A NUMERICAL INVESTIGATION OF CURRENT LACING ON THE ELECTRODES IN A GLOW DISCHARGE

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It is well known that, due to the absence of generation of charged particles of a gas discharge plasma on cold electrodes near the latter, layers are formed with properties which differ significantly from the properties of a column [1]. An appreciable voltage is applied to these layers, which in some current range drops off as the current density increases. Engel and Stenbeck, who have calculated the near-cathode volt–ampere characteristic, have postulated that the section on this characteristic with a negative differential resistance is unstable. The compression of the discharge on the cathode which occurred in the experiment was associated with the development of this instability. This phenomenon is called the law of normal current density in the literature – as the current increases, the emitting region on the cathode expands, so that the current density remains constant and equal to the normal current density.

Nonuniform burning of the discharge is also observed on the anode, although here the phenomenon occurs somewhat differently and has been investigated less rigorously [2]. It is shown analytically and numerically in [3] that the near-anode volt–ampere characteristic (VAC) has, just as does the near-cathode one, a section with negative differential resistance.

The phenomenon of current lacing on the electrodes is interesting from the physical standpoint and is also important in practical applications of a glow discharge: gas-discharge devices, powerful gas lasers, and so on. In the latter case current lacing on the electrodes can be the cause of current lacing in the volume, which limits the power of the devices. Various technical means are used to control this phenomenon; for example, one may subdivide the electrodes [4].

A theory of the current lacing which is compulsory for the presence of a section with negative differential resistance on the VAC has been created, for example, for semiconductors with an S-like characteristic. The important feature of the problem under discussion here consists of the fact that as the current increases not only does the near-electrode drop increase but also the thickness of the near-electrode layer increases. The latter circumstance makes the problem essentially two-dimensional, which significantly complicates its solution.

This paper is devoted to a numerical investigation of the theoretical possibility of current lacing on the cathode due to taking account of ionization, recombination, and the drift of charged particles through the field. This eliminates the need to confine ourselves to a specific experimental situation, and in particular permits treating the two-dimensional problem in plane geometry, which simplifies the calculations. The time it takes to do the calculation will depend on to what extent the effects of interest to us are exhibited.

Statement of the Problem. The phenomenon of breakdown and the development of a discharge between two plane electrodes is investigated in this paper by the numerical integration of the time-dependent two-dimensional system of equations which describes the motion of electrons and ions in a self-consistent electric field with ionization and recombination processes taken into account. It is assumed that the transverse dimensions of the electrodes are much larger than the distance $L = 1$ cm between the electrodes. The volume of the interelectrode gap is filled with nitrogen at a pressure $p = 666.6$ Pa. The choice of this pressure is related to the need to maintain the thickness of the near-electrode layer on the cathode (in the normal burning regime [5]) at a level no less than 0.1 L: the constraint arises due to the finite number of nodes in the numerical modeling by the finite-difference method.

We will introduce a cartesian coordinate system whose two axes Oz and Oy lie in the plane of the cathode, and the Ox-axis is directed from the cathode to the anode. Neglecting edge effects, we will assume that the discharge is uniform in z and periodic in y with the period 2L. Then one can proceed to consideration of the working volume of a capacitor having dimensions along the axes Ox, Oy, and Oz equal to L, 2L, and L, respectively, which is included in a circuit with a voltage source $\mathscr{E}$ and an external resistance $R = 250$ kΩ.

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We have the following equations for the concentrations of the electrons n_e and ions n_i with the drift of particles along the electric field taken into account [5]:

$$\frac{\partial n_e}{\partial t} + \operatorname{div} \mathbf{j}_e = \alpha j_e - \beta n_e n_i, \quad \mathbf{j}_e = \mu_e n_e \nabla\varphi; \tag{1}$$

$$\frac{\partial n_i}{\partial t} + \operatorname{div} \mathbf{j}_i = \alpha j_e - \beta n_e n_i, \quad \mathbf{j}_i = -\mu_i n_i \nabla\varphi, \tag{2}$$

where α is the first Townsend coefficient for nitrogen [5], $\beta = 2 \cdot 10^{-7}$ cm^3/sec is the recombination coefficient, and $\mu_e = 0.88 \cdot 10^5$ cm^2/(sec · V) and $\mu_i = 290$ cm^2/(sec · V) are the mobility coefficients of the electrons and ions, respectively. The system of Eqs. (1) and (2) is supplemented by boundary conditions on the cathode and the anode

$$(j_e - \gamma j_i)|_{x=0} = 0, \; j_i|_{x=L} = 0, \tag{3}$$

where γ is the coefficient of secondary emission of electrons from the cathode. The distribution of the potential φ of the electric field is found from Poisson's equation, which is solved together with the boundary conditions on the electrodes and the lateral boundaries of the chamber:

$$\Delta\varphi = -\varepsilon(n_i - n_e); \tag{4}$$

$$\varphi(0, y) = 0, \quad \frac{\partial\varphi}{\partial y}\bigg|_{y=\pm L} = 0, \quad \varphi(L, y) = U, \quad \int_{-L}^{L} \frac{\partial\varphi}{\partial x}\bigg|_{x=L} L\,dy = \varepsilon Q. \tag{5}$$

Here $\varepsilon = 1.81 \cdot 10^{-6}$ V/cm, U is the voltage on the discharge in volts, and Q is the amount of electrons accumulated on the anode plate as a result of the imbalance between the current to the anode from the discharge and the current in the external circuit. The quantity Q is found as a result of integration of the ordinary differential equation

$$\frac{dQ}{dt} = \frac{10^{19}}{1,6} \frac{\mathcal{E} - U}{R} - \int_{-L}^{L} j_e(L, y)\,L\,dy. \tag{6}$$

A narrow layer of neutral plasma of variable density with its maximum on the symmetry axis of the chamber was arranged along the cathode at the initial instant of time to initiate the discharge:

$$n_e|_{t=0} = n_i|_{t=0} = 10^8 \cos(\pi y/2L).$$

The voltage on the capacitor was assumed to be equal to zero, i.e., $Q|_{t=0} = 0$. Previously [6] the phenomenon of breakdown between a plane and a point was investigated within the framework of the system of Eqs. (1)-(5), and the results were compared with analytic dependences.

The results of calculations performed for two values of the power supply voltage $\mathcal{E}$ = 500 and 700 V with an external load resistance R = 250 kΩ and the other conditions remaining the same are outlined in this paper. The value $\mathcal{E}$ = 500 V corresponds to approximately 10% of the overvoltage with respect to the breakdown value determined in accordance with Paschen's criterion [5]. The choice of the resistance R was dictated by the need to obtain a value of the total current I such that the average value of the current density on the cathode $I/2L^2$ would be less than the normal current density j_n. In accordance with the theory of Engel and Stenbeck, j_n = 2.8 mA/cm^2 for our parameters [5]. Specifying the expected average current density to be five times smaller and bearing in mind that the voltage on the discharge for small pL is determined mainly by the near-electrode drop of approximately 250 V, we obtain the necessary value of the resistance R. In the second case (for $\mathcal{E}$ = 700 V) the expected value of the total current should increase by a factor of two. Thus the average current density in the capacitor for both alternatives will be less than the normal value, and it corresponds to the declining section of the VAC.

The Breakdown Phenomenon and Entering the Quasistationary Regime

1. After the capacitor is switched into the circuit the voltage on the discharge reaches its maximum value, which is equal to $\mathcal{E}$, in a time of the order of 0.1 μsec, i.e., the capacitor plates are charged and a uniform electric field is established in the volume. The burning stage, which occurs with a practically constant electric field, directly precedes the breakdown phenomenon, which is accompanied by a sharp increase in the total current and the formation of a near-cathode layer. With $\mathcal{E}$ = 500 V this weak-current stage is realized over a period of almost 20 μsec in view of the insignificant amount by which the breakdown voltage is exceeded. The stage of formation of near-electrode layers and the subsequent quasisteady course of the process are of the greatest interest. The breakdown of the capacitor occurs in a qualitatively identical way.

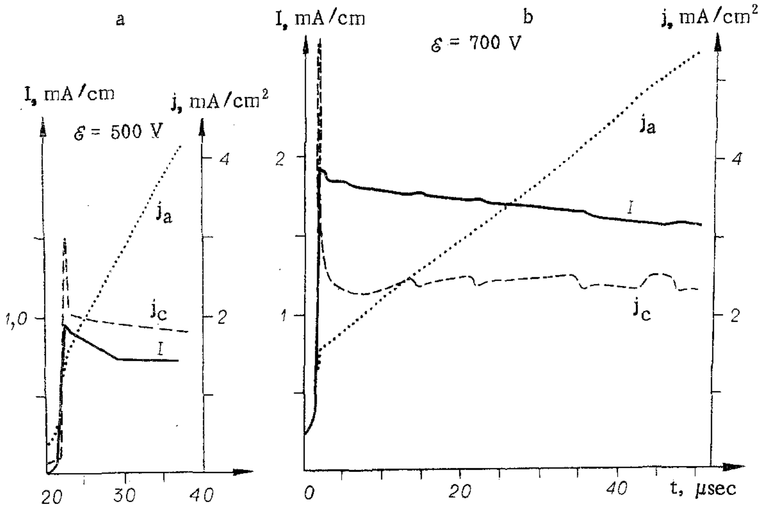

Fig. 1

independently of the value of the voltage on the power source, and is described in detail in [7] of the authors for the case $\mathcal{E}$ = 500 V. However, the subsequent quasisteady course of the discharge reveals appreciable differences (Fig. 1), which are associated with the nature of the temporal behavior of both the total current I and the current density on the cathode j_c and on the anode j_a on the discharge axis.

A near-electrode layer is formed near the cathode immediately after the breakdown for both alternatives considered, and a quasineutral plasma with a highly nonuniform distribution of values is formed in the volume. The corresponding distribution of the density of ions n_i and electrons n_e, the current density j, the potential φ, and the voltage of the electric field $\mathcal{E}$ on the discharge axis (t = 4 μsec, $\mathcal{E}$ = 700 V) is shown in Fig. 2. Near the cathode the plasma density exceeds the analogous quantity near the anode by approximately an order of magnitude, which produces a nonuniform distribution of the electric field voltage and a concentration of stream lines near the cathode in the region of enhanced conductivity (Fig. 2). Nevertheless, since the cross section of the conducting channel is wider near the anode than near the cathode, the distribution of the parameters in the chamber can be characterized as corresponding to the diffuse burning regime. The three-dimensional distribution of ions, electrons (the contour lines are in units of 10^9 cm^{-3}), and equipotentials and stream function lines normalized to unity (t = 4 μsec, $\mathcal{E}$ = 700 V) are shown in Fig. 3a-c, respectively. Smoothing of the parameters occurs at a significant time interval after the breakdown (7 μsec for $\mathcal{E}$ = 500 V and 50 μsec for $\mathcal{E}$ = 700 V): a blob of plasma near the cathode disappears due to drift removal of ions to the cathode by the electric field, and the plasma concentration in the rest of the volume on the discharge axis increases due to ionization processes. Simultaneously with this a uniform electric field is established on the axis in the volume, the maximum of the current density shifts from the cathode to the anode, and an appreciable decrease of the cross section of the conducting channel occurs both in the volume and on the anode. One can speak at this stage of a constricted discharge [7].

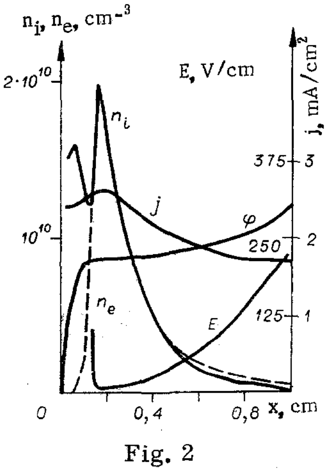

Fig. 2

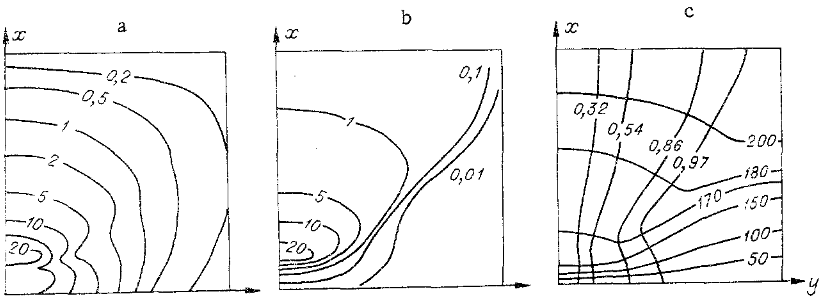

Fig. 3

2. It is meaningful to consider the transition from the diffuse state to a constricted one in more detail. The nature of this process depends on the value of the voltage at the power source. With $\mathcal{E}$ = 500 V a uniform field is established in the positive column due to a wave of electric field intensity which propagates from the anode to the cathode at a velocity of the order of the ion drift velocity [Fig. 4a, $\mathcal{E}$ = 500 V, 1) t = 23.16, 2) 25.14, and 3) 27.3 μsec]. At the same time with $\mathcal{E}$ = 700 V equalization of the field in the volume takes incomparably longer (almost 50 μsec is required instead of the 7 μsec in the first alternative) and is accomplished due to a simultaneous increase of the intensity at each point on the discharge axis [Fig. 4b, $\mathcal{E}$ = 700 V, 1) t = 19.88, 2) 32.01, and 3) 49.90 μsec]. As simple discussions show [7], a wave of the electric field intensity cannot in principle be realized in the one-dimensional case, i.e., in the form of a plane wave. Narrowing of the conducting channel behind the wave front is a necessary condition for compensation of the increase in conductivity which is mandatory for the propagation of a field wave and the ionization associated with it. The total current I or the cross section of the conducting channel formed after the breakdown emerges as the parameter here: the larger the cross section is, the more difficult it is for a wave to propagate. We will analyze this situation within the framework of a simplified model. A schematic diagram of (a) the field of the wave E, (b) the variation of the cross section of the conducting channel S associated with it, and (c) the plasma density n is given in Fig. 5 for two instants of time – directly after the breakdown prior to the onset of the wave (curve 1) and some time later (curve 2). The values of the quantities E, S, and n behind the wave front (the x_* coordinate) are assumed to be independent of x and equal, respectively, to E_*, S_*, and n_*. Thus, according to this simplified picture, the field wave has the form of a small shelf with a fixed height (Fig. 5a) propagating from the anode to the cathode at a velocity, as follows from the results of the numerical solution, equal to the drift velocity of the ions behind the wave front. In addition it is assumed that the stream lines which diverge from the cathode become parallel to each other and to the discharge axis after crossing the wave front (Fig. 5b). The conducting channel behind the wave front is a rectangular region filled with a uniform plasma (Fig. 5c). One can calculate the rate of change of the plasma concentration n_* behind the front which is necessary for ionization processes, and with approximate constancy in time of the total current one can determine the rate of decrease of the cross section S_*:

$$d\ln n_*/dt = -d\ln S_*/dt = \nu_i(E_*), \tag{7}$$

where ν_i is the ionization frequency. On the other hand it follows from the condition of continuity of n(x) and S(x) that the rate of change of these quantities behind the wave front should be equal to the rate of change of these very same quantities in front of the front: the latter is of a kinematic nature and is necessary simply for shifting the wave in a nonuniform plasma. Using Eq. (7), we obtain

$$\left.\frac{d\ln n}{dx}\right|_{x_*-0} = -\left.\frac{d\ln S}{dx}\right|_{x_*-0} = \frac{\mu_e}{\mu_i}\alpha(E_*). \tag{8}$$

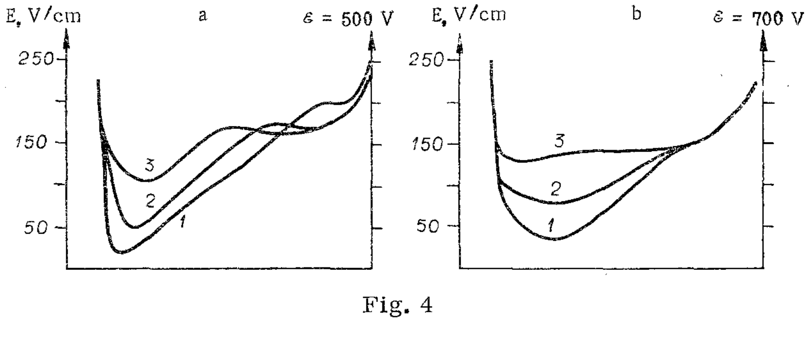

Fig. 4

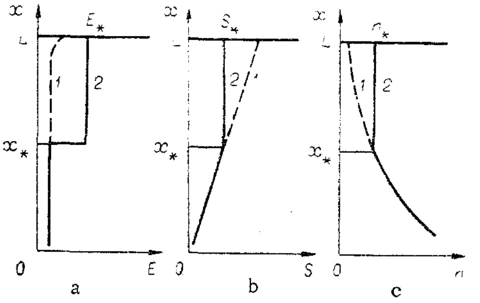

Fig. 5

Thus it follows from this simplified discussion that it is necessary for the realization of a field wave that the logarithmic derivative of the cross section of the conducting channel after the breakdown be commensurable with the logarithmic derivative of the conductivity. Since the plasma distribution is highly nonuniform as a rule, then for the identical expansion angle of the flow tubes more favorable conditions for a wave are realized in the case of smaller cross sections and currents. This result is in qualitative agreement with the results obtained for $\mathscr{E}$ = 500 and 700 V.

3. Now we will dwell on another qualitative difference between the discharges at $\mathscr{E}$ = 500 and 700 V. If in the first alternative the current density on the cathode at the center j_c is practically constant (see Fig. 1a) and a decrease in the total current occurs due to a proportional decrease in the cross section of the emitting surface [7], then such a trend of the process in the second alternative occurs only on the average in time (see Fig. 1b). A qualitative picture of the course of the flow near the cathode for $\mathscr{E}$ = 700 V is appreciably more complicated: periodically repeating oscillations of the current density on the cathode at the center are related to a redistribution of the current along the cathode [Fig. 6, where *a* is the stage corresponding to a slow increase of the current j at the center due to contraction of the emitting surface on the cathode: 1) t = 15.44, 2) 18.90, and 3) 21.05 μsec; and b is the stage corresponding to a rapid decrease of the current density at the center: 1) t = 21.44, 2) 21.74, and 3) 22.03 μsec].

First we will say a few words about the mechanism due to which the reduction of the area of the emitting surface on the cathode occurs; it is one and the same for both alternatives. The current distribution along the cathode is nonuniform, as follows from the solution (see Fig. 6): the current density on the outer boundary of the conducting channel for $\mathscr{E}$ = 700 V is almost 1.3 times larger than at the center. Therefore one can separate the near-cathode region into two parts: a central part and an outer one, having taken the point on the cathode at which there is a local minimum of the current density as the boundary between the two parts. As an analysis of the computational results shows, a relatively high current density is mandatory in the outer region for the uncompensated charge of the ions which are located above the near-cathode layer next to the quasineutral plasma of the positive column. These ions are formed in proportion to the compression of the current-conducting channel, precipitating out of the region through which electrons pass. The additional electric field created by them near the cathode also leads to increased ion generation and consequently an increased current density on the periphery of the emitting surface. This uncompensated positive charge migrates towards the discharge axis as time goes by, on the one hand due to drift departure of ions to the cathode, and on the other hand due to a narrowing of the current channel. From the physical standpoint the first situation is the principal one, and the second one is an induced situation.

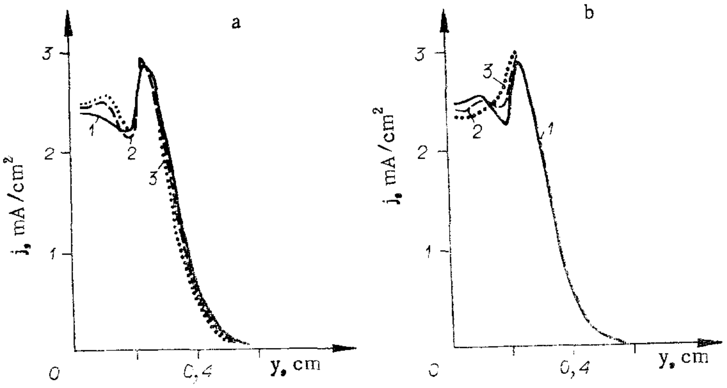

Fig. 6

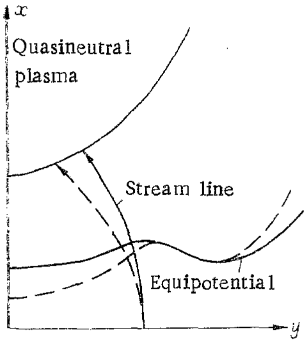

Fig. 7

The basic cause for the decrease in the total discharge current I (see Fig. 1) is associated with the contraction of the cross section of the current-conducting channel near the cathode; for $\mathscr{E}$ = 500 V the rapid increase in the voltage on the discharge between the 23rd and the 30th μsec results in the propagation of a wave of electric field intensity from the anode to the cathode (see Fig. 4a). At the same time for $\mathscr{E}$ = 700 V the propagation of a field wave from the anode to the cathode proves to be impossible according to the simplified model which was spoken of above (see Fig. 5), and a rapid increase in the voltage on the discharge turns out to be impossible. The decrease in the total current due to the contraction of the cross section of the emitting channel on the cathode is compensated to a significant extent by the increase in the current density on the discharge axis (at the center of the cathode) (see Fig. 6a), leading to a consistent slow decline of the total current I (see Fig. 1b) and an increase in the voltage on the discharge between the 4th and 50th μsec.

However, as the calculation shows, as the current density at the center of the cathode increases, it reaches the critical value of 2.45 mA/cm^2, after which redistribution of the current in the cross section occurs relatively rapidly in a time $\Delta t \approx 1$ μsec (see Fig. 6b): the current density on the discharge axis decreases to a value of 2.35 mA/cm^2 due to an increase in the current density in the outer region. After this a repeated increase in the current density on the discharge axis begins with a simultaneous reduction in the width of the current channel near the cathode.

It is of interest to discuss the mechanism of this phenomenon. As the calculation shows, it is related to a rearrangement of the structure of the electric field near the cathode. We will discuss the current tube which starts from a specified point on the cathode and terminates in the quasineutral plasma. From the standpoint of maintaining the current, the main process is ionization in the near-cathode layer. The ions which enter from the volume of the quasineutral plasma have a definite value, although their amount is undoubtedly small in comparison with the ions formed in the near-cathode potential jump. The principal role of these ions consists of the fact that they create an additional electric field intensity, and therefore the reaction of the near-electrode layer and the current density for these ions is significantly nonlinear. Thus for an amount of current at some point or other on the cathode the plasma concentration from the other end of the current tube can have a definite value. From this standpoint the point on the cathode at which there is a local minimum of the current density is of the greatest interest: according to the theory of Engel and Stenbeck, the strongest dependence of the current on the near-cathode potential drop in the anomalous branch is realized for smaller currents; it is natural to assume that this property is preserved, depending on the concentration of ions entering from the column. It is furthermore clear that as the current on the discharge axis increases, a distortion of the potential occurs which corresponds to a constriction of the stream lines towards the center (Fig. 7, in which the solid lines denote one instant of time and the dashed lines another later instant of time). Under some conditions the stream line which emerges from the point of minimum current density on the cathode is deflected and enters a region of sufficiently high plasma density that an increase in the current density at the corresponding point on the cathode results. Due to this an increase in the total current occurs, which leads to a decline in the voltage on the discharge and a decrease in the current density on the discharge axis. Such smoothing of the current density distribution along the cathode leads to a straightening of the field lines; they branch out from the discharge axis, migrating into a region of reduced plasma density in the positive column, the current density in these current tubes drops off, the total current also drops off, and the voltage on the discharge increases; and as a result the current at the center starts to increase. The system returns to the state from which the reduction in the width of the current channel starts with a simultaneous increase of the current density on the discharge axis (see Fig. 6a) to the critical value, after which a redistribution of the current on the cathode again occurs (see Fig. 6b). The picture described above explains the first three rapid oscillations observed in the current density on the cathode. This same mechanism is responsible for the following nonstationary phenomena, which occur with some difference from the first ones. Completing the discussion of nonstationary effects in the near-cathode region for $\mathscr{E} = 700$ V, we note that the time-average value of the current density on the cathode in the center remains practically constant and approximately 20% higher than the current density on the cathode for $\mathscr{E} = 500$ V. Taking account of the fact that the total currents for the two calculated alternatives differ by almost a factor of two, one can speak of a theoretical confirmation of the law of normal current density for the cathode.

4. A characteristic general feature of the development of discharges for $\mathscr{E} = 500$ and 700 V is the linear increase of the current density on the anode (see Fig. 1) for a relatively weak variation of the total current and the decrease which occurs in the cross section of the conducting channel on the anode and in the volume.

The increase of the plasma density in the volume is related to the fact that the intensity of the uniform electric field established by this or the other means in the positive column turns out to be higher than the value corresponding to the condition of ionization–recombination equilibrium for a given plasma concentration. However, in accordance with the law of normal current density, the total current is proportional to the cross section of the emitting surface on the cathode, whose laws of variation are determined by near-electrode processes, and the increase in the conductivity in the volume is not accompanied by an increase in the total current. According to the increase in conductivity in the volume in the case of a weakly varying total current, a transition of the discharge from the diffuse regime to a constricted discharge is accomplished: the current density on the discharge axis and in the volume exceeds by more than a factor of two the current density on the cathode at the end of the calculations.

A steady discharge was not obtained in this research in view of the large expenditures of machine time. However, states in which the total current already ceases to vary further in time (see Fig. 1) are attained at the final calculated instant of time. Accordingly, the intensity of the uniform electric field in the volume ceases to vary. Proceeding from the condition of ionization–recombination equilibrium, one can compare the conductivity and the cross section of the conducting channel in the column for $\mathscr{E} = 500$ and 700 V in the final state with each other. Since in the first case the field intensity is greater than in the second [it is sufficient to compare the rates of increase of the current density on the anode j_a (see Fig. 1)], the equilibrium conductivity is also larger. It follows from this that the cross section of the conducting channel in the volume increases not in proportion to the total current but more rapidly.

The calculations performed of a glow discharge for two values of the total current differing by a factor of two have shown that a near-cathode layer of space charge arises simultaneously with the breakdown of the discharge gap in a time of ≈ 1.5 μsec. With the initial data used, a near-electrode layer is formed both along the field and along the cathode, covering only a small part of the latter: the current density on the cathode (at the center) is practically constant thereafter and is approximately identical for both alternatives. This fact permits speaking of a theoretical confirmation of the law of normal current density for the cathode.

Directly after the breakdown, the distribution of the parameters can be characterized as corresponding to a diffuse burning regime: the current density on the anode is less than on the cathode. As time progresses, the field in the volume equalizes and reaches a value which exceeds the value of the equilibrium intensity for the given plasma concentration. This circumstance results in a linear increase in the current density on the anode and a compression of the conducting channel in the volume: in the final stage the discharge burns in a constricted fashion.

Thus it has been shown by the example of computational data that the mechanism of compression of a quasineutral column mandatory for phenomena on the electrodes can be realized. Due to the inconsistency between the value of the field in the column and the value of the total current established after the breakdown, a continuous compression of the current channel in the column and on the anode occurs. In the case of low gas pressure a similar agreement can be accomplished subsequently on account of expansion of the cathode spot due to diffusion. For high pressures such a mechanism is ineffective, and compression of the discharge can only be aggravated by subsequent heating of the gas.

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MEASUREMENT OF THE BRIGHTNESS TEMPERATURE DISTRIBUTION OF PLASMA BUNCHES

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UDC 533.9.07+535.231.6

The study of the radiation characteristics of a moving plasma bunch occupies an important place in the investigations of high-velocity plasma jets. One of the aspects of these researches is the development of experimental methods of investigating the distribution of the radiation spectral intensity and of the brightness temperature along a plasma (gas-plasma) jet. Thus, the radiation intensity and brightness temperature of a gas jet were measured in [1, 2] by using stationarily mounted light guides that recorded the radiation intensity as a function of the time. The resolution of such a method is constrained by the "viewing angle" of the light guides since the integrated intensity over the apertures was actually recorded.

The possibility is shown in this paper of reproducing the brightness temperature distribution along a plasma jet on the basis of a simple high-speed photographic sweep (for instance, by using a SFR) and subsequent photometric processing. The method developed was used to find the distribution of the radiation spectral intensity and the brightness temperature of plasma jets from a tubular, cumulative-gas charge [3, 4] and an explosive plasma compressor [5]. The shock front was successfully resolved, i.e., distributions were obtained of the above-mentioned parameters starting with the domain preceding the shock.

1. Let us consider a plasma jet being propagated over an opaque channel along which a narrow transparent slit of width a very much less than the transverse channel dimension is made. The slit image rotates continuously on a film in a direction perpendicular to the channel axis. A photographic sweep is made through a light filter that cuts off radiation in a narrow wavelength band. It is assumed that continuous photographic recording is accomplished by using the ideal photorecorder introduced in [6]. The velocity D of jet motion during the recording is considered constant. A continuous photographic sweep at velocity u yields the image displayed in Fig. 1 on the film, where 1 is the channel over which the plasma moves, 2 is the direction of plasma jet motion, 3 is the transparent slit in the channel and 4 is the photographic film. Time is measured from the arrival of the first perturbation in the channel section AB selected. Projection of the section AB on the film corresponds to the segment A'B' of the x axis. The position x = 0 is determined by the initial increase in the optical density, which exceeds the fog density. It is seen that the line CD on the recording, and all the lines parallel to it, are lines of constant blackening. If y is the coordinate along the plasma jet (in a coordinate system coupled to the jet) and I(y) is the radiation intensity distribution along the jet (at the wavelength cut off by the light filter), then the energetic exposure on the film along the x axis is determined by the following relationships [6]:

$$H(x) = \begin{cases} K\int\limits_{0}^{x/u} I(Dt)\,dt, & 0 \leqslant x \leqslant \alpha a, \\ K\int\limits_{(x-\alpha a)/u}^{x/u} I(Dt)\,dt, & x \geqslant \alpha a, \end{cases} \qquad (1.1)$$

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