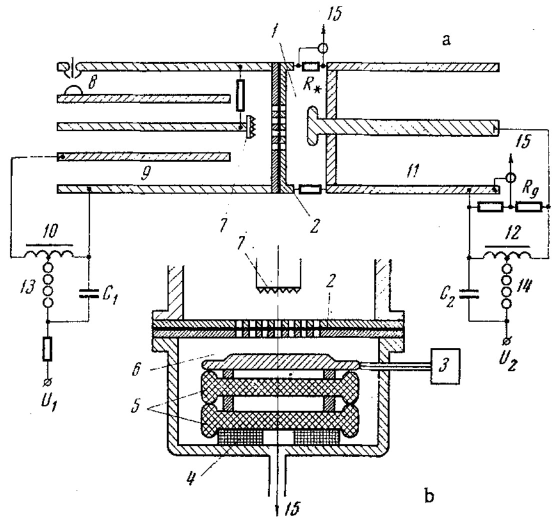

Fig. 1

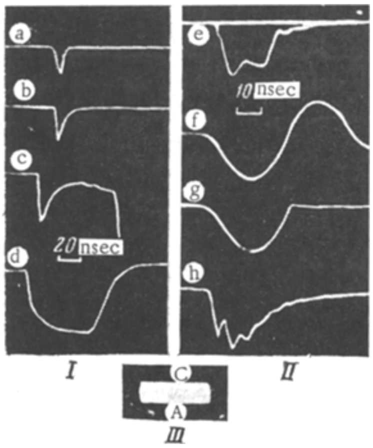

Fig. 2

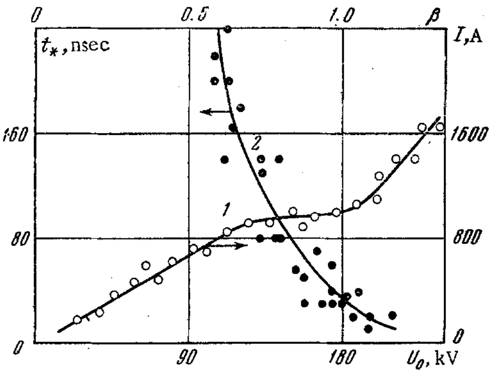

Fig. 3

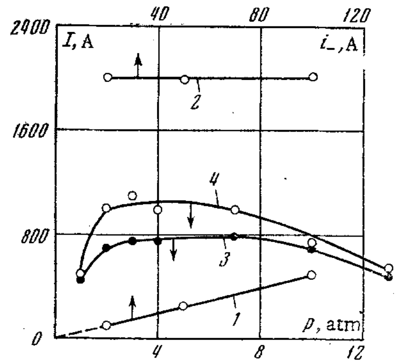

Fig. 4

The test discharge gap 1 of controlled length d=2 to 20 mm was filled with nitrogen at pressure p=1 to 16 atm.

Preliminary experiments were done with a discharge circuit (Fig. 1b) in which the storage element was a group of noninductive ceramic capacitors 5, series connected, with equivalent capacitance C=3400 pF. The capacitors were charged from the DC voltage source 3 to $U_0 \leq 50$ kV (the gap voltage did not exceed the static breakdown value, $U_0 \leq U_*$, $\beta \leq 1$). The length of the discharge gap 6 was varied in the range d=2 to 10 mm, and the nitrogen pressure in the discharge chamber was p=1 to 16 atm. The discharge current was measured by means of the carbon shunt 4 whose signal was recorded on the I-2-7 oscilloscope. The electron beam in this case was formed by a direct nanosecond accelerator [5] with a pointed cathode 7. The tests were made with electron energy $W_*=350$ keV and electron current behind the tungsten foil of the collimator 2 of $i_-=200$ A; the current pulse duration was $2 \cdot 10^{-8}$ sec; the pulse risetime was $3 \cdot 10^{-9}$ sec (Fig. 2e).

2. Experimental Results. Discharge of Long Line. Figure 2, I shows oscillograms of the electron (a) and discharge (b, c, d) currents during discharge of the long line; Fig. 2, II shows oscillograms of the electron (e) and discharge (f, g, h) currents during discharge of the capacitor; and Fig. 2, III shows photographs of the integrated light in the discharge gap during discharge of the capacitor. For a discharge gap voltage of less than the static breakdown ($U_0 < U_*$), Fig. 2b shows oscillograms of discharge current at pressures p=1 to 16 atm and gap lengths d=2 to 20 mm. Here a weak reddish glow is seen in the discharge gap, uniformly distributed over the interelectrode volume, and increasing with increase of the discharge voltage U_0. For voltages $U_0 > U_*$ (at pressures $p \geq 3$ atm) there is a sharp jump in the switched current (Fig. 2c) at some time delay t_* following the initial discharge current peak; and the usual narrow, brightly luminous spark channel is seen in the discharge gap. For a discharge gap pressure of $p \sim 1$ atm

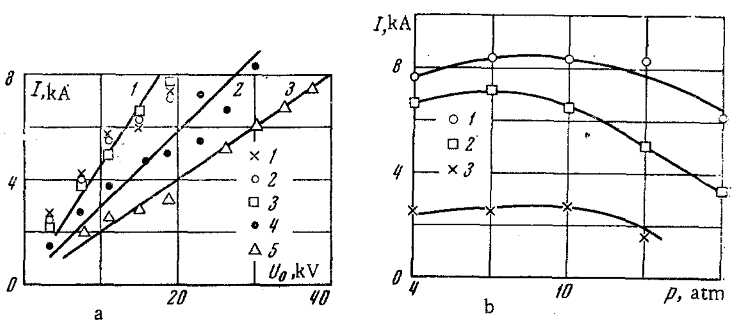

Fig. 5

and increased discharge voltage $U_0 > U_*$, the luminosity in the discharge gap increases with no visible signs of the volume charge being constricted into the spark channel; the discharge current has then the form of Fig. 2d.

Figure 3 (curve 1) shows a typical volt–ampere characteristic for discharge of the long line in the pre-spark stage, with $i_- = 50$ A, p = 7 atm, and d = 1 cm.

Three sections can be identified in the characteristic: for $U_0 \ll U_*$ the discharge current increases linearly with increase in voltage; then the discharge current "saturates" for voltages from U° to U_*; and finally, for larger U_* (for $\beta > 1$) there is a further linear increase of discharge current.

Figure 3 (curve 2) shows a typical dependence of the time delay for excitation of the spark stage of the discharge t_* on the gap voltage U_0, for the case $i_- = 20$ A, p = 7 atm, and d = 1 cm. For $\beta = 1$ to 1.2 the delay time $t_* = 10$ to 20 nsec, and for further increase in β, t_* is practically $\sim 10^{-9}$ sec and below.

Figure 4 shows the discharge current I as a function of the initial electron current i_- for $U^\circ < U_0 < U_*$ (curve 1) and for $U_0 > U_*$ (curve 2) with pd = 760 torr · cm, and also I as a function of p in the discharge gap for E/p = const and d = 1 cm, $i_- = 50$ A (curves 3 and 4). The curves have a maximum in the pressure range p = 3 to 8 atm.

Discharge of the Capacitor. Experiments were done on discharging the capacitor 5 (Fig. 1b) from constant voltage $U_0 \le U_*$ ($\beta \le 1$). As regards the volt–ampere characteristic the discharge has typically only two sections present in the volt–ampere characteristic of discharge of a long line (Fig. 3, curve 1): an initial linear growth of the discharge current with increase of the voltage, and discharge current saturation at voltage close to the static breakdown value U_*.

Figure 5a shows the discharge current I as a function of the charge voltage on the capacitor U_0 for nitrogen pressures p = 4, 7, 10, 13, and 16 atm (curves 1 to 5, respectively); Fig. 5b shows I as a function of p for different voltages U_0 (30, 18, and 4 kV for curves 1 to 3, respectively).

Figure 2, III is a photograph of the integrated luminescence from the gap during discharge of the capacitor charged to $U_0 = 30$ kV (p = 1 atm, d = 1 cm, A – anode, C – cathode).

Figure 2f is a current oscillogram of the capacitor discharge with $U_0 = U_*$ through an ordinary spark channel with no initial beam current. The discharge current is oscillatory with period and amplitude determined by the capacitor (C = 3400 pF), the inductance (which consists of the inductance of the spark and that of the discharge system), and the active resistance, which decides the decrement of the current oscillations.

The electron-beam-initiated current oscillograms are shown in Fig. 2g for p = 1 atm, and in Fig. 2h for p = 6 atm; for $p \gg 1$ atm the curvature of the switched current front is greater.

The discharge current initiated by the electron beam attains values equal to the first half-wave of the switched current when the discharge gap is short-circuited by an ordinary spark channel (Fig. 2f, g, h).

It should be noted that in these experiments the electron beam is injected into the discharge gap from both the cathode and the anode sides. No difference was noted in the nature of the gas luminescence, the current oscillograms, and the main experimental dependences in the conditions investigated.

3. Derivation of Theoretical Relations. We consider a gas gap of length d with electric field E_0 and gas pressure p. If a uniform electron beam of cross section S, current density j_-, and energy W (Fig. 6b)

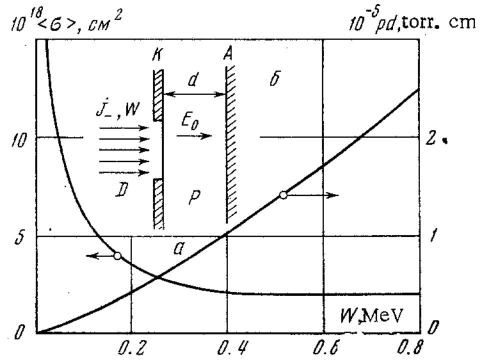

Fig. 6

is injected into the gap from the cathode E through the aperture D to the anode A, then, neglecting secondary processes at the cathode, and taking account of collisional ionization (ionization by beam electrons) and electron drift, we obtain the electron continuity equation

$$\frac{\partial \rho_-(x, t)}{\partial t} = -\frac{\partial \rho_-(x, t) v_-(x, t)}{\partial x} + \alpha(x, t) v_-(x, t) \rho_-(x, t) + \psi(t) \quad (3.1)$$

We use the Poisson equation to calculate the effect of space charge:

$$\frac{\partial E(x, t)}{\partial x} = \frac{\rho_+(x, t) - \rho_-(x, t)}{\varepsilon_0} \quad (3.2)$$

where $\rho_-(x, t)$ and $\rho_+(x, t)$ are the charge densities of electrons and ions in the gap, $v_-(x, t)$ and $\alpha(x, t)$ are the drift velocity and collisional ionization coefficient, ε_0 is the dielectric permeability of vacuum, E(x, t) is the field strength in the gap.

$$\psi(t) = j_-(t) n_0 p \langle\sigma\rangle \quad (3.3)$$

$n_0 = 3.5 \cdot 10^{16}$ cm$^{-3}\cdot$torr^{-1}, $\langle\sigma\rangle$ is the average ionization cross section (cm^2), and p is the gas pressure in the gap (torr). The boundary and initial conditions are

$$\rho_-(0, t) = 0, \qquad \rho_-(x, 0) = 0 \quad (3.4)$$

The quantities $v_-(x, t)$ and $\alpha(x, t)$ are determined by the field strength E(x, t), and the latter is determined by the potential difference across the gap U(t). The value of U(t) is determined from the Kirchhoff equation for the circuit.

In the general case it is difficult to solve the system of equations (3.1) and (3.2) and therefore we make certain simplifications. We assume that the gap current is determined by drift of positive column electrons, for which at any time instant $\partial E/dx = 0$ because the plasma is quasi-neutral. If the condition

$$\tau \ll t^\circ, \quad \int_0^{t^\circ} \alpha(t) v_-(t)\, dt \gg 1, \quad \int_0^{t^\circ} \frac{v_-(t)\, dt}{d} \ll 1 \quad (3.5)$$

holds for the electron flux duration τ and gap length d, where t° is the discharge development time, then from Eq. (3.1) the discharge circuit current is given by

$$i(t) \approx \frac{N_0 e v_-(t)}{d} \exp\left(\int_0^t \alpha(t_2) v_-(t_2)\, dt_2\right) \quad (3.6)$$

$$N_0 = \frac{\langle\sigma\rangle n_0 p S d}{e} \int_0^\tau j_-(t_1)\, dt_1$$

This avalanche current growth process was considered in detail in [1, 2].

We now turn to the other case, where

$$\tau = t^\circ, \quad \int_0^{t^\circ} \alpha(t) v_-(t)\, dt \ll 1 \quad (3.7)$$

If the potential difference between the cathode and anode is such that $U_0 = E_0 d < U_*$ (U_* is the static breakdown voltage), then, when conditions (3.7) hold, we have

$$\int_0^{t^\circ} v_-(t)\, dt \ll d \quad (3.8)$$

Conditions (3.7) and (3.8) mean that collisional ionization by electrons can be neglected and that the electron drift length is much less than the gap length.

With condition (3.7) and taking into account that

$$v_-(t) = k_0 \frac{U(t)}{pd}$$

the solution of Eq. (3.6) for the capacitor discharge leads to a circuit current of

$$i(t) = U_0 \lambda t \exp\left(-\frac{t^2\lambda}{2C}\right) \tag{3.9}$$

and for line discharge the current is

$$i(t) = \frac{U_0 \lambda t}{1 + R\lambda t}, \quad \lambda = \frac{n_0 k_0 \langle\sigma\rangle i_-}{d}, \quad i_- = j_- S = \text{const} \tag{3.10}$$

where i_- is the initiating electron beam current for $t<\tau$. For $t<0$, $i_-=0$. It follows from Eq. (3.9) that the current pulse amplitude is

$$I = U_0 \sqrt{\lambda C / 2.73} \tag{3.11}$$

Substituting the value of λ from Eq. (3.10), we obtain

$$\frac{U_0}{I} = 1.6 \sqrt{d / n_0 k_0 \langle\sigma\rangle i_- C} \tag{3.12}$$

From Eqs. (3.9) and (3.10) and the Kirchhoff equations we obtain, respectively

$$W = \frac{U_0 C}{2}\left[1 - \exp\left(\frac{-t^2\lambda}{C}\right)\right]$$

$$W = \frac{U_0^2 t}{4R}\left[\frac{4}{R\lambda t}\ln(1 + R\lambda t) - \frac{4}{1 + R\lambda t}\right] \tag{3.13}$$

for the energy in the gap.

Equations (3.9)-(3.13) were obtained for the following conditions: the field along the gap $E=E(t)$ is uniform and the ionization cross section $\sigma = \langle\sigma\rangle$ = const throughout the whole gap. This last condition requires that the beam electron energy $\sim 10^5$ eV, and that the loss in the gas $\Delta W \ll W$.

Figure 6a [6] shows $\langle\sigma\rangle$ (W) for nitrogen. Figure 6a also shows the product pd as a function of electron energy W, from which we can see what minimum electron energy W is required for the beam to cross a gap of length d at a pressure p of nitrogen.

The effect of space charge on the field strength along the gap was calculated in solving the system (3.1) and (3.2) by a method of successive approximations. In the calculation the voltage drop in the switch was assumed constant and equal to U_0, and avalanche multiplication of electrons was not taken into account. As a zero order approximation the field strength over the whole gap was taken to be constant. The solution of Eq. (3.1) with $\psi(t)$ = const has the form

$$\rho_-(x, t) = \psi x / v_- \ \text{ for } \ 0 < x < v_-^\circ t, \quad \rho_-(x, t) = \psi t \ \text{ for } \ v_-^\circ t < x < d \tag{3.14}$$

The cathode voltage drop was obtained by solving Eq. (3.2) in the second approximation, i.e.,

$$U_- \approx U_0 \omega \left(2t^* - e^{-t^{*2}} \int_0^{t^*} e^{\xi^2} d\xi\right) \tag{3.15}$$

where

$$t^* = t\,\frac{\sqrt{k_0 \psi}}{2\sqrt{p\varepsilon_0}},$$

$$\omega = \frac{2\sqrt{k_0 \varepsilon_0}\, U_0}{\sqrt{\psi p}\, d^2}$$

Putting $U_-/U_0 \ll 1$, we have from Eq. (3.15) and for $t^* > 2$

$$U_- / U_0 \leqslant 2k_0 U_0 t / pd^2 \approx 2v_-^\circ\, t/d \tag{3.16}$$

It is not difficult to see that with condition (3.8), according to Eq. (3.16), $U_- \ll U_0$. This means that when Eq. (3.8) is satisfied the effect of space charge on the current can be neglected.

4. Discussion of Results. Photograph III in Fig. 2 of the discharge of the capacitor in the gap with the electron beam shows the three-dimensional nature of the discharge. In the case of the long line this kind of discharge was observed at a pressure p = 1 atm for an overvoltage $\beta \leq 2$ during the whole pulse formed by the line (Fig. 2d); for p > 3 atm a volume discharge was observed at $\beta \leq 1.2$ for a time t_* before

the advent of the spark stage (Fig. 2c); for $\beta \leq 0.6$ and $p > 3$ atm there was no spark stage, i.e., $t_* > 0.3 \cdot 10^{-6}$ sec (Fig. 3, curve 2). The processes leading to breakdown with $U_0 < U_*$ are evidently analogous to the case where the discharge is triggered by intense UV illumination. It should be noted that even for $\beta > 1$ and $p > 3$ atm one can obtain a channel-less discharge by using high initial electron currents ($i_- > 10^3$ A). For conditions $t < t_*$ there are no traces of electrode erosion. Thus, it has been confirmed experimentally [2] that the channel can be eliminated if one passes an electron beam through the discharge gap.

The unipolar nature of the current pulses (Fig. 2g and h) with the electron beam present, and the continuous oscillatory nature of the discharge with the beam absent (Fig. 2f), indicate an increase in the power of the volume discharge with the beam, compared to that of the spark discharge. For $C = 3400$ pF, $U_0 = 45$ kV, the average power in the discharge with the beam for a time $t \approx 2 \cdot 10^{-8}$ sec is more than 10^8 W, and the specific value is $\sim 10^7$ W/cm^3.

The absence of sparks, the large specific power, and the delay in the appearance of the spark stage after curtailment of the beam current mean that a discharge with a beam can be used without obtaining short high-intensity current pulses, in a switch with voltage $U_0 > 10^5$ V and short trigger time, for pumping gas lasers, etc.

The theoretical relations of Sec. 3 allow us to explain the experimental data for strong overvoltages and low voltages, and also in conditions where $\langle\sigma\rangle$ depends only a little on the parameter pd of the gas gap and the beam current does not change in passing through the gas. For example, according to Eq. (3.12), the slope of curve 1 (Fig. 5) for the capacitance is practically independent of p in the range 4 to 10 atm. Similarly, the current I (curves 1 to 3 in Fig. 5b) for the capacitance in the range $p = 4$ to 10 atm does not depend on p, as follows from Eq. (3.11). In these conditions $pd = (0.2 \text{ to } 0.8) \cdot 10^4$ torr, corresponding to $\Delta W \leq 50$ keV. Taking into account that the most probable electron energy $W \approx 70$ keV in this experiment, we obtain for $p < 10$ atm $\langle\sigma\rangle \approx 10^{-17}$ cm^2. From Eq. (3.12), with $\langle\sigma\rangle \approx 10^{-17}$ cm^2, $C = 3400$ pF, $i_- = 200$ A, $d = 0.8$ cm, we have $U_0/I \approx 4$ ohm. The experimental value of $U_0/I = (2.2 \text{ to } 3.3)$ ohm, according to Fig. 5. The discrepancy apparently arises from our neglect of beam electrons with energy $W < 10$ keV in calculating the ionization.

The decrease in I/U_0 with increase of p for $p > 10$ atm (curves 2 and 3) occurs for $\Delta W \sim W$ and larger when there is absorption of a considerable fraction of the beam electrons in the gap. In this case

$$I/U_0 = ek_0N/pd^2 \tag{4.1}$$

where $N \approx$ const is the number of electrons formed by the beam in the gap. Then, for $d =$ const, $I/U_0 \sim 1/p$. An analogous phenomenon apparently takes place in discharge of the line (curves 3 and 4 of Fig. 4). If we put $E_0/p =$ const in Eq. (4.1), then for $d =$ const the current I does not depend on the pressure p (the flat part of the curves with $p = 2$ to 8 atm).

The recombination losses apparently become appreciable at large pressure. According to [7], for $\sqrt{\beta_* \psi / et} > 1$, where β_* is the recombination coefficient, the density of electrons tends towards saturation. For example, for nitrogen ($\beta_* = 3 \cdot 10^{-7}$ cm^3/sec [7]), when $t = 10^{-8}$ sec, $j_- = 5$ A/cm^2, $\langle\sigma\rangle = 4 \cdot 10^{-18}$ cm^2, this occurs for $p > 10$ atm. Unfortunately β_* depends strongly on the temperatures of the molecules and electrons and the type of recombination, and therefore one must have additional information on the gas-discharge plasma in order to calculate the recombination losses. Clearly, the current drop for $p > 8$ atm (curves 3 and 4 in Fig. 4) is due to recombination losses when a considerable fraction of the electron beam is absorbed in the near-cathode region of the discharge gap.

The linear increase of the current $I(i_-)$ for the line (curve 1 of Fig. 4) for $U_0 =$ const ($\beta < 1$) agrees with the theoretical relation Eq. (3.10) for $R\lambda t \ll 1$ and low values of p. The constant value of I (curve 2 of Fig. 4) with increase of i_- for $U_0 > U_*$ is easily explained by the laws obtained in [1]. According to [1], with avalanche multiplication of electrons in the gap, I does not depend on the initial number of electrons. The linear dependence of the discharge volt-ampere characteristic (curve 1 of Fig. 3) for $U_0 \ll U_*$ has the same cause as curve 1 of Fig. 4; there is "saturation" for $120 < U_0 < 180$ kV when condition (3.16) does not hold. In that case the decrease in current is due to a volume charge effect. The further increase of $I(U_0)$ for $U_0 > 180$ kV is due to avalanche multiplication of electrons.

A number of experiments were also conducted with discharge of a line, the aim being practical use of the phenomenon under study. With the nanosecond pulse generator at 1 MV a beam with $i_- = 2000$ A and electron energy ~ 350 keV was used. With nitrogen pressure $p = 7$ atm the maximum current in a channel-less discharge was $I = 4 \cdot 10^4$ A at $U_0 = 700$ kV, and the specific energy then dissipated was ~ 10 J/cm³. The possibility was also investigated of obtaining the largest plasma volume. Here the cathode and anode area was $S = 40 \times 1$ cm². A band-type line was discharged in the gap. The electrons were injected through the cathode from a thin foil, the spike of the cathode of the accelerator being located along the entire cathode of the discharge gap (i.e., over a length of 40 cm). The injected electron current was ~ 10^3 A at energy up to 400 keV. With d = 1 cm, p ≤ 6 atm (CO_2 or O_2) and voltage on the band line of 70 kV, a discharge throughout the whole gas volume was obtained.

In addition, the storage line was discharged using the so-called "self-trigger" of the discharge gap. To do this the cathode of the spark-gap was joined to ground via an inductance, and a vacuum diode with a multi-point cathode was placed between the spark-gap cathode and ground. During the discharge in the gap a voltage was applied to the diode, causing emission of electrons in the diode and accelerating the breakdown of the gap.

The possibility of using a channel-less discharge to make up a zero-inductance switch has already been discussed [2]. The channeled discharge excited by the beam can also be used. In fact, the discharge channel can be triggered in a time of 10^{-9} sec (Fig. 3). This would allow parallel triggering of several channels in a single gap, which would appreciably reduce the losses in the spark and its inductance.

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