Influence of accelerating gap configuration on parameters of a forevacuum plasma-cathode source of pulsed electron beam

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Abstract. The research of influence of accelerating gap configuration on parameters of a forevacuum plasma-cathode source of a pulsed low-energy (up to 10 keV) large-radius electron beam is presented. An increase in cell sizes of a mesh emission electrode increases electron emission efficiency, but leads to a decrease in electric strength of an accelerating gap. Larger cell sizes of a mesh extractor provide higher electron beam current. An increase in the length of the accelerating gap first leads to an increase in the electron emission efficiency, but when optimal value is reached, a further increase in the length leads to a decrease in the emission efficiency. This optimal length of the accelerating gap is about 25 mm. However, the electron emission efficiency changes relatively small (within 15%). The dependencies of maximum emission current and maximum operating gas pressure on the length of acceleration gap is similar to the dependence for the emission efficiency, but the gap length much stronger influences on these maximum values. Moreover, the optimal length, at which maximum emission current or maximum pressure is provided, is depended on gas pressure (for current) or emission current (for pressure), accelerating voltage and pulse duration.

1. Introduction

Electron beams are used in different technologies and medical therapy [1-7], which causes interest in further research and modernization of electron beam sources. Compared to electron beam sources based on thermionic cathodes, plasma-cathode electron sources allow to generate electron beams at higher gas pressure, and these electron sources operate sufficiently long time in case of use chemically active (aggressive) gases [8-10]. Moreover, it is much easier to form pulsed electron beams with a large cross-section area (or large-radius) by the plasma-cathode electron beam sources [9, 10].

The plasma-cathode sources generating low-energy (up to 35 keV) large cross-section electron beams in “standard” gas pressure range of $10^{-4}-10^{-1}$ Pa are mainly used for treatment of electrically conductive materials [5-7]. In case of treatment of dielectric materials by the low-energy electron beam at pressures of $10^{-2}-10^{-1}$ Pa, difficulties arise due to charging of the dielectric surface by the electron beam [11]. The potential created by negative charge, brought by electron beam to surface of the dielectric, can reach value of the accelerating voltage, and this potential decelerate beam’s electrons. This leads to a significant decrease in the efficiency of treatment of dielectric materials by the low-energy electron beams. Therefore, it is necessary to provide special conditions to compensate
the negative charge on the surface of the dielectric, being treated by the low-energy electron beam in the pressure range of $10^{-4}$–$10^{-1}$ Pa. Forevacuum plasma-cathode electron sources, which generate low-energy (up to 20 keV) electron beams in the pressure range of 3–100 Pa (forevacuum pressure range) [12-14], provide treating of various dielectric materials (glasses, ceramics, and polymers) [15, 16]. The possibility of treatment of dielectrics in the forevacuum pressure range is provided by sufficiently dense plasma generated as a result of ionization of the working gas by the electron beam (beam-produced plasma). The flow of positive ions from this beam-produced plasma provides compensation of the negative potential on the surface of the dielectric [15]. On the other hand, generation of the electron beam in the forevacuum pressure range is accompanied by the formation of back-streaming ion flow from beam-produced plasma formed in the accelerating gap and in the beam propagation region [12, 17]. This ion flow, accelerated towards the emission electrode, affects the emission characteristics of the plasma-cathode electron sources [12, 14, 17].

The parameters of the electron beams generated by the plasma-cathode electron sources are determined by the discharge forming emission plasma, electrode system, configuration of accelerating gap and the processes occurring in this gap, as well as the processes in the region of formation and propagation of the electron beam [8-10]. The use of an arc discharge with a cathode spot (cathodic arc) in a forevacuum plasma-cathode source of the pulsed large-radius electron beam provides to increase the current amplitude and pulse duration of the electron beam [14] in comparison with the forevacuum electron beam source based on a glow discharge with a hollow cathode [13]. The detailed research of the features of the cathodic arc operation and the influence of the configuration of the discharge system on the electron emission from arc plasma have been carried out for the forevacuum plasma-cathode electron source based on the cathodic arc [14, 18]. Features of generation of the pulsed low-energy (up to 10–12 keV) large-radius electron beam and beam propagation in the forevacuum pressure range have also been investigated [14, 17, 19]. The purpose of this work is to further research of formation electron beam in the forevacuum pressure range, in particular, to research influence of the configuration of the accelerating gap of the forevacuum plasma-cathode electron source on the generation of the pulsed low-energy large-radius electron beam.

2. Experimental setup and techniques

A schematic of the experimental setup is shown in figure 1. In this research, we have used a forevacuum plasma-cathode source of a pulsed large-radius electron beam based on the cathodic arc; a detailed description of this electron source is presented in [14]. The forevacuum plasma-cathode electron source is mounted on a flange of a vacuum chamber. A plane-parallel accelerating gap of this electron source is formed by a mesh emission electrode (a fine mesh, which covers an emission window in a plane part of an anode) and a mesh accelerating electrode (mesh extractor). The mesh extractor is installed on a ring-shaped holder with supports. The design of the accelerating gap has been modified to investigate influence of the accelerating gap configuration on parameters of the forevacuum plasma-cathode electron source. The holder of the mesh extractor has been modernized to provide changing the length $l_e$ of the accelerating gap ($l_e$ is distance between the mesh emission electrode and the mesh extractor). The modified holder is installed on a linear manipulator, which provides up and down movement of the mesh accelerating electrode, and thus changes the gap length $l_e$. The fine-structure meshes with different cell sizes are used to cover the emission window in the plane part of the anode, i.e., different mesh emission electrodes are used. The meshes with different cell sizes are also used to form the mesh extractor. All meshes are made of stainless steel. In some experiments, a plane probe is used to measure the current density $j_i$ of the back-streaming ion flow entering the emission electrode from the side of accelerating gap. The probe consists of a ceramic tubular insulator and a stainless-steel rod that is housed inside this insulator. To install the probe, a hole is made in the emission electrode. The area of the working (collecting) surface of the probe (the area of the bottom end surface of the rod) is about 0.54 cm$^2$. The probe is connected to the plane part of the anode by a conductor. The current $I_i$ in this conductor is measured by a current transformer.
The vacuum chamber is pump out using a forevacuum pump. The vacuum chamber is preliminarily pumped out to pressure of 2.5 Pa. Then, the working gas is injected into the vacuum chamber. Gas pressure $p$ in the chamber is controlled by the gas flow rate (at constant pumping out rate). Argon (Ar) and nitrogen (N$_2$) are used as working gases. The forevacuum plasma-cathode electron source is powered by a pulsed discharge power supply unit and a DC high-voltage power supply unit. In the experiments, the arc discharge current $I_d$ is up to 130 A, the pulse duration $\tau_d$ is varied from 100 $\mu$s to 800 $\mu$s, the pulse repetition rate is 1 Hz, and the DC accelerating voltage $U_a$ is up to 10 kV. The discharge current $I_d$ and emission current $I_e$ are measured by current transformers installed in the respective electrical circuits. The electron beam current $I_b$ is measured by a Faraday cup and a current transformer installed in the grounding circuit of this cup. The voltage across the accelerating gap is measured using a TESTEC HVP-15HF oscilloscope probe.

3. Experimental results and discussion

The cell sizes of the mesh emission electrode significantly influence on the parameters of the forevacuum plasma-cathode electron source. The larger cell sizes of the emission mesh, as expected, provide higher efficiency of electron emission $\eta_e = I_e/I_d$ from the arc plasma (table 1). However, an increase in the cell sizes of the mesh emission electrode decreases the electric strength of the accelerating gap, which leads to a decrease in the maximum emission current $I_{e\text{-max}}$ and a decrease in the maximum operating gas pressure $p_{\text{max}}$ (table 2), as well as a decrease in the maximum pulse duration $\tau_{d\text{-max}}$. The values of $I_{e\text{-max}}$, $\tau_{d\text{-max}}$, and $p_{\text{max}}$ are defined as maximum values of $I_e$, $\tau_d$, and $p$, at which probability of breakdown of the accelerating gap does not exceed 5%. The probability of the accelerating gap breakdown is estimated as the ratio of the number of beam pulses, at which the breakdown of the accelerating gap occurred, to the total number of beam pulses. The observed increase in the electric strength of the accelerating gap with decreasing of cell sizes of the mesh emission electrode is due to a higher efficiency of so-called the effect of mesh stabilization (grid stabilization) of surface of emission plasma [20, 21]. A decrease in cell sizes of the emission mesh provides smaller open surface of the emission plasma, and thus better feedback between the random fluctuation of the electron emission and the area of the plasma emission surface (an increase in local
emission current density leads to thicker ion sheath near the emission electrode, which causes an increase in potential barrier for electrons and smaller open surface of plasma inside the mesh’s cell).

Figure 2 shows the typical pulse shapes of the discharge current $I_d$, emission current $I_e$, and electron beam current $I_b$. The pulse shapes of emission current $I_e$ and electron beam current $I_b$ are close to rectangular pulse shape for any configuration of the accelerating gap. The rise time $\tau_b$ of the beam current pulse is a little longer than the rise time $\tau_e$ of the emission current pulse.

**Table 1.** The efficiency of electron emission $\eta_e = I_e/I_d$ from arc plasma at different cell sizes of the mesh emission electrode, $U_a = 8$ kV, $l_a = 15$ mm.

| Parameters | Cell sizes of the emission mesh |
|------------|---------------------------------|
|            | 0.5×0.5 mm$^2$ | 0.3×0.3 mm$^2$ |
| $\eta_e$ at $p = 4$ Pa, gas: Ar | 0.90 – 0.92 | 0.76 – 0.78 |
| $\eta_e$ at $p = 4$ Pa, gas: N$_2$ | 0.87 – 0.89 | 0.70 – 0.72 |

**Table 2.** The maximum emission current $I_{e\text{-max}}$ and gas pressure $p_{\text{max}}$ at different cell sizes of the mesh emission electrode, $U_a = 8$ kV, $l_a = 15$ mm.

| Parameters | Cell sizes of the emission mesh |
|------------|---------------------------------|
|            | 0.5×0.5 mm$^2$ | 0.3×0.3 mm$^2$ |
| $I_{e\text{-max}}$ at $p = 5$ Pa, $\tau_d = 300$ μs, gas: Ar | 14 A | 45 A |
| $p_{\text{max}}$ at $I_e = 38$ A, $\tau_d = 300$ μs, gas: N$_2$ | 7 Pa | 15 Pa |
| $p_{\text{max}}$ at $I_e = 30$ A, $\tau_d = 300$ μs, gas: Ar | 4.5 Pa | 9 Pa |

The length $l_a$ of the accelerating gap influences parameters of the forevacuum plasma-cathode source of the pulsed low-energy large-radius electron beam. In particular, the length $l_a$ influences on the electron emission current $I_e$ and, accordingly, on the electron beam current $I_b$ (figure 3 (a)), and thus the efficiency $\eta_e$ of electron emission changes (figure 3 (b)). The efficiency of electron emission $\eta_e$ from the arc plasma depends non-monotonically on the length $l_a$. An increase in the length $l_a$ first leads to an increase in the efficiency $\eta_e$, but when a certain optimal value $l_{a\text{-opt}}$ is reached, a further increase in the length $l_a$ leads to a decrease in the efficiency $\eta_e$. An increase in gas pressure $p$ leads to an increase in overall efficiency $\eta_e$ of electron emission from arc plasma, but the dependence of the efficiency $\eta_e$ on the length $l_a$ remains (figure 3 (b)). The influence of the length $l_a$ on the efficiency $\eta_e$ is stronger for gas with a large ionization cross section. However, a change in the length $l_a$ of the
accelerating gap leads to a relatively small change in the electron emission efficiency $\eta_e$ (within 15%). The optimal value of the length $l_{a,oe}$ of the accelerating gap, at which the maximum efficiency $\eta_e$ is provided, is about 25 mm. An increase in the length $l_a$ also provides to decrease the rise time $\tau_e$ of the emission current pulse. For example, at gas (N$_2$) pressure $p = 8$ Pa the time, during which the emission current rises from 10% to 50% of the pulse amplitude, decreases from 2.3 $\mu$s to 1.9 $\mu$s with increasing of the length $l_a$ from 10 mm to 35 mm.

$$I_e, A \quad I_b, A$$

| $l_a$, mm | $I_e$ | $I_b$ |
|----------|-------|-------|
| 10       | 24.0  |       |
| 15       | 24.5  |       |
| 20       | 25.0  |       |
| 25       | 25.5  |       |
| 30       | 26.0  |       |
| 35       | 26.5  |       |

Figure 3. Dependencies of the emission current $I_e$ and beam current $I_b$ (a), and the efficiency of electron emission $\eta_e = I_e/I_d$ (b) on the length $l_a$ of the accelerating gap: a) – Ar, $p = 8$ Pa, $U_a = 5$ kV; b) – N$_2$, $U_a = 5$ kV.

The changes in the electron emission efficiency $\eta_e$ are associated with the back-streaming ion flow. The increase in the electron emission efficiency $\eta_e$ with increasing gas pressure $p$ is due to the effect of “switching” the electron component of the discharge current into emission [20]. In the forevacuum pressure range, this effect is caused by the back-streaming ion flow [17]. The current of back-streaming ion flow increases with increasing in gas pressure and using gas with larger ionization cross section. The emission current $I_e$ also increases due to ion-induced secondary electron emission, occurring due to the emission electrode is bombarded by the back-streaming ions. The increase of emission current due to the ion-induced secondary electron emission has also been observed in pressure range $10^{-3}$–$10^{-1}$ Pa [22]. Therefore, an increase in the back-streaming ion flow provides an increase in emission current, and thus an increase in efficiency $\eta_e$. The efficiency $\eta_e$ of electron emission can exceed 1 due to electron component of discharge current to the anode can exceed total arc discharge current $I_a$ by 10% (the positive ion current to the anode can reach 10% of the total discharge current [23]) and due to the ion-induced secondary electron emission from the emission electrode. The probe measurements demonstrated that current density $j_i$ of the back-streaming ions increases with increasing in the length $l_a$ from 10 mm to about 25–27.5 mm (figure 4). At longer length $l_a$, the current density $j_i$ remains practically unchanged or, in some cases, slightly decreases with increasing $l_a$. Thus, the increase in the electron emission efficiency $\eta_e$ with increasing length $l_a$ up to optimal value $l_{a,oe}$ is caused by an increase in the back-streaming ion current. In case of $l_a > l_{a,oe}$, a decrease in the efficiency $\eta_e$ is probably due to length of the ion mean free path in the forevacuum pressure range. At $l_a > l_{a,oe}$, back-streaming ions in the accelerating gap lose more kinetic energy with increasing of $l_a$, and some ion even cannot reach the emission electrode. Therefore, fewer back-streaming ions are able to penetrate into the discharge system through the emission electrode, and the ion-induced secondary electron emission from the emission electrode also decreases.

One of the operating features of the forevacuum plasma-cathode electron sources is a “parasitic” high-voltage glow discharge (HVGD) occurring in the accelerating gap [12, 24]. Ion flow, formed by this “parasitic” HVGD, provides a decrease in the ignition voltage and ignition delay time of the
Discharge which generates the emission plasma in the forevacuum plasma cathode electron source [24]. For the used accelerating gap, current of the “parasitic” HVGD, and thus value of the ion flow, moving towards the emission electrode, increases with increasing distance between the electrodes of the accelerating gap. For example, at gas pressure of 8 Pa (N₂) and \( U_a = 5 \) kV, an increase in the length \( l_a \) from 10 mm to 35 mm leads to an increase in the current of the “parasitic” HVGD from 0.4 mA to 3.5 mA. Therefore, a decrease in the rise time \( \tau_e \) of the emission current pulse, occurring as length \( l_a \) increases, is caused by an increase in current of the “parasitic” HVGD.

The length \( l_a \) much stronger influences on the electric strength of the accelerating gap. In particular, the length \( l_a \) has a strong influence on the maximum emission current \( I_{e,\text{max}} \) (figure 5, curves 1 and 2) and on the maximum operating gas pressure \( p_{\text{max}} \) (figure 5, curve 3). At first, an increase in the length \( l_a \) leads to an increase in \( I_{e,\text{max}} \) and \( p_{\text{max}} \), but when a certain optimal length \( l_{a,\text{om}} \) is reached, a further increase in \( l_a \) leads to a decrease in current \( I_{e,\text{max}} \) and pressure \( p_{\text{max}} \). For the maximum emission current \( I_{e,\text{max}} \), the optimal length \( l_{a,\text{om}} \) decreases with increasing in gas pressure \( p \). For the maximum operating gas pressure \( p_{\text{max}} \), the optimal length \( l_{a,\text{om}} \) decreases with increasing in the emission current \( I_e \). An increase in pulse duration \( \tau_d \) and an increase in accelerating voltage \( U_a \), and the use of gas with larger ionization cross section leads to a decrease in optimal length \( l_{a,\text{om}} \) for both \( I_{e,\text{max}} \) and \( p_{\text{max}} \).

![Image](image-url)  
**Figure 4.** Dependencies of the current density \( j_e \), of back-streaming ion flow on the length \( l_a \) of the accelerating gap, \( p = 8 \) Pa, gas - N₂, \( U_a = 5 \) kV, \( I_c = 20 \) A.

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**Figure 5.** Dependencies of maximum emission current \( I_{e,\text{max}} \) (curve 1 and 2) and maximum gas pressure \( p_{\text{max}} \) (curve 3) on the length \( l_a \) of the accelerating gap; working gas - N₂, \( U_a = 10 \) kV, \( \tau_d = 200 \) μs; 1 - \( p = 10 \) Pa; 2 - \( p = 12 \) Pa; 3 - \( I_c = 38 \) A.

The maximum emission current \( I_{e,\text{max}} \) and pressure \( p_{\text{max}} \) are limited by the breakdown of the accelerating gap. Therefore, the observed dependencies \( I_{e,\text{max}} \) and \( p_{\text{max}} \) on \( l_a \) can be explained by using the model of breakdown of the accelerating gap due to the cathode spot initiated on the surface of the emission electrode [17]. According to this model, the initiation of a cathode spot occurs due to the breakdown of a thin dielectric film (or contamination) on the surface of the emission electrode. This cathode spot generates plasma, which leads to the breakdown of the accelerating gap. Thin films and contaminations are almost always present on the surface of a metal electrode. Even on a cleaned metal surface, the films are formed due to gas absorption [25]. According to the model [26], under our experimental conditions (gas pressure, pulse duration and pulse repetition rate) a monolayer of adsorbates and oxides can forms on the surface of the emission electrode between the beam pulses. The total electric field strength \( E \) in the dielectric film is the sum of the electric field \( E_{\text{in}} \) created by the accelerating gap electrodes, and the electric field \( E_{\text{in}} \) created by positive charge on the surface of the dielectric film. This positive charge is formed by ion flow, moving towards the emission electrode.
When the total electric field $E$ reaches a critical value, breakdown of the dielectric film occurs, and the cathode spot is initiated. The electric field $E_0$ decreases with an increase in the length $l_a$. Therefore, current $I_{\text{max}}$ and pressure $p_{\text{max}}$ increase with increasing length $l_a$ up to $l_{a_{\text{opt}}}$. As the length $l_a$ increases, the ion flow, formed by the “parasitic” HVGD, significantly increases, and the current of the back-steaming ion flow from beam-produced plasma also increases. An increase in ion flows leads to a higher positive charge on the film, and thus it creates stronger electric field $E_i$. The ion current, formed by the “parasitic” HVGD, increases with increasing gas pressure $p$, and the back-streaming ion flow from the beam-produced plasma increases with increasing emission current $I_e$ and pressure $p$. Therefore, in order to decrease the value of the ion flows, it is necessary to decrease the emission current and/or gas pressure, and thus this leads to decrease in $I_{\text{e\_max}}$ and $p_{\text{max}}$. In addition, since the electric field $E_0$ weakens with increasing length $l_a$, the emission plasma can penetrate into the accelerating gap through the cells of the emission mesh. To reduce the probability of penetration of the emission plasma into the accelerating gap, it is necessary to decrease emission plasma density (the arc discharge current), which leads to a decrease in the emission current $I_{e_{\text{max}}}$.

The cell sizes of the mesh extractor do not significantly influence on the dependence of electron emission efficiency $\eta_e$ on the length $l_a$. However, the cell sizes of the mesh extractor influence strongly on the electron beam current $I_b$. An increase in the cell sizes of the extractor provide to increase the electron beam current, i.e., provides to increase efficiency of electron beam generation $\eta_b = I_b/I_e$ (figure 6). The efficiency of electron beam generation $\eta_b$ slightly increases with increasing length $l_a$ up to about 30–32.5 mm, but at longer length $l_a$ the efficiency $\eta_b$ decreases.

![Figure 6](image_url)

**Figure 6.** Dependencies of the efficiency of electron beam generation $\eta_b = I_b/I_e$ on the length $l_a$ of the accelerating gap at different cell sizes of the mesh accelerating electrode (mesh extractor), $p = 8$ Pa (N$_2$), $U_a = 5$ kV: 1 – 1.2×1.2 mm$^2$; 2 – 2.0×2.0 mm$^2$; 3 – 3.0×3.0 mm$^2$.

4. **Conclusion**

The configuration of the plane-parallel accelerating gap, formed by a fine mesh emission electrode and a mesh accelerating electrode (mesh extractor), influences on parameters of the forevacuum plasma-cathode source of the pulsed low-energy (up to 10 keV) large-radius electron beam. An increase in cell sizes of the mesh emission electrode increases the electron emission efficiency, but leads to a decrease in electric strength of an accelerating gap, which leads to decrease in maximum emission current and maximum operating gas pressure. Larger cell sizes of the mesh extractor provide higher electron beam current. An increase in the length of the accelerating gap first leads to an increase in the electron emission efficiency, but when optimal value is reached, a further increase in the length leads to a decrease in the emission efficiency. This optimal length of the accelerating gap is about 25 mm. However, the emission efficiency changes relatively small (within 15%) with changing in the accelerating gap length. The dependencies of maximum emission current and maximum operating gas pressure on the length of acceleration gap is similar to the dependence for the electron emission efficiency, but the gap length much stronger influences on these maximum values. Moreover, the optimal length of the accelerating gap, at which maximum emission current or maximum operating gas pressure is provided, is depended on gas pressure (for maximum current) or emission current (for...
maximum pressure), accelerating voltage and pulse duration. The influence of the length of the accelerating gap on the parameters of the forevacuum plasma-cathode electron source is caused by a change in the value of the ion flows moving towards the mesh emission electrode and by change in the electric field strength in the accelerating gap.

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References
[1] Węglowski M S, Blacha S and Phillips A 2016 Vacuum 130 72–92
[2] Hogstrom K R and Almond P R 2006 Phys. Med. Biol. 51 R455
[3] Hyams T C, Mam K and Killingsworth M C 2020 Micron 130 102797
[4] Engelko V I and Mueller G 2013 IEEE T. Plasma Sci. 41 2769–73
[5] Zhang C, Tian N, Li L, Yang Z, Lv P, Yunxue J, Zhua H and Guan Q 2020 Vacuum 174 109222
[6] Proskurovsky D I, Rotshtein V P, Ozur G E, Markov A B, Nazarov D S, Shulov V A, Ivanov Yu F and Buchheit R G 1998 J. Vac. Sci. Technol. A 16 2480–8
[7] Fetzer R, Mueller G, An W and Weisenburger A 2014 Surf. Coat. Tech. 258 549–56
[8] Koval N N, Oks E M, Schanin P M, Kreindel Yu E and Gavrilov N V 1992 Nucl. Instrum. Meth. A 321 417–28
[9] Oks E 2006 Plasma Cathode Electron Sources: Physics Technology, Applications (Weinheim: Wiley-VCH)
[10] Krasik Y E, Yarmolich D, Gleizer J Z, Vekselman V, Hadas Y, Gurovich V T and Felsteiner J 2009 Phys. Plasmas 16 057103
[11] Evstafeva E N, Rau E I, Mileev V N, Novikov L S, Disman S A and Sennov R A 2011 Inorganic Materials: Applied Research 2 106–13
[12] Zinin A A, Klimov A S, Burdovitsin V A and Oks E M 2013 Tech. Phys. Lett. 39 454–6
[13] Yushkov Y G, Burdovitsin V A, Medovnik A V and Oks E M 2011 Instrum. Exp. Tech. 54 226
[14] Kazakov A V, Medovnik A V and Oks E M 2019 IEEE T. Plasma Sci. 47 3579–85
[15] Burdovitsin A V, Klimov A S, Medovnik A V and Oks E M 2010 Plasma Sources Sci. T. 19 055003
[16] Burdovitsin V A, Dvillis E S, Medovnik A V, Oks E M, Khasanov I L and Yushkov G Y 2013 Tech. Phys. 58 111–3
[17] Burdovitsin V A, Kazakov A V, Medovnik A V and Oks E M 2018 Phys. Plasmas 25 073109
[18] Kazakov A V, Medovnik A V, Burdovitsin V A and Oks E M 2015 IEEE T. Plasma Sci. 43 2345–8
[19] Burdovitsin V A, Kazakov A V, Medovnik A V and Oks E M 2017 Phys. Plasmas 24 093109
[20] Zharnirnov A V, Kovalenko Y A, Roganov I S and Tyuryukanov P M 1986 Sov. Phys. Tech. Phys. 31 413
[21] Zharnirnov A V, Kovalenko Y A, Roganov I S and Tyuryukanov P M 1986 Sov. Phys. Tech. Phys. 31 39
[22] Koval N N, Grigoryev S V, Devyatkov V N, Teresov A D and Schanin P M 2009 IEEE T. Plasma Sci. 37 1890–6
[23] Anders A 2008 Cathodic Arcs: From Fractal Spots to Energetic Condensation (New York: Springer Inc.)
[24] Zhirkov I S, Burdovitsin V A, Oks E M and Osipov I V 2006 Tech. Phys. 51 1379–82
[25] O’Hanlon J F 1989 A User’s Guide to Vacuum Technology (New York: Wiley)
[26] Yushkov G Y and Anders A 1998 IEEE T. Plasma Sci. 26 220–6