Measurements of electric field distribution in open discharge

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The results of measurements of the electric field distribution in the so-called open discharge are presented. The measurements were conducted with the electrostatic probes (set of diaphragms). Thus obtained field profiles $E(x)$ are in a good agreement with the results of optical measurements [V.P. Demkin, B.V. Korolev, and S.V. Mel'nichuk, Fiz. Plazmy **21**, No. 1, 81–84 (1995)]. It was found that efficient e-beam generation occurs at the transient phase of the discharge at a great delay of the processes of space charge accumulation in the interelectrode gap and formation of the cathode drop region regarding the discharge current. It is shown that treatment of the open discharge as a glow one is unjustified.

In 1980 it was found[1] that e-beams with the energy from 2 to 7 keV can be successfully generated in a narrow discharge gap with a solid metal cathode and grid anode at a gas pressure of tens of kilopascals. Then the pulsed discharge occurring under these conditions was called the open discharge.[2] The mechanism of the open discharge is still an open question.[3–5]

Sorokin[3] argues that it is an anomalous form of the well known glow discharge, whereas in Refs. 4 and 5 it is considered as a process different from the glow discharge, but even these papers treat it differently. In our opinion, the reliable data on distribution of the electric field over the length of the discharge gap and its evolution could make the situation significantly more clear.

By now there is only one paper[5] which reports on measurements of the field profile in the open discharge in neon. The measurements were conducted by the probe method. It turned out that already at the discharge current density about 0.6 A/cm^2 (discharge voltage $U_\text{d} \sim 2.4$ kV) the cathode drop region (CDR) with the size $\delta \sim 0.9$ mm was formed in the gap $d = 1.2$ mm in length at the neon pressure $P = 600$ Pa. At the current density about 4 A/cm^2 ($U_\text{d} \approx 4$ kV) the field was almost completely localized in the near-cathode layer about 0.2 mm thick. Grids set crosswise the discharge gap and connected to the cathode and anode by the voltage divider served as probes. However, our experiments on e-beam acceleration in sequential gaps between grid electrodes have shown their low electrical strength in the presence of even very weak e-beam passing-through. As the potential difference at grid electrodes reaches several hundreds volts, an electric discharge arises between them. Thus, setting the grid probes in the interelectrode gap strongly changes the dynamics of the discharge and distribution of the field in it. Therefore, the results of Ref. 5 cannot be used in our study.

In 1995 the paper[6] was published, which illustrated the applicability of the method of polarization spectroscopy to measurement of strong electric fields in a gas and, in particular, in the open discharge. Unfortunately, the measurements were conducted for only one specific case in a rather long discharge gap and at low voltage, that is, under conditions of poor e-beam generation. These data are certainly insufficient for revealing the physics of the open discharge.

The goal of this paper was to study the electric field distribution in the open discharge at different moments in time with the current typical of the e-beam generation process.

Experimental technique and results

The potential was measured with electrostatic probes. Copper foil diaphragms 50 μm thick with an aperture 11.5 mm in diameter served as probes. A set of coaxial diaphragms and isolating layers 0.2 mm thick and 1.2 mm in total length determined the cross section of the open discharge ($S_\text{d} \approx 1$ cm^2).

Preliminary tests of the gap with one probe of this type in the open discharge as well as in an anomalous glow discharge have demonstrated its capability of operating in strong electric fields. The measurements of the potential directly at a diaphragm faces some problems associated with the necessity of minimizing the effect of a measuring circuitry on the value of the potential, suppressing the noise from neighboring high-voltage circuits, correcting for signal distortion by spurious capacitance, and others. Therefore, prior to measurements the measuring system was tested regarding to the following parameters.

1. Possibility of achieving a given maximum duration of undistorted signal. Fulfillment of this condition was checked by superimposing oscillograms of signals from the probes on the signal of voltage across the cathode (certainly, at the corresponding amplification of the former) recorded in the evacuated discharge chamber. The distortion is connected with the discharge of the probe capacity through the measuring circuit; therefore, it grows with time. Coincidence of these signals accurate to 10% was achieved 2 μs after applying the voltage.

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2. Achieving the required speed of a response at absence of signal delay in the probes. This was checked by the response of the measured signals to a short perturbation of the electric field in the discharge gap. Such perturbations arise as the cathode is weakly sparking. In this case current pulses with the amplitude about 0.5 A and 2 to 5 ns in duration are generated. The check was conducted at sparking in the central part of the cathode surface, that is, in the case of maximum separation of the perturbation from the probes.

3. Check for the adequacy of the response of signals in the probes to perturbation of the field in the gap, that means signal calibration. This check was done for the two limiting cases: (a) with no discharge in the gap (then the amplitudes of the signals in the diaphragms decrease linearly with the distance from the cathode); (b) at strong sparking of the cathode far from the diaphragm edges with the formation of a highly conductive plasma channel (then the signals in the probes vanish simultaneously).

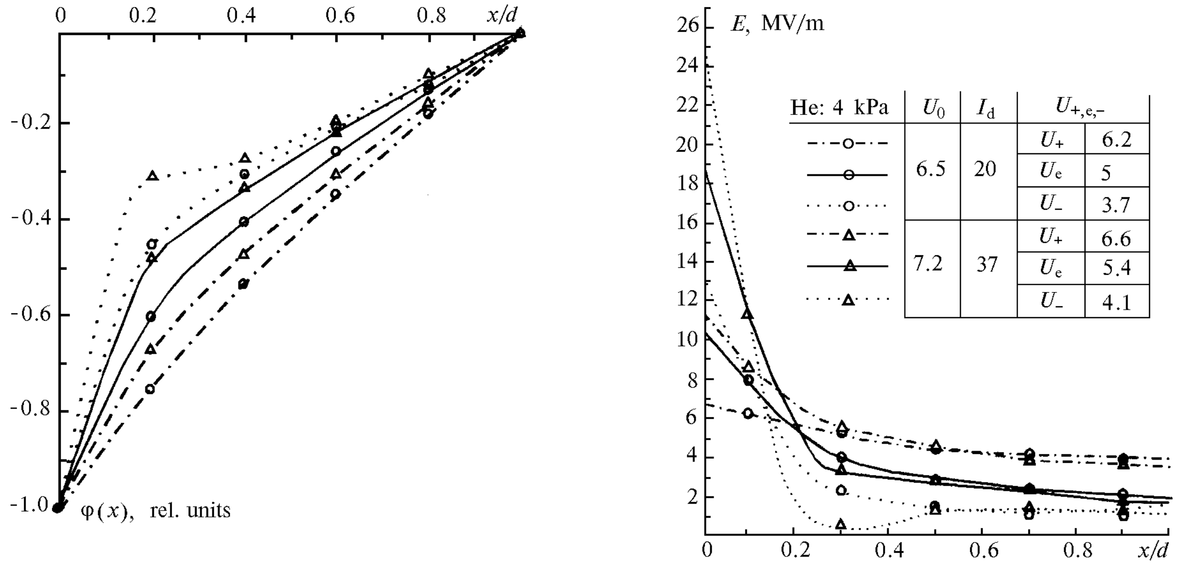
The measurements were conducted in helium. An e-beam collector was set 45 mm far from the anode. The discharge capacity was 470 pF. With the discharge gap $d \sim 0.5$ mm long, the anode current usually markedly lags behind the beam current.[4] However, in our case at $d = 1.2$ mm, the amplitudes of pulses of the beam current and anode current were achieved at the same time at the helium pressure in the range of practical interest. Then the beam current decreased much more rapidly than the current in the anode circuit. In particular, as the beam current was halved, the anode current decreased only by 20 to 30%.

The distribution of the electric field was measured at three moments in time: at the half-way of the beam current growth, as it achieved its amplitude value, and at the half-way of its decrease. At each moment the absolute value of the cathode voltage was measured: U_+, U_e, U_-, respectively, as well as the corresponding values of the potential at the probes. Then the mean value of the field strength was determined from the potential difference at the neighboring probes, and the determined value was assigned to the midpoint between these two probes. The measured distributions of the potential in the discharge gap and the distributions of the field strength calculated from them are shown in Figs. 1 and 2. Of course, the field distribution $e(x)$ between the cathode and the first probe, as well as that nearby the anode, can be shown only supposedly.

Discussion

Note first, that the distributions $e(x)$ shown in Figs. 1 and 2, which were obtained at CDR already formed, are similar to that from Ref. 1 obtained using an optical method. This similarity seems important, because it is indicative of the correctness of the test methods.

Then, the experiment showed that at the half-way of the current growth, the field in the discharge gap was still weakly distorted by the volume discharge of ions, but the latter factor grew fast. Nevertheless, at the moment of the maximum beam current (the total discharge current I_d was about 40 A at 2.6 kPa, about 35 A at 4 kPa, and about 20 A at 5.3 kPa), the strong field, which exceeded by an order of magnitude the threshold value for the electron runaway, was observed all over the length of the discharge gap. However, in the near-cathode region about 0.3 mm wide it dropped down to the half of the applied voltage.



a *b*

Fig. 1. Measured distributions of the potential $\varphi(x)$ (*a*) and the distributions of the electric field strength calculated from them (*b*) over the length of the discharge gap ($U_{0,+,e,-}$, in kV; I_d, in A/cm^2) at the half of the leading edge of the current pulse (dot-and-dash curves), at the amplitude value of the current (solid curves), and at the half of the trailing edge of the current pulse (dotted curves).

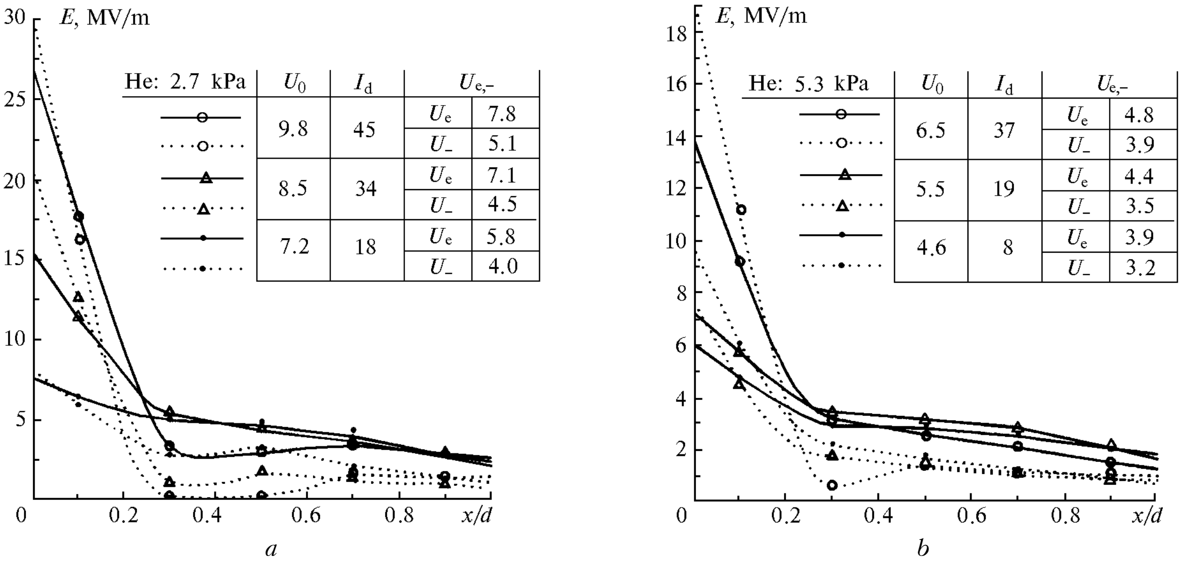


Fig. 2. Distributions of the electric field strength over the length of the discharge gap obtained under different conditions. The units are the same as in Fig. 1.

Then, despite the decrease of the discharge current had already started, the process of field localization near the cathode and formation of the CDR continued. Consequently, the e-beam generation in our case occurred under significantly nonstationary conditions. This stage of the discharge is generally called the phase of fast switching.

Let us consider what processes determine the evolution of the discharge at this stage in a narrow interelectrode gap under conditions of efficient e-beam generation. Sorokin[3] and Kolbychev et al.[7] state that (a) the quasistationary phase following the phase of fast switching is the anomalous glow discharge; (b) e-beam is generated in the anomalous glow discharge with the efficiency about 80 ... 90%; (c) the phase of fast switching and glow discharge have the same mechanisms of evolution. First, let us refer to Ref. 7, because the conclusions drawn in it are basic for the reasoning given in Ref. 3. In Ref. 7 the volt–ampere characteristic (VAC) at the quasistationary phase of the discharge was measured. Then it was compared with the equation for VAC of the stationary anomalous glow discharge

$$I_d/P_2 = 2.5\cdot10^{-12}\, U_c^3\,, \qquad (1)$$

where I_d is in A/cm^2; P is in Torr; and U_c is in V.

The agreement of the measured VAC with Eq. (1) proves the statement (a). Kolbychev et al.[7] stated that such an agreement was obtained in all measurements. However, Fig. 2*b* from Ref. 7 shows the oscillograms of the current I_e and U_c recorded in the gap 0.5 mm long at the helium pressure of 26.6 Torr, cathode area of 0.8 cm^2, initial voltage across the discharge capacitor of 10 kV, and ballast resistance of 75 Ω. At the quasistationary phase the beam current was about 7 A and $U_c \approx 6.5$ kV. From this we have $I_d \approx (10 - 6.5)\cdot10^3/(75\cdot0.8) \approx 68$ A/cm^2. However, Eq. (1) for these values of U_c and P gives $I_d \approx 485$ A/cm^2, that is, seven times larger value! This is far from agreement. Then, taking into account the transmittance of the anode grid ($\mu = 75\%$), we obtain the efficiency of the e-beam generation in this experiment: $\eta = 4\,I_e/(3\cdot I_d) = 28/163 = 17.2\%$. At $p = 40$ Torr (Ref. 7, Fig. 1*a*) it is even smaller. Thus, the statement (b) has also poor grounds. The statement (c) is based on the identical switching characteristics of the discharge at $d \gg \delta$ (Ref. 7, Fig. 4): characteristics are independent of the length of the discharge gap, so there are no peculiarities in the mechanism of the discharge evolution in narrow gaps.

In our opinion, this argument does not prove the identity of the mechanisms of the open discharge and the phase of fast switching of the volume discharges. Actually, the dependence of the switching characteristics on d can be weak or does not manifest itself at all. It is another factor that is of principal importance: the structure of the current in the open discharge changes as the length of the discharge gap changes. For example, in helium with $p = 80$ Torr at $U_0 = 8$ kV and the anode–collector separation $L = 2.2$ cm, we have obtained pulses of the discharge current $I_d = I_e + I_a$ with almost same amplitude and duration about 75 A and 25 ns in the gaps of 0.5 and 1 mm lengths. However, at $d = 1$ mm the ratio I_e/I_a was 20/55, whereas at $d = 0.5$ mm it was 32/41. If, taking into account that a part of a beam was not transmitted by the anode grid ($\mu = 75\%$), these ratios would be 27/48 and 43/30, respectively. Consequently, the size of the interelectrode gap is an important factor determining the e-beam generation. But the efficiency of generation strongly affects the VAC of the open discharge,[4,8] whose change indicates the change in the mode, which in turn is indicative of the change in the mechanism of the discharge process.

Thus, analysis showed that the statements (b) and (c) being of principal importance were not proved in Ref. 7 and therefore referring to this work, as in Ref. 3, is unjustified. As to the statement (a), in Ref. 4 we classified the discharge generating an e-beam with low efficiency as a glow discharge. It was shown that this discharge possesses a certain transient VAC $F(U_\mathrm{d}) = \mathrm{d}(\ln I(t))/\mathrm{d}t \propto U_\mathrm{d}^{\beta}$ with $\beta \sim 2.5$. In this respect the results of Ref. 7 only support the conclusions drawn in Ref. 8. However, the efficient e-beam generation occurs, according to Refs. 4 and 8, in a different mode, in which $F(U) \propto U_\mathrm{d}^{\beta}$ at $\beta \le 1$. This mode takes place at a strong effect of a UV illumination.

Let us turn to Ref. 3. Note that the discharge was studied in it at very low gas pressure (helium pressure from 200 to 340 Pa at high voltage, neon pressure up to 600 Pa at low voltage) and a short anode–collector separation (~ 20 to 30 mm). Under such conditions the UV illumination of the cathode by radiation from the excited gas in the area behind the anode by e-beam or back current is apparently very low.[9] The discharge was, certainly, the glow discharge. Since the retarding ability of the gas on its way to the collector is also very low, practically all electrons generated in the cathode drop region reach the collector and contribute to the beam current. In this case the generation efficiency is described by the equation

$$\eta = 1 - I_+(\delta)/[I_+(0)(1+\gamma)] , \qquad (2)$$

where γ is the electron emission coefficient of the cathode; $I_+(\delta)$ and $I_+(0)$ are the ion current at the CDR boundaries. If the condition of existence of an independent discharge is fulfilled in the CDR, then $I_+(\delta) = 0$ and $\eta \to 100\%$. However, even if this condition is not fulfilled, then under conditions of the experiments [$U \sim 10$ kV, $p \sim 290$ Pa (helium), $\delta \sim 3$ mm, see Ref. 3, Fig. 4] the value of γ, according to Ref. 10, is about three, and the efficiency η is still rather high. Guns for electron-ray welding (helium 133 Pa, 10 kV) operate in the mode close to the above-considered.[11] Sorokin[3] believes that as the pressure increases, the discharge mode and the efficiency of e-beam generation remain unchanged. However, the experiments[7] showed drastic decrease in the efficiency with the increasing gas pressure.

The data we have obtained experimentally give new arguments against classification of the open discharge as a glow discharge. The data shown in Figs. 1 and 2 evidence that accumulation of the space charge in the interelectrode gap and formation of the CDR lag far behind the discharge current. The oscillograms of the I_e and I_a pulses show that the instantaneous value of the e-beam generation efficiency[4,12] monotonically decreases as the discharge evolves. Based on the ideas from Refs. 3 and 7 on the mechanism of the open discharge, the decrease in the generation efficiency in the process of discharge evolution can hardly be explained. Actually, formation of the CDR and its narrowing lead to an increase in the field strength at the cathode. The energy of ions and fast atoms increases therewith, and so the coefficient of the electron emission from the cathode increases as well.[10] As a result, the instantaneous value of the e-beam generation efficiency must increase. However, in practice we observe just the opposite situation.

It is believed that in short interelectrode gaps the weak field area arises near the anode and then expands to the cathode.[3,12] The data shown in Figs. 1 and 2 disagree with this concept. It proves that the local area of a weak field arises inside the discharge gap, thus cutting the CDR off the rest part of the discharge, and only then expands toward the anode. Such a pattern corresponds rather to the formation of discharge in a long interelectrode gap, for which the condition for discharge occurrence

$$\gamma \cdot K(x) = 1 \qquad (3)$$

is fulfilled at a point $x < d$. Here $K(x)$ is the charge multiplication coefficient as the electron avalanche sweeps from the cathode to the point x. However, the long lag of the space charge accumulation in the gap behind the discharge current is possible only at very small $K(d)$ because of the electron transition into the runaway mode.[12] In this case a high value of the coefficient γ is required for the condition (3) to hold. The bombardment of the cathode with ions and fast-atoms in the fields achievable under conditions of our experiments (see Figs. 1 and 2) does not provide for such values of γ (Ref. 10). In our opinion, the observed field distribution in the interelectrode gap is explained by a large contribution to the coefficient γ coming from the photoelectron emission caused by the UV illumination of the cathode from the region behind the anode. Determination of the source of this illumination is the subject of a separate study.

Conclusion

Our research has demonstrated the possibility of measuring the potential along the discharge gap with electrostatic probes made as diaphragms enveloping the discharge column. The testing procedure suggests that the probes do not distort the discharge dynamics and their signals represent actual values of the potential at the given distance from the cathode with a sufficient accuracy. However, the final conclusion on the reliability of the proposed method can certainly be made only after comparison of our results with those obtained by other methods; optical methods, such as polarization spectroscopy,[6] are preferable.

It was found experimentally that accumulation of the space charge in the interelectrode gap and formation of the cathode drop region lag far behind the discharge current. This manifests itself in the fact that in the absence of the CDR the current with the density up to 30 ...40 A/cm^2 and this transient phase of the discharge lasts about 20 to 40 ns. During this phase the efficiency of e-beam generation is high (~70...90%) and decreases with time. As the narrow cathode drop region is formed ($\delta \ll d$), the discharge transforms into the quasi-stationary phase of the anomalous glow discharge. The efficiency of e-beam generation in this phase is low (~ 10 ... 20%) at the helium pressure above 2 kPa (Ref. 7).

The mechanisms governing the dynamics of the glow discharge do not explain the high efficiency of e-beam generation at the phase of fast switching. However, this phenomenon can be naturally explained by the photoelectron mechanism we studied earlier.[4,8,12]

References

1. P.A. Bokhan and G.V. Kolbychev, Pis'ma Zh. Tekh. Fiz. **6**, No. 7, 418–421 (1980).
2. P.A. Bokhan and A.R. Sorokin, Zh. Tekh. Fiz. **55**, No. 1, 88–95 (1985).
3. A.R. Sorokin, Zh. Tekh. Fiz. **68**, No. 3, 33–38 (1998).
4. G.V. Kolbychev and I.V. Ptashnik, Zh. Tekh. Fiz. **59**, No. 9, 104–110 (1989).
5. P.A. Bokhan, Zh. Tekh. Fiz. **61**, No. 6, 61–68 (1991).
6. V.P. Demkin, B.V. Korolev, and S.V. Mel'nichuk, Fiz. Plazmy **21**, No. 1, 81–84 (1995).
7. K.A. Klimenko and Yu.D. Korolev, Zh. Tekh. Fiz. **60**, No. 9, 138–142 (1990).
8. G.V. Kolbychev and I.V. Ptashnik, Pis'ma Zh. Tekh. Fiz. **11**, No. 18, 1106–1110 (1985).
9. G.V. Kolbychev, P.D. Kolbycheva, and O.B. Zabudskii, Atmos. Oceanic Opt. **6**, No. 3, 153–156 (1993).
10. H.C. Hayden and N.G. Utterback, Phys. Rev. **135**, No. 6A, 1575–1579 (1964).
11. V.I. Mel'nik and A.A. Novikov, Elektronnaya Obrabotka Materialov, No. 1, 84–86 (1972).
12. G.V. Kolbychev, Atmos. Oceanic Opt. **6**, No. 6, 375–382 (1993).