Electron beams in hollow-cathode and open discharges

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The discussion on whether an impeded discharge with a grid anode, i.e., an open discharge, is a photoelectron one is continued. From the most general point of view and based on new experimental data, formation of electron beams (e-beams) under various glow discharge conditions is considered. The author returns to the conclusion he has drawn earlier that the electron emission necessary for high-efficiency e-beam generation is created in the open discharge due to bombardment of the cathode with fast atoms generated in the process of ion recharging. The latter fact has been reliably established long ago for the case of open discharge with a single-hole grid, i.e., in the discharge tube with a hollow anode.

1. The conditions of e-beam generation in a glow discharge are usually associated with the left-hand branch of the Paschen curve. However, in the open discharge (OD), the conditions near the minimum of the Paschen curve $(p_{\mathrm{He}}d)_{\min} = 4$ Torr · cm and even deeper into the right-hand branch are often used. In particular, in Ref. 1, the laser emission from Eu^+ ions at a pressure up to 1 atm was studied.

In this paper, by analyzing the peculiarities of e-beam generation under conditions corresponding to the left-hand and right-hand branches of the Paschen curve in different discharges, we try to reveal whether or not there are distinctions of kind in the e-beam generation in these two cases and, if any, are they beyond known forms of the glow discharge.

Our consideration is based on the non-traditional classification of the glow-discharge forms proposed in Ref. 2, because it reflects most simply and clearly the basic features of the glow discharge (see Fig. 1). Zone *1* corresponds to the simplest discharge (the field in the gap is weakly distorted by charges); zone *2* corresponds to the dense discharge (field distortion is significant); and intermediate zone *3* corresponds to the normal glow discharge. For the simplest discharge, the cross section in the plane U, pd gives the Paschen curve, and the cross section in the plane U, j is the volt-ampere characteristic (VAC). It is seen from Fig. 1 that for the dense discharge, the VAC rise is the same for the left-hand and the right-hand branches of the Paschen curve. If, for the normal discharge, we plot the ratio of the current to the cathode area actually occupied by the discharge, rather than the total cathode area, along the axis j, which only makes sense, then zone *3* disappears, thus emphasizing once more the identity of the processes yielding both branches of the curve.

Actually, under conditions corresponding to the right-hand branch, i.e., at a sufficiently free development of the electron avalanches, the charge current in one of the avalanches at the electric breakdown of the gap due to fluctuations proves to be sufficient for a significant distortion of the field. As a result, the field nearby the cathode increases locally, cathode fall (CF) occurs, and the feedback mechanism turns on, namely, the emission of electrons from the cathode starts under cathode bombardment by heavy particles. The voltage decreases, and the current increases up to the value determined by the ballast resistance. Just this determines the cathode area occupied by the discharge. If U is slightly increased, then the excess of ions arisen spreads toward the discharge column, the cathode area occupied by the discharge increases, and U decreases down to its previous value. This process continues until the discharge occupies the whole cathode surface. With the further increase of U, the dense discharge starts to glow.

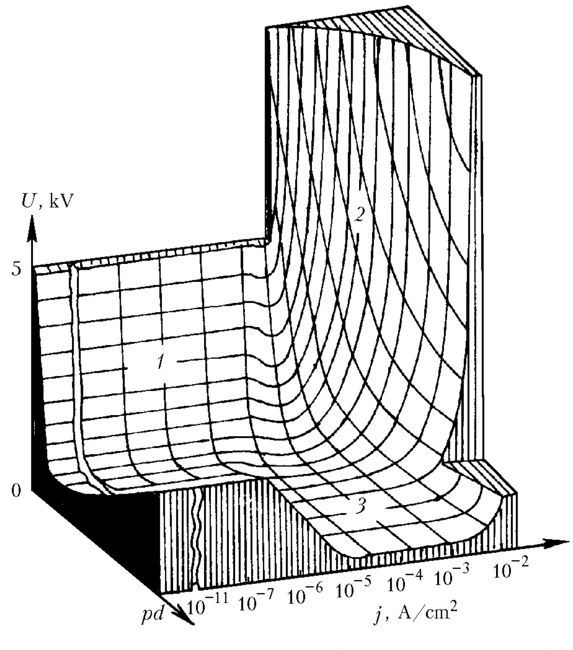

Fig. 1. Various forms of the glow discharge in the coordinate system U, j, pd (Ref. 2).

Let us complement the described pattern. It is known that as the anode approaches the cathode, the discharge does not change its form at least until the

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near-boundary area of the negative glow is present in the gap, the rise of the curves in the left-hand branch, in the case of a dense discharge is just indicative of the penetration of the negative glow into the gap. The negative glow also manifests its presence in the right-hand branch, in the form of the normal glow, which is already the dense glow by its physical nature.

2. Consider now the electron beams. The glow discharge with the anode plasma is widely used in the electron-beam tubes starting late in the 19th century and in technological electron guns in the form of hollow anode discharge starting from the late 60's (Fig. 2) in the 20th century. Long time ago it was established[3] that such discharges are supported by the ion flow from the near-anode plasma, strong field can hardly penetrate in, because there ($E/p_{\mathrm{He}} > 150\ \mathrm{V\cdot cm^{-1}\cdot Torr^{-1}}$) the electrons escape collisions and ionization is very weak. Photoemission from the cathode is thought low and neglected ($\gamma_v \approx 0$).

Deep into the region corresponding to the left-hand branch of the Paschen curve, plasma is formed in the weakened sagged field behind the anode. Since heavy ions move along lines of force, they, along with fast atoms generated in the recharging processes, give rise to the emission at the center of the hole. As a result, a narrow electron beam is generated (Fig. 2*a*). In the form, it is the simplest discharge intensified by the ion flow from the plasma behind the anode.

Under conditions corresponding to the right-hand branch, as well as the left-hand branch, if the CF length l occupies only a part of d (the minimum value $l_{\min} = 0.37(pl_n)p^{-1}$ (Ref. 4), where l_n is taken for the normal discharge, $p_{\mathrm{He}}l_n = 1.3\ \mathrm{Torr\cdot cm}$), plasma is formed in front of the anode (Fig. 2*b*) and the beam occupies the entire area of the hole (in this case, the discharge parameters may change only slightly, if the anode is solid or arranged arbitrarily, for example, as shown in Fig. 2*c*, and this fact was noticed in Ref. 5). In the form, it is the dense discharge, sometimes intensified by ionization in the residual sagged field.

The efficiency of e-beam generation, i.e., the ratio of the power emitted by the anode (as measured by a calorimeter) to the total power in the discharge, is determined by the generalized emission coefficient $\gamma = \gamma_i + \gamma_a$ (Ref. 3): $\xi = \gamma(\gamma + 1)^{-1}$. The typical working pressures in hollow-anode guns are hundredths and tenths of Torr, and the typical voltage is from tens to hundreds kilovolts.

If we connect many hollow-anode discharges in parallel by taking an anode grid, then we obtain open discharge.[6] Now the conditions of efficient e-beam generation at a large area under the pressure up to hundreds of Torrs can be fulfilled, if we take A, $d < 1$ mm (A is the size of the grid holes). The working voltage in the open discharge usually does not exceed 15–20 kV. The beam transmission coefficient η varies within $\eta = \xi$ to $\xi \cdot \mu$ (μ is the geometric transparency of the grid); $\eta \approx \xi$, if the current through the grid is negligibly small, what can take place in the simplest discharge and can be observed at the initial stage of the still undeveloped dense discharge at a pulsed excitation.[7] In the open discharge, η is usually determined by the ratio of the beam current (as measured by a collector) to the total current, what overestimates somewhat the true values of η and ξ (electrons recorded by the collector are generated in the weakened or sagged anode field and they are accelerated only in part, to which U is applied). In all cases, ξ is close to unity under optimal conditions. This discharge was specially developed for excitation of lasers and turned out to be rather promising.

3. In Ref. 6 (1985), the nontraditional photoelectron mechanism was proposed for the open discharge. This mechanism was formulated most clearly in Ref. 8: the open discharge "is, in fact, semi-self-maintained with the initiation and support by UV radiation from the zone behind the anode." This assumption is clear, because the drift region, from which the UV radiation comes, can exceed sometimes by hundred times the area of the discharge gap itself; in the OD the geometry of irradiation is much better than in the case with the hollow anode. Therefore, qualitative changes are possible at transition to the OD. The processes of ionization in the discharge gap are considered as a harmful factor decreasing the efficiency. Actually, for the photodischarge ($\gamma_v \gg \gamma_i + \gamma_a$) we have $\xi = \gamma_v(\gamma_v + I_i/I_{\mathrm{EB}})^{-1}$, where I_i and I_{EB} are the currents of ions and e-beam.

The photodischarge was criticized in Ref. 9 and the following papers with the conclusion drawn in Ref. 10. It was shown that the OD, as well as the hollow-anode discharge, keeps all the properties of known forms of the glow discharge, and the photoelectron mechanism is in the deep and insoluble disagreement with the experiment.

Contradictions are numerous and, what is especially important, having the general character. For the photodischarge, the photoemission coefficient γ_v must be larger than unity for the discharge to begin. Then the current increases up to the value limited by the "3/2" law.[9] But such currents do not occur in the OD.

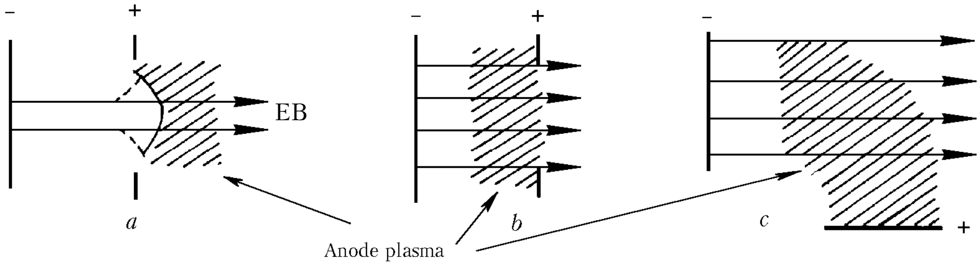


Fig. 2. Versions of the electron gun with anode plasma.

Then, it was noticed[10] that in the glow discharge the dependence of the current on the length of the discharge gap is typical of the OD (cf. Fig. 3 with the cross section in the plane pd, j in Fig. 1). This dependence absolutely does not fit with the photodischarge pattern, because the current changes by two orders of magnitude. The question arises: what has the photodischarge to do with this? It cannot have such a dependence on d. Note that in the experiment the efficiency was kept close to unity ($\xi \sim 1$) even at $d > l_n$ for the normal glow discharge, when the holes in the anode already do not effect the discharge parameters. The holes here played the role of exit windows for the e-beam in the gap.

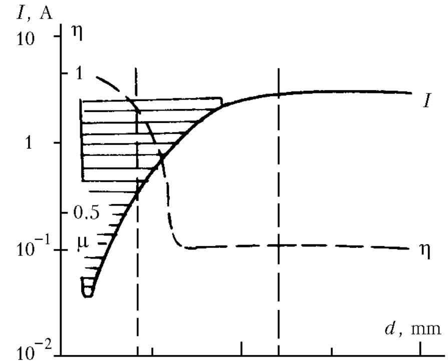


Fig. 3. Dependence of the total current I and the e-beam transmission coefficient η on the interelectrode separation d (Ref. 10). The amplitude of the voltage $U_0 = 10.8$ kV, $p_{He} = 2.2$ Torr.

However, the papers in support of the photodischarge version continue to be published, see, for example, Ref. 11. This all complicates selection of the proper OD modes. Because of the large differences in operation of guns and OD mentioned above, it is quite likely that the followers of the photodischarge version do not pay due attention to the thoroughly studied processes proceeding in guns with the anode plasma, which can be directly applied to the OD. The differences are motivated only by different application of guns and OD.

Therefore, let us continue the consideration of the OD with the attention given to the right-hand Paschen branch at large d in a wide range of pressure values, because all experiments with the OD for the pressure higher than 1 Torr were conducted for the gaps no longer than 1 mm, and the parameter pd cannot serve a similarity parameter for the photodischarge.

Consider the discharge in the cell with the geometry depicted in Fig. 4. First, let us consider the discharge with the hollow anode, when no grid is used.

At low voltages and pressures, no higher than several Torrs, the beam is formed only in the narrow (several millimeters wide) central part of the cathode. As U increases, volume discharges straighten, more and more strongly, the lines of force, along which ions move, and the beam occupies larger area of the cathode and then uniformly fills the entire aperture of the hole $A = 20$ mm. Starting from the current ~50 A/cm^2, self-focusing of the beam is observed and a bright waist arises at the drift center.

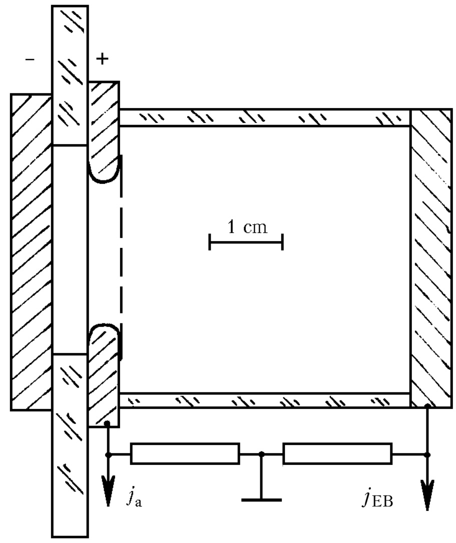


Fig. 4. Design of the discharge cell. The geometric transmittance of the grid $\mu' = 0.85$, the total transmittance of the anode $\mu = 0.37$, the cathode is made of duralumin.

All the effects listed above take place, if the hole is covered by a grid. In particular, narrow beams are observed, because the solid part of the anode distorts the field.

At a low pressure, the e-beam current even in the maximum was almost equal to the total discharge current (Fig. 5). The transmission coefficient η was larger than the geometric transparency of the grid $\mu' = 0.85$ (Fig. 6), i.e., the beam passed through the grid not touching it. With the increasing pressure, the discharge to the grid and the solid part of the anode begins to form, and η decreases down to almost full geometric transparency of the anode $\mu = 0.37$. There is an interesting effect: with the further increase of the pressure, η grows rather than drops and at 1 kPa it again is almost equal to μ'. This happens because of the current shortening by more than an order of magnitude, when the discharge to the solid part of the anode has no time to develop.

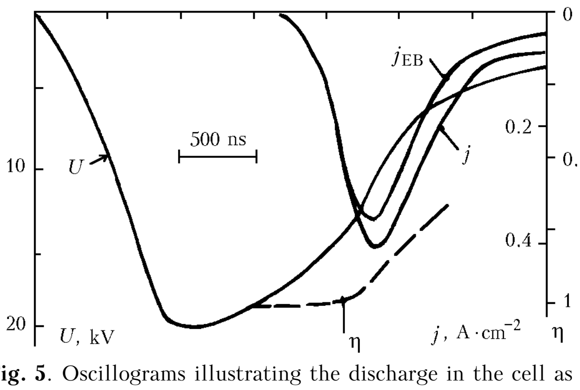


Fig. 5. Oscillograms illustrating the discharge in the cell as in Fig. 4: j_{EB} and j are the e-beam current and the total discharge current; $p_{He} = 0.2$ Torr.

Note that for small d at the initial stage of the discharge, when it works at field sag, $\eta \sim 1$ even at a high pressure (in Ref. 7 $p_{He} = 30$ Torr for $d = 0.5$ mm).

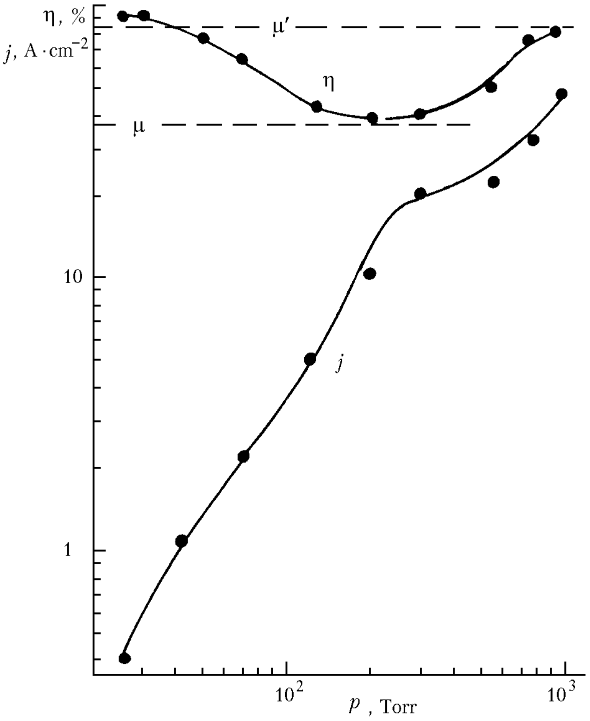
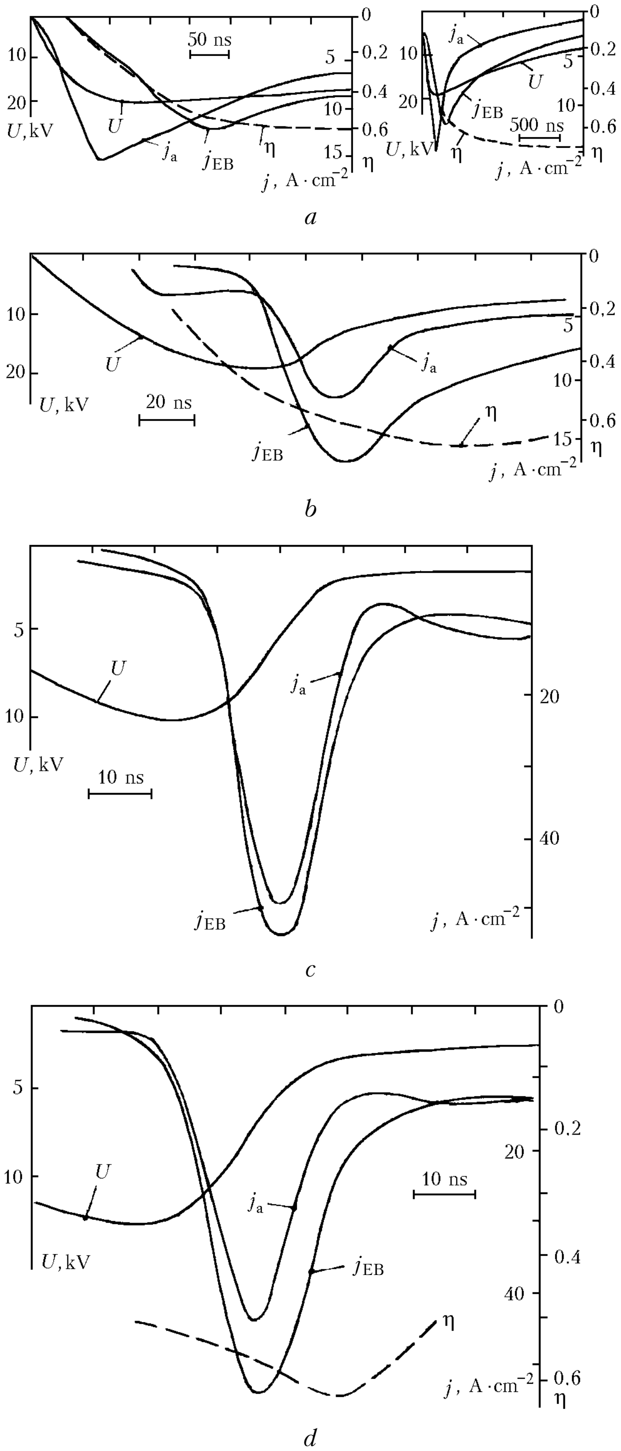


Fig. 6. The total current $j = I/S$ (S is the area of the hole in the ring anode) and e-beam transmission coefficient η as functions of the gas pressure p, the cell is as in Fig. 4. To improve the discharge stability, 1% oxygen was added to helium, the first two points correspond to the discharge without oxygen; $U_0 = 18.3$ kV.

Different pattern is observed at even larger d (compared with that in Fig. 4). Let us consider the experiments with the discharge, when the distance between the duralumin cathode and the grid was $d = 26$ mm. A movable collector of porous graphite was set in the drift (to diminish the effect of electrons reflected from it). The position of the collector had no effect on the discharge parameters. It can be put right against the grid. Therefore, the term “open discharge” is not appropriate here, because the processes in drift do not affect the discharge.

At a low pressure (Fig. 7*a*), when the field in the gap is weakly distorted by charges, the conditions near the grid are most favorable for ionization. An atom with the energy $W_a = U(d\sigma_{ct}N_{He})^{-1} = 690$ V generated there due to recharging (recharging cross section $\sigma_{ct} = 1.5\cdot 10^{-15}$ cm^2, $U = 20$ kV) passes the gap d for the time $t_a = d/v_{He} = d(0.69\cdot 10^6\sqrt{U})^{-1} = 1.4$ μs. Ions at their motion to the cathode immediately contribute to the anode current j_a, and high-efficiency emission from the cathode turns on as fast atoms come to the cathode, i.e., by t_a later, and then η becomes equal to $\mu = 0.64$, just what was observed in the experiment. The corresponding times coincide.

With the increase of pressure, conditions become more favorable for the ionization in the entire gap. The field tightens to the cathode faster, the high-efficiency emission of electrons from the cathode turns on sooner, and η reaches the μ value (Figs. 7*b* and *c*) sooner as well.



a

b

c

d

Fig. 7. Oscillograms of discharge in the cell with $d = 26$ mm and $\mu = 0.64$. Helium pressure of 0.2 (*a*), 3 (*b*), 9.6 (*c*), and 13.7 Torr (*d*); j_{EB} and j_a are the e-beam and anode currents; η is the e-beam transmission coefficient.

It should be noted that under conditions of Figs. 7*c* and *d* the e-beam is already self-focused: behind the grid in Fig. 7*c* and in front of it in Fig. 7*d*. The plasma oscillations that appear partly screen the beam passage to the collector and lead to efficient extra ionization and, if the beam is focused in the gap, to the increase of the current. Therefore, under conditions of Fig. 7*d*, the current $j = j_a + j_{EB} = 104$ A/cm^2 almost twice exceeds the current of the abnormal discharge[4] $j_{ab} = p^2 U^3 \cdot 2.5 \cdot 10^{-12} = 59$ A/cm^2 and almost coincides with it under conditions of Fig. 7*c*: $j = 90$ A/cm^2, $j_{ab} = 98$ A/cm^2.

It is worth noting the qualitatively different oscillograms taken at low and high pressure. At the low pressure (Fig. 7*a*), the current increases smoothly almost immediately after the application of U to the gap – the discharge passes the stage close to the simplest discharge. The transition to the dense discharge (if any, here $l_{min} = 21$ mm) is also smooth. In the right-hand branch of the Paschen curve (Figs. 7*b*–*d*) we can see, in addition to low-current stage, the characteristic pulsed breakdown of the gap with the sharp decrease of U. It seems as if the discharge passes the low-current stage of the simplest discharge, and then, in the process of breakdown and transition to the dense discharge, skips the form of the normal discharge with the formation of the CF, anode plasma, and current grows by one or two orders of magnitude. Such a behavior of the OD was observed earlier (p_{He} up to 30 Torr), but did not find its explanation from the viewpoint of the photodischarge,[8] what was noticed in Ref. 10.

It should be noted (Figs. 7*c* and *d*) that at the initial stage of the discharge in the field still undistorted by charges, the energy of atoms is negligibly small, not exceeding 10 eV, therefore $\gamma_a = 0$, and only in the process of CF formation their energy increases and the feedback turns on, namely, the emission of electrons from the cathode becomes sufficient for high-efficiency e-beam generation. Note also that, for example, the parameter $p_{He}d = 36$ Torr · cm is an order of magnitude larger than $(p_{He}d)_{min} = 4$ Torr · cm (Fig. 7*d*), i.e., we are deep in the right-hand branch of the Paschen curve.

4. This analysis of the e-beam generation under various conditions of the glow discharge is based on the most general approaches and therefore can be obviously generalized to the entire range of conditions practically realizable in the OD. It is important to emphasize that the glow discharge with the positive VAC, which is usually used in the OD, at any parameters *pd* belongs to one its form – dense discharge, and therefore the mechanism of the e-beam generation in it does not change.

The consideration becomes simpler, if the parameter *pd* is fixed (see Fig. 1). Thus, if under conditions of Fig. 7*c* ($pd = 25$ Torr·cm, $U \approx 5$ kV) we pass to $d = 0.5$ mm, then we obtain that similar in value parameters of the discharge must take place at $p = 500$ Torr. However, because of the possible loss of the discharge stability, when the field near the cathode $E > (1–5) \cdot 10^5$ V/cm (Refs. 3 and 4), one has to decrease the working pressure, in our case, down to $p < (p_{He}\, l_{min})E/2U = 5–25$ Torr. Practically in the pulsed mode, when l_{min} or the discharge instability has no time to form, the working pressure at $d = 0.5$ mm achieves hundreds of Torrs. For example, under conditions of Fig. 7*b*, l_{min} is not fully formed ($j = 28$ A/cm^2, $j_{ab} = 56$ A/cm^2), although $d/l_{min} = 16$. To decrease E, we can decrease U, but within certain limits to keep high efficiency (calculation in Ref. 12).

5. In the wide range of existence of known forms of the glow discharge, it has been shown from the most general point of view that the atom-electron emission provides for high efficiency of the e-beam generation, if the field provides for generation of rather fast ions in recharging processes in the entire discharge gap or in the near-cathode region. This was confirmed earlier by calculation and is in agreement with the concept of the glow discharge established for a long time.

The assumption of the photoemission open discharge is not confirmed in the experiments, which always form the basis for the study of physical phenomena. If a theory or calculation contradicts the experiment, then they are incorrect.

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