Mechanism of evolution of an open discharge

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Various points of view on the mechanism of evolution of an open discharge are analyzed. This problem is important for understanding the physics of generation of an electron beam, whose efficiency η achieves 90% and even higher. For this purpose, a technique is proposed for calculating the factors of electron emission from a cathode whose surface is bombarded by fast gas particles and ions. The calculation has shown that this process fails to provide for the efficiency η observed in experiments. The calculated results gave an additional proof of the dominating effect of photoelectron emission from the cathode on dynamics of the open discharge and e-beam generation in it.

The question on the mechanism of discharge evolution in a medium-pressure gas in a narrow (~ 1 mm) gap between a massive metal cathode and a grid anode (the discharge received the name an open discharge[1]) arose already at the early stage of investigation of electron-beam (e-beam) generation under these conditions.[1–3] Very high efficiency of the e-beam generation, which achieved ~ 0.8–0.9–0.95 in experiments at the gas pressure of ~ 2–7 kPa and the voltage ~ 4–7 kV across the electrodes needed clarification. If the mechanism of evolution of the open discharge is analogous to the well-studied volume discharge of nanosecond duration,[4] then the low efficiency of e-beam generation in the latter is unclear. Besides, strong dependence of the generation parameters on the length of the interelectrode gap calls for explanation.[2,3] The need to understand these phenomena motivated a sophisticated treatment of the open discharge and lively discussion of the mechanism of its evolution. Now there are a variety of opinions on both the main process determining the discharge evolution and the discharge dynamics as a whole.

In Refs. 5–7, the authors assume that the high efficiency of e-beam generation is due to the photoelectron emission from the cathode caused by its lightning by UV radiation from the zone behind the anode. Another point of view is justified in Refs. 8 and 9: the open discharge is an abnormal glow discharge (AGD), and the main mechanism of the highly efficient e-beam generation is caused by the high (~ 10) values of the coefficient of electron emission from the cathode under its bombardment by fast atoms. At the same time, Refs. 5 and 6 present different opinions on the discharge phase, in which the highly efficient (~ 0.8–1) e-beam generation occurs. In Ref. 5 it is believed that the e-beam generation completes with localization of the field in a narrow zone near the cathode. By contrast, in Ref. 6 it is stated that at the time of generation the size of the cathode fall (CF) zone δ is extremely small: $\delta \sim \lambda_r$ (λ_r is the mean recharging length). The difference in opinions on the open discharge is so large, that it seems that the investigators deal with different objects. Therefore, the aim of this paper is to resolve the existing contradictions.

In the first turn, we consider arguments[8] in support of the abnormal glow discharge and calculate the electron emission coefficient of the cathode in the AGD. Based on these calculations, we analyze the measurements of the electric field profile in the open discharge[10] and then estimate the possibility of the high-efficiency e-beam generation at $\delta \sim \lambda_r$. The obtained results allow us to draw the conclusion on the mechanism of evolution of the open discharge and e-beam generation in it.

1. Analysis of the concept of open discharge as AGD

In Refs. 8 and 9, the main arguments in support of AGD are the following:

1. The effect of UV irradiation from the zone behind the anode on the e-beam and discharge parameters was not found.
2. The efficiency of e-beam generation is independent of the length of the discharge gap d at $d \geq 2\delta_{AGD}$ (where δ_{AGD} is the length of the CF zone in the AGD).
3. The coefficient of electron emission from the cathode under bombardment by fast atoms γ_a and ions γ_i in the AGD is high enough ($\gamma_d = \gamma_a + \gamma_i = 6.7$ at 5 kV) to provide the experimentally observed efficiency of e-beam generation $\eta = 0.85$–1 (with allowance for intersecting the part of an electron beam by the anode grid).

Let us discuss these arguments.

As to the first argument, it should be noted that the working range of the helium pressure in the experiments[8] was 0.2–0.4 kPa and that of the voltage was 8–10 kV. Under these conditions, the energy loss of e-beam in the drift space does not exceed 15 eV/cm, only about ~ 30% of which goes into the excitation of atoms. This means that every electron in the beam, when crossing the drift space, excites less than one UV quantum emitted in the total solid angle 4π (Ref. 11), which is a negligibly small value. The UV radiation from the compensating current arising in the drift space at the e-beam passage is also very weak, because the current flows through the drift tube at the low volume potential.[12] The glow of the beam-plasma filament at the low gas pressure is always very faint.[13] Thus, all possible sources of UV irradiation in the open discharge at the helium pressure exceeding ~ 2 kPa (Ref. 14) are absent in the experiments[8,9] and the discharge is actually a glow discharge.[13,15] Then the second argument is quite logical and clear.

The third argument is also proved in Ref. 8 by the experiments conducted in helium at the pressure of about 0.3 kPa and voltage of 10 kV. Finally, Ref. 9 presents the equation for calculation of the coefficient γ_d in the AGD. In the author's opinion, it proves the high efficiency of e-beam generation in this type of discharge. The technique of calculation is not described in Ref. 9, but the author's reasoning and the derived equation are indicative of the simplified scheme, in which all cross sections are assumed constant, all initial ions start from the plasma boundary of the CF zone, and all fast atoms, produced due to recharging, reach the cathode without losses of energy and momentum. Naturally, because of these simplifications, the estimates of errors in calculation of the coefficients γ_a and γ_i are absent. The obtained values of γ_d seem to be incredibly large.

To summarize: First, the experiments in Refs. 8 and 9 were conducted under the conditions certainly excluding the appearance of UV irradiation; consequently, the observed discharge can be only a glow discharge. The high efficiency of e-beam generation in it was achieved due to rather high voltage at low gas pressure, i.e., beyond the usual working range of e-beam generation in the open discharge. Therefore, the extension of the obtained results to the open discharge is unjustified. Second, the performed calculations of the emission coefficients γ_a and γ_i are to be checked. Just this problem is considered in the next section.

2. Calculation of the coefficient of electron emission from cathode in AGD

Our task is to calculate γ_d with allowance for (a) the energy dependence of cross sections of resonant recharging σ_r and elastic collisions σ_e and (b) energy loss of fast atoms in elastic collisions. In what follows, for convenience, the linear dimensions and path lengths are reduced to δ, and energies and the electric potential are reduced to the ionization potential J.

An ion, produced at the distance x_0 from the cathode, in its motion through strong field of the CF zone, in the processes of resonance recharging generates a chain of fast atoms with the initial energy $\varepsilon_a(x)$ depending on the place of birth. Its mean value is determined by the equation

$$1 = -(N\delta) \int\limits_{x+\lambda_r(x)}^{x} \sigma_r(x)\,\mathrm{d}x\,, \tag{1}$$

where N is the gas density. The total coefficient from the entire chain

$$\gamma_d = \gamma_a + \gamma_i = \int\limits_0^{x_0} \gamma_{a1}(x)\frac{\mathrm{d}x}{\lambda_r(x)} + \int\limits_0^{\lambda_r(0)} \gamma_{i1}(x)\frac{\mathrm{d}x}{\lambda_r(x)}\,, \tag{2}$$

where $\gamma_{a1}(x)$ and $\gamma_{i1}(x)$ are the contributions to γ of the fast atom and ion, respectively, generated at the point x in the process of recharging. The parameter $1/\lambda_r(x)$ is the density of generation of fast atoms. Assume that the field strength $E(x)$ in the CF zone varies linearly, i.e.,

$$E(x) = 2\,[V(0)/\delta]\,[1-x];\; V(x) = V(0)\,[1-x]^2, \tag{3}$$

where $V(x)$ is the voltage. For the cross section of the resonance recharging He$^+$–He, we use the equation[16,17]:

$$\sigma_r(\varepsilon_i) = A\,[1 - B\,\ln(\varepsilon_i)]^2. \tag{4}$$

The factors A and B, constant for every gas, are fitted to the experimental cross sections. As the latters, we take such cross sections, whose values are close although obtained by different authors. One of them was obtained at low energy ($\varepsilon_i \sim 1$), and another – at high energy ($\varepsilon_i \sim 200$) (Ref. 18). Finally, for helium we obtain $A = 1.8\cdot10^{-19}$ m^2 and $B = 6.5\cdot10^{-2}$. The cross section of elastic scattering of a fast helium atom with the energy $\varepsilon_a \sim 100$ eV and higher will be described through the repulsive term of the Lennard–Jones potential[16] with reference to the Amdur et al. measurements[17]:

$$\sigma_e(\varepsilon_a) = \sigma_{e0}(\varepsilon_a)^{-1/6},\; \sigma_{e0} \approx 2.27\cdot10^{-20}\ \mathrm{m}^2. \tag{5}$$

It is generally agreed that the dependence $\sigma_e(\varepsilon_a)$ is weak, whereas $\sigma_r(\varepsilon_i)$ is strong. However, Eqs. (4) and (5) show that $\sigma_r(\varepsilon_i)/\sigma_e(\varepsilon_a) = 8.41 \pm 0.08$ at $\varepsilon_i = \varepsilon_a = 4–48$ (100–1200 eV). Thus, the elastic scattering cross section also changes rather markedly with the speed of the flying particle, and there is a simple and rather reliable relation between σ_r and σ_e.

The dependence of coefficients γ_{i1} and γ_{a1} on the energy of helium atoms and ions bombarding the cathode is taken, as in Ref. 9, from the measurements.[18] It should be taken into account that the values of γ_{a1} reported in that paper are overestimated by ~ 20%, what is equal to the measurement error. Considering this, we can approximate γ_{i1} and γ_{a1} as follows:

$$\gamma_{i1}(\varepsilon_i) = b_{i1}\,\varepsilon_i^{0.6} + b_{i2},\; b_{i1} = 0.12,\; b_{i2} = 0.1; \tag{6}$$

$$\gamma_{a1}(\varepsilon_a) = c_{a1}\,\varepsilon_a^2 + c_{a2}\,\varepsilon_a + c_{a3}; \tag{7}$$

$$c_{a1} = -2.12\cdot10^{-4},\; c_{a2} = 3.39\cdot10^{-2};\; c_{a3} = -5.85\cdot10^{-2}$$

at $\varepsilon_{i,a} = 4–500$.

Equations (1), (3), and (4) have a solution in the form

$$\varepsilon_a(x) \approx \frac{2V(x)}{A(N\delta)[1 - B\ln\varepsilon_a(x)]^2} \approx$$
$$\approx \frac{RV(x)}{1 + (2B)^{-1} - \ln[\varepsilon_a(x)/V(x)] - \ln V(x)}, \tag{8a}$$

where $R = [AB\ (N\delta)]^{-1}$. Since $\ln[\varepsilon_a(x)/V(x)]$ varies only slightly with x, it can be assumed constant $[\varepsilon/V]_{av}$ with a sufficient accuracy. Its particular value depends on the value of R and the variability range of $V(x)$. Then Eq. (8a) can be reduced to the convenient form

$$\varepsilon_a(x) = RV(x)/\ln[G/V(x)],$$

$$G = [\varepsilon/V]_{av}\exp[1 + 1/(2B)]. \qquad (8b)$$

In the strongly abnormal glow discharge, $(N\delta)_{AGD} = 1.5\cdot10^{20}$ m^{-2} and the calculation gives $[\varepsilon/V]_{av} \approx 0.1$. Then Eq. (8b) takes the form

$$\frac{\varepsilon_a(x)}{V(x)} \approx 0.57\left[\ln\left(\frac{6\cdot10^4}{V(x)}\right)\right]^{-1}. \qquad (8c)$$

The number of fast atoms $k(x_0)$ in the chain of length x_0 is equal to

$$k(x_0) = \int\limits_0^{x_0}\frac{\mathrm{d}x}{\lambda_r(x)} =$$

$$= \frac{2}{R}\left\{x_0\left[2+\ln\frac{G}{V(0)}\right] + 2(1-x_0)\ln(1-x_0)\right\}. \qquad (9)$$

Fast atoms come to the cathode with the energy $\varepsilon_c(x) \le \varepsilon_a(x)$ due to scattering in elastic collisions:

$$\mathrm{d}\varepsilon_a(x) = -\,\alpha\ (N\delta)\ \sigma_e(x)\ \mathrm{d}x, \Rightarrow$$

$$\Rightarrow \varepsilon_c(x) = \varepsilon_a(x)\ [1 - (\alpha/6)\ (N\delta)\ \sigma_e(x)\ x]^6, \quad (10)$$

where α is the energy transfer coefficient equal to 0.5. The values of $\varepsilon_a(x)$, $\varepsilon_c(x)$, and $\lambda_e(x) = 1/[(N\delta)\ \sigma_e(x)]$ calculated for the AGD at $V(0) = 400$ (10 kV) are shown in Fig. 1. The intersection of the curve $\lambda_e(x)$ and the straight line $y = x$ gives the coordinate $x_m = \lambda_e(x_m)$. We can see that elastic collisions significantly decrease the low energy of fast atoms coming from far away. Taking into account the fact that the dependence $\gamma_a(\varepsilon_a)$ has a threshold character with $\varepsilon_{th} = 4$ (100–120 eV) (Ref. 18), we come to the conclusion that fast atoms generated at the distances farther than x_m from the cathode give no contribution to the cathode emission. At the same time, energy loss by the fast atom at $\varepsilon_a \ge \varepsilon_{th}$ has practically no effect on λ_e and x_m. At the point x_m, the equation

$$(N\delta)\sigma_{e0}\,x_m = \left[\frac{RV(0)(1-x_m)^2}{\ln\left(\dfrac{G}{V(0)(1-x_m)^2}\right)}\right]^{1/6} \qquad (11)$$

following from Eqs. (3), (5), and (8b) is fulfilled. At low voltages ($V(x) \le 100$), the chain lengths for fast atoms is restricted by the condition $\varepsilon(x_{th}) \approx \varepsilon_{th} \approx 4$, i.e., $x_{th} < x_m$ and x_{th} can be found from Eq. (8b).

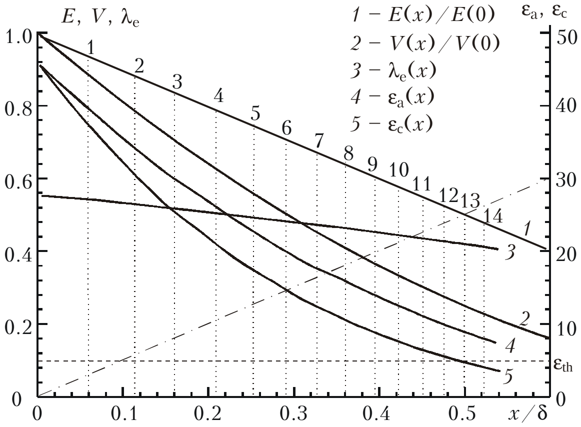

Fig. 1. Distribution of main parameters in the CF zone in strongly abnormal glow discharge. The vertical dashed straight lines show the length λ_r measured from the cathode.

The obtained data allow us to estimate the maximum value of $\gamma_{a,i}(x_0)$ from the chain of fast atoms generated by one ion starting from the point $x_0 \le x_m$:

$$\gamma_a(x_0) \le \frac{2c_{a1}\,R}{5\ln[G/V(0)]}V^2(0) +$$

$$+\ 2c_{a2}\ V(0)\ x_0\ (1 - x_0) + c_{a3}\ k(x_0), \qquad (12)$$

$$\gamma_i = b_{i1}\int\limits_0^{\lambda_r(0)}[V(0)-V(x)]^{0.6}\frac{\mathrm{d}x}{\lambda_r(x)} + b_{i2} \le$$

$$\le 0.95\ b_{i1}\ [V(0)\ \lambda_r(0)]^{0.6} + b_{i2}. \qquad (13)$$

Here $\lambda_r(0) = 1 - [1 - \varepsilon(0)/V(0)]^{1/2}$. The limiting value for γ_a is obtained with neglecting the energy loss by fast atoms generated in the interval $[0,\ x_m]$ because of the complexity of calculations at substitution of Eq. (9) into Eq. (12). The losses are taken into account only in determination of the chain length and its restriction by the length x_m.

For the strongly abnormal glow discharge, we obtain from Eqs. (8c) and (10)–(13) the following results for the chain of the length $x \ge x_m$, x_{th}. At the voltage $V(0) = 400$ (10 kV): $x_m = 0.55$, $k(x_m) = 10.8$, $\lambda_r(0) = 5.87\cdot10^{-2}$. Consequently, $\gamma_a \le 4.3$, $\gamma_i \le 0.9$, $\gamma_d \le 5.2$. At the voltage $V(0) = 200$ (5 kV): $x_m = 0.4$, $k_m = 8.65$, $\lambda_r = 5.3\cdot10^{-2}$, $\gamma_a \le 2.4$, $\gamma_i \le 0.57$, and $\gamma_d \le 3.0$. At the voltage $V(0) = 80$ (2 kV) $x_{th} = 0.21$, $k_{th} = 5.1$, $\lambda_r = 7\cdot10^{-2}$, $\gamma_a = 0.22$, $\gamma_i = 0.43$, and $\gamma_d = 0.65$. At the same voltages, the equation in Ref. 9 gives $\gamma_d = 14.8$, 6.7, and 2.0, respectively, i.e., 2.8, 2.3, and 3.1 times larger. The difference of 2.3–3.1 times in the obtained values of γ_d within the domain of applicability of the equation in Ref. 9 points to somewhat incorrect computational technique in Ref. 9.

Equations (8b) and (9)–(13) describe the general case and are valid at any values of $(N\delta)$ and at linear character of variation of the field (3). They suggest the following conclusions.

1. At $V(0)$ = const with the increase of $(N\delta)$, the parameters R and G decrease in the inverse proportion. The parameter $(1 - x_m)^2$ increases with $(N\delta)$, but somewhat slower. Therefore, although x_m decreases, $k(x_m)$ increases. As a result, the second (positive) term in Eq. (12) for γ_a decreases very slightly, and the negative first and last terms change significantly in the opposite directions. In fact, the integrated effect is determined by the relationship between the first and the last terms. Thus, the value of γ_a in our case can both increase and decrease at the increase of $(N\delta)$ depending on the particular conditions. However, taking into account the character of variation of G and $(1 - x_m)^2$ depending on $(N\delta)$, as well as the dependence of the first and the third terms on R, we conclude that if the first term is smaller than the third one in the absolute value, then γ_a decreases at increase of $(N\delta)$. This is in fact the condition imposed on the magnitude of $V(0)$. It can be expressed in the following form:

$$V(0) \le \frac{1 + \ln[G/V(0)]}{R}\sqrt{\frac{5c_{\rm i3}}{c_{\rm i1}}}\sqrt{x_{m,\rm th}}\ . \qquad (14)$$

For orientation, we estimate the value in the right-hand side of Eq. (14) under the AGD conditions. Substituting the values of R and G (estimated above) and $(1 - x_m)^2 \approx 0.31$–0.36 in AGD, we obtain

$$V_{\rm th}(0) \approx 44\ \{1 + \ln\,[6{\cdot}10^4/V_{\rm th}(0)]\},\ \Rightarrow$$

$$\Rightarrow V_{\rm th}(0) \approx 280\ (6.9\ \text{kV}). \qquad (15)$$

At $V(0) \le V_{\rm th}(0)$, the coefficient γ_a decreases with the increase of $(N\delta)$, and at $V(0) \ge V_{\rm th}(0)$ it increases.

2. It also follows from Eq. (14) that the larger is $(N\delta)$ in discharge, the higher is $V_{\rm th}(0)$.

3. Evolution of the emission coefficient γ_d in the open discharge

The recent measurements of profiles of the field $E(x)$ in different moments of time[10] gave an interesting material for analysis of the processes proceeding in the open discharge. The measurements are depicted in Fig. 2. They allow us to determine the coefficient γ_d at the time when: (a) the discharge current pulse achieves its maximum (superscript (m)) and (b) at the mid-point of the drop (superscript $(-)$):

$$\gamma_{\rm d}^{(m)} = \frac{j_{\rm d}^{(m)}}{j_{\rm i}^{(m)}(0)} - 1; \qquad \gamma_{\rm d}^{(-)} = \frac{j_{\rm d}^{(m)}}{2\,j_{\rm i}^{(-)}(0)} - 1, \qquad (16)$$

where $j_{\rm d}^{(m)}$ is the density of the total discharge current at the maximum; $j_{\rm i}^{(m,-)}(0)$ is the density of the ion current at the cathode at the corresponding time. The latter can be calculated from the well-known equations

$$j_{\rm i}(x) = n_{\rm i}(x)\ v_{\rm i}(x);\ n_{\rm i}(x) = -\ \varepsilon_0\ {\rm d}E(x)/{\rm d}x;$$

$$v_{\rm i}(x) = \Gamma\sqrt{E(x)/N}, \qquad (17)$$

where ε_0 is the dielectric constant; $n_{\rm i}$ and $v_{\rm i}$ are the ion density and the drift speed; Γ is the known constant equal to $1{\cdot}10^{13}$ for He$^+$ ion in helium. The values of $E(0)$ and ${\rm d}E(x)/{\rm d}x\,|_{x=0}$ can be determined from the profiles of $E(x)$ in Fig. 2. Likewise, we find $U_\delta = E(0)\ \delta/2$. Some examples of calculation of $U_\delta^{(m,-)}$, $j_{\rm i}^{(m,-)}(0)$, and $\gamma_{\rm d}^{(m,-)}$ are tabulated below.

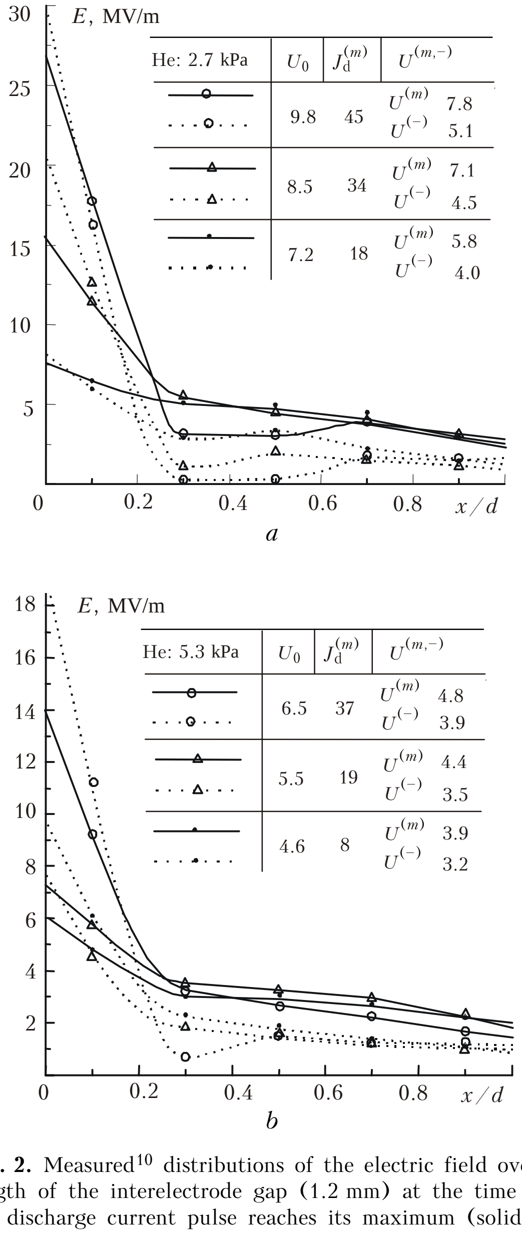

Fig. 2. Measured[10] distributions of the electric field over the length of the interelectrode gap (1.2 mm) at the time when the discharge current pulse reaches its maximum (solid line) and at the mid-point of its drop (dashed line); U_0 are the values of voltages in kV: initial voltage, voltage at the maximum, and voltage at the mid-point of the drop; $J_{\rm d}$ is the discharge current density, in A/cm^2, at the maximum.

Table

P, kPa	j, A/cm^2			U_δ, kV		γ_d		γ_v	
	$j_d^{(m)}$	$j_i^{(m)}(0)$	$j_i^{(-)}$	$U_\delta^{(m)}$	$U_\delta^{(-)}$	$\gamma_d^{(m)}$	$\gamma_d^{(-)}$	$\gamma_v^{(m)}$	$\gamma_v^{(-)}$
2.7	45	4.5	7.5	4.8	4.1	9	2	7	0
5.3	37	1.3	2.4	2.8	2.5	27.4	7.7	>25.4	>5.7

First of all, it should be noted that $(N\delta) \approx (N\delta)_{AGD}$ and $\gamma_d^{(-)} \approx \gamma_{AGD}$ at a pressure of 2.7 kPa at the mid-point of the drop (see calculations in Section 2). On the one hand, it is known that in the AGD the contribution of photoelectronic emission from the cathode to the discharge current is insignificant.[19,20] On the other hand, taking into account the dependence of γ_{AGD} on U_δ and $(N\delta)$ obtained in Section 2, we come to the conclusion that $\gamma_{i+a} \sim 2$ at 2.7 kPa at the maximum discharge current and $\gamma_{i+a}^{(m,-)} < 2$ at 5.3 kPa both at the maximum current and at the mid-drop. Consequently, the rest of $\gamma_d^{(m,-)}$ is the contribution of photoelectronic emission from the cathode: $\gamma_v^{(m,-)} = \gamma_d^{(m,-)} - \gamma_{i+a} > \gamma_d - 2$. These values of $\gamma_v^{(m,-)}$ are given in the last two columns of the Table. It turned out that at the maximum discharge current the photoeffect under external UV irradiation is the dominant process of the electron emission from the cathode, and its role increases as the gas density increases. It follows herefrom that already at rather low discharge voltages the efficiency of e-beam generation achieves ~ 0.9 and even ~ 0.96. The obtained data are in a close agreement with the experimental results.[21]

4. Possibility of the efficient e-beam generation at $\delta < \lambda_r$

Consider the statement formulated in Refs. 1 and 6 and somewhat corrected in Ref. 7: in the open discharge with the grid cathode, the electron beam is generated with $\eta \sim 100\%$ at the size of the CF zone $\delta \le \lambda_r$. Let us estimate some results of experiments[1,6] conducted in neon. In the approximation of the linear field (3), from Eq. (1) we find $\lambda_r = \delta$:

$$\lambda_r^{-1} = (AN)\ [1 - B \ln V(0)]\ [1 + 4B - B \ln V(0)]. \quad (18)$$

In neon $A = 2.33{\cdot}10^{-19}$ m^2 and $B = 7.5{\cdot}10^{-2}$ (Ref. 16). Herefrom, at $V(0) = 200$ (i.e., 5 kV) and the neon pressure of 1 kPa ($N = 2.34 \cdot 10^{23}$ m^{-3}), we obtain $\lambda_r \approx 3.4 \cdot 10^{-5}$ m. In this case, the strength of the field at the cathode $E_c \approx 2.9 \cdot 10^8$ V/m, and this value 5 to 6 times exceeds the ultimate value for appearance of explosive-emission processes.[19,22] Consequently, the case $\delta \approx \lambda_r$ at cathode sparking (i.e., under the conditions observed in Refs. 1 and 6) is possible only at the voltage in the CF zone no higher than 2 kV, which was actually realized in these experiments (the value of the voltage can be judged from the depth of e-beam penetration in the gas).

Another important parameter is the value of the ion current at the cathode, which is determined by the "3/2" law at $\delta \approx \lambda_r$ (Ref. 20). In neon at a voltage of 2 kV across the CF zone, we obtain $\delta \approx 2.8 \cdot 10^{-5}$ m and $j_i = 1.38 \cdot 10^6$ A/m^2. This situation corresponds to the conditions of the initial voltage of 5 kV and the neon pressure of 1 kPa in Ref. 6, at which the inverse e-beam with the current of 30 A was obtained at the discharge cross section of 1 cm^2. Then, with allowance for the anode grid geometric transparency of 0.75, we obtain the ion current of ~ 34 A to the cathode. Consequently, the efficiency of generation of the inverse e-beam (IEB) in the discharge with the grid cathode is $\eta = I_{IEB}/[I_{IEB} + I_i] \le 50\%$. We can hardly expect the significant increase in η at $\delta \approx \lambda_r$ without decreasing the gas pressure.

Thus, we present the technique for calculation of the coefficient of electron emission from the cathode under bombardment of its surface by fast gas particles. The estimates obtained for the abnormal glow discharge $\gamma_{a,i}$ agree well with the literature data, which, unfortunately, are very scant. It has been shown that the values of γ_d in the AGD calculated in Ref. 9 are strongly (2.3–3 times) overestimated. This means that the e-beam generation with the efficiency of 0.9 and higher in the open discharge at the voltage of 4–7 kV and the helium pressure of 2 kPa cannot be explained by the mechanisms of electron emission from the cathode that are responsible for development of the glow discharge. The behavior of the emission coefficient $\gamma_{a,i}$ was studied as a function of parameters of the CF zone. The obtained dependences were used to analyze the experimental results. As a result, the dominant effect of the photoelectron emission from the cathode was shown for the phase of the open discharge evolution, in which the high-efficiency e-beam generation occurs.

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