Influence of electron emission on operation of a constricted arc discharge in a pulsed forevacuum plasma-cathode electron source

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Abstract. The research of influence of electron emission and processes associated with the formation of a pulsed large-radius electron beam on operation of a constricted arc discharge, which forms emission plasma in a forevacuum plasma-cathode electron source, is presented. Processes, occurring in case of generation of the electron beam at forevacuum pressure range 3–20 Pa, provide lower operating voltage of the constricted arc discharge. The constricted arc voltage decreases with increasing pressure and increasing accelerating voltage. However, at pressure more than 15 Pa, the arc voltage decreases until a certain minimum value is reached, and then arc voltage is almost independent on pressure and accelerating voltage. This minimum value of the constricted arc voltage is on average 1.5–2 times higher as compared with voltage of the cathodic arc at the same discharge current. The observed decrease of operating voltage of the constricted arc is most likely caused by accelerated back-streaming ions, which move toward the emission electrode from beam-produced plasma. These accelerated ions partially penetrate into the hollow anode of discharge system through the mesh emission electrode and facilitate formation of the arc plasma, and thus provides lower voltage of the constricted arc.

1. Introduction
Electron sources with plasma cathodes generate continuous and pulsed electron beams in the presence of chemically aggressive gas media (e.g., O₂, N₂) and at higher operating pressures as compared to electron sources with hot cathodes (thermionic cathodes) [1–3]. Moreover, it is easier to generate pulsed electron beams in emission systems with plasma cathodes [1–3]. The pulsed electron beams are used for modification of surface properties of different materials [4, 5], for pumping of gas lasers [6], for the polymerization and vulcanization of polymers [7, 8], and for some other applications [9–11]. The improvement of ability to form electron beam at higher pressure has led to development of so-called forevacuum plasma-cathode electron sources [12–14]. These electron beam sources generate continuous and pulsed low-energy (up to 20 keV) electron beams in pressure range 1–100 Pa (forevacuum pressure range) [13, 14]. The forevacuum e-beam sources provide to treat dielectric materials due to in the forevacuum pressure range the ion flow from beam-produced plasma prevents growth of negative charge on the surface of the dielectric [15].
Type of a gas discharge, that generate emission plasma, has a big influence on parameters of the electron sources with plasma-cathodes \([1–3]\). For such type of electron sources, generating pulsed e-beams, an emission plasma is often formed by a cathodic arc (an arc discharge with cathode spots) \([1, 2]\). Pulse duration and amplitude of discharge current of the cathodic arc almost have no limits, but instabilities, caused by micro-droplets and vapors of cathode material, and cathode spots operation modes lead to instability of emission plasma \([16]\). For instance, micro-droplets and vapors could reduce electric strength of an accelerating gap and could contaminate surface of material processed by the electron beam. Applying a constricted arc discharge for emission plasma generation at standard gas pressure range of \(10^{-3}–10^{-1}\) Pa leads to significantly reduction or even elimination of a negative influence of cathode spots operation modes \([2, 17–20]\). The plasma-cathode of electron sources based on the constricted arc discharge usually realized by compressing positive column of the arc discharge with an intermediate metal electrode with a narrow channel (a constricting channel). This intermediate electrode is placed between a cathode and an anode of the discharge gap; therefore, it shields cathode region from the region of formation of the emission plasma. E-beams generated by the plasma-cathode sources based on the constricted arc discharge operating in gas pressure range of \(10^{-3}–10^{-1}\) Pa have been well researched \([2, 17–20]\).

Parameters of pulsed electron beams sources operating in forevacuum pressure range with plasma cathode can be improved by using the constricted arc discharge as a source of emission plasma. Due to a small difference of gas pressures between anode and cathode regions of the discharge system operation mode of constricted arc discharge could be considered as an isobaric. In this operating mode such type of a discharge has some features \([21]\). This work is a continuation of research of features of the constricted arc discharge operating in the forevacuum pressure range, and its purpose is to investigate influence of electron emission and processes associated with the generation of the pulsed large-radius e-beam on the constricted arc forming emission plasma in the forevacuum plasma-cathode electron source.

2. Experimental setup and techniques
A schematic of the experimental setup is presented in figure 1. A cathode assembly of a forevacuum plasma-cathode electron source based on a pulsed constricted arc discharge consists of a stainless-steel current lead, a cathode, a ceramic insulator and an ignitor electrode. The cathode is copper rod (diameter of 6 mm). The side surface of cathode is covered by the tubular ceramic insulator, and the bottom end of the copper rod is working (operating) surface of the cathode. The ignitor electrode is stainless-steel ring located on the ceramic insulator. The cathode and the ceramic insulator are assembled on the current lead. The cathode assembly is installed in an insulator with special shape, which provides a cavity in the cathode part of the discharge system. The anode consists of 2 parts: a cylindrical hollow anode (diameter 114 mm and height 150 mm) and a plane anode with an emission window (diameter of this window is 114 mm). Both anode parts are made of stainless steel. As described in \([14]\), to increase maximum gas pressure, at which the e-beam source operates, the emission window in the plane anode is covered by two stainless-steel meshes. These meshes are spaced 2 mm apart. The mesh with cell sizes of \(2.0\times2.0\) mm\(^2\) is located inside the emission window, and the fine mesh (emission electrode) with cell sizes of \(0.3\times0.3\) mm\(^2\) is located on the side of the emission window facing to an accelerating gap. The hollow anode and the plane anode are separated by an insulator, and the hollow anode is connected through a resistance \(R_a = 5\ \Omega\) to a power supply unite. This \(R_a\) provides an increase in the efficiency of electron emission from the constricted arc plasma \([21]\). The arc discharge is constricted by an intermediate electrode with a narrow channel (a constricting channel). The constricted arc discharge has some limitations. In particular, in case of the current of the constricted arc reaches a certain threshold (maximum) value \(I_{\text{d,max}}\), the discharge current breaks (discharge extinction) and transitions to the cascade mode of arc operation occur \([2, 18]\). In case of the cascade mode of arc operation, cathode spots are initiated on the intermediate electrode (on the side facing the anode) and two serial cathodic arcs appear. Maximum current \(I_{\text{d,max}}\) of the constricted arc, operating in the forevacuum plasma-cathode electron source, is depended on the
geometry of the constricting channel, pulse repetition rate, pulse duration, pressure and type of gas [21]. To detect undesirable transition of the constricted arc discharge to the cascade operation mode, by analogy with [18, 21], the intermediate electrode is made of two insulated parallel stainless-steel plates. These plates are 1 mm thick each and are spaced 1 mm apart. Coaxial holes (diameter $d_c$ of 3 mm), which have been made in the plates, form the constricting channel of length $h_c = 3$ mm. A copper wire connects these plates to each other. The transition to the cascade mode of operation is accompanied by the current $I_c$ flow through this copper wire, and an amplitude of $I_c$ is close to the full discharge current $I_d$. The current $I_c$ through the copper wire is measured by a current transformer. The accelerating gap of the forevacuum e-beam source is formed by a fine mesh (0.3×0.3 mm$^2$), covering the emission window, and an accelerating electrode (extractor). The accelerating electrode is stainless-steel mesh with cell sizes 3.0×3.0 mm$^2$. The electrodes of the accelerating gap are electrically insulated by a high-voltage insulator of complex shape described in detail elsewhere [14]. All insulators are made of polyamide or ceramic.

**Figure 1.** Schematic of the experimental setup.

The forevacuum plasma-cathode electron source based on the constricted arc discharge is placed on a vacuum chamber. The vacuum chamber is first evacuated by a vacuum pump down to pressure of 2.5 Pa, and then a working gas (nitrogen) is supplied to the chamber. The working gas pressure $p$ is controlled by the gas $N_2$ flow rate into the vacuum chamber at constant pumping rate. A pulsed discharge power supply unit powers the pulsed constricted arc discharge. Amplitude of the discharge current $I_d$ is regulated by the input voltage $U_0$ of the pulsed discharge power supply unit. This power supply unit for the pulsed discharge provides a close to rectangular pulses with current $I_d$ of up to 100 A and a pulse duration $\tau_d$ of up to several milliseconds. For this work we have used $\tau_d = 120 \mu$s and the pulse repetition rate of 1pps (pulse per second). A DC high-voltage power supply unit provides a DC accelerating voltage $U_a$. The constricted arc discharge current $I_d$ and the electron emission current $I_e$ are measured by current transformers installed in the respective electrical circuits. The voltage $U_a$
across the accelerating gap (i.e., the voltage between the anode and the grounded extractor) and the voltage $U_a$ between the cathode and the grounded extractor are measured using TESTEC HVP-15HF oscilloscope probes. The probes have been pre-calibrated. The operating voltage $U_d$ of the constricted arc discharge is determined by subtracting the probe signal $U_a$ from the probe signal $U_b$ ($U_d = U_b - U_a$).

3. Experimental results and discussion
Shape of pulses of the constricted arc discharge current $I_d$ is close to a rectangular in certain current range ($U_a = 0$). In case of current $I_d$ exceeding a “borderline” value of current $I_{d,b}$, the current of the constricted arc decreases during the pulse. This “borderline” current $I_{d,b}$, as well as the maximum (threshold) arc current $I_{d,max}$, depends on $p$ and $t_a$. The arc current $I_d$ decreases due to a change in gas conditions in the constricting channel, i.e., decreasing density of neutral gas particles, which is caused by “electron pumping” of gas and by escaping of ions from the channel [17–18]. Without electron emission ($U_a = 0$), the decrease in the arc current during the pulse causes an increase in the arc voltage $U_d$ [21]. At $I_d > I_{d,b}$, the voltage $U_d$ can increase 2–3 times during the pulse. The operating voltage $U_d$ increases to provide ionization processes, and thus to provide current flow through the constricting channel [18].

Figure 2 shows the pulse shapes of the constricted arc current $I_d$, the emission current $I_e$ and the arc voltage $U_d$ in case of electron emission ($U_a > 0$). The emission current $I_e$ appears with some delay $t_a$ relative to the current $I_d$, and the rise time of current $I_e$ front $t_f$ can significantly exceed the rise time of the current $I_d$ front (figure 2). Previous research has shown that the observed delay time $t_a$ and increased front time $t_f$ are caused by relatively slow formation of the discharge plasma near the emission window covered by the meshes, and $t_a$ and $t_f$ depend on the pressure $p$ and the accelerating voltage $U_a$ [22]. In case of e-beam generation, the changing in $t_a$ and $t_f$ is caused by the back-streaming ion flow from beam-produced plasma, which is formed in the acceleration region and propagation region of the electron beam. Experiments have shown the emission of electrons leads to a decrease in the constricted arc voltage $U_d$, which provides to increase $I_d$ at invariable input voltage ($U_0 = \text{const}$) of the pulsed discharge power supply unit, as compared to the $U_d$ and $I_d$ without electron emission ($I_e = 0$). For the case $I_e > 0$ and $I_d < I_{d,b}$, constricted arc current $I_d$ increases as voltage $U_d$ decreases (figure 2a). In case of electron emission ($I_e > 0$) and decrease in arc current during pulse ($I_d > I_{d,b}$), the operating voltage $U_d$ of the constricted arc discharge increases much weaker during the pulse (figure 2b) as compared with constricted arc operating without electron emission ($I_e = 0$).

![Figure 2](image_url)

**Figure 2.** Pulse shapes of the constricted arc discharge current $I_d$, emission current $I_e$ and arc voltage $U_d$: (a) $U_a = 0.8 \text{ kV}$, $p = 15 \text{ Pa}$; (b) $U_a = 4.0 \text{ kV}$, $p = 10.6 \text{ Pa}$.

Figure 3a shows the dependences of the constricted arc current $I_d$, emission current $I_e$ and arc voltage $U_d$ on the accelerating voltage $U_a$ at invariable input voltage $U_0$ of the discharge power supply
unit \((U_0 = \text{const})\). Hereinafter, all values presented on the graphs are the pulse-averaged. The emission current \(I_e\) increases with an increase in the accelerating voltage \(U_a\), which causes decrease in the arc voltage \(U_d\). Since the discharge current \(I_d\) rises with decreasing of \(U_d\) \((U_0 = \text{const})\), to show relative influence of electron emission on operation of the constricted arc discharge, we have introduced normalized arc voltage \(U_d/I_d\). Dependence of normalized voltage \(U_d/I_d\) on \(U_a\) is presented in figure 3b. At accelerating voltage \(U_a < 0.6–0.8\) kV the normalized voltage \(U_d/I_d\) decreases sharply as \(U_d\) increases. At \(U_a > 0.6–0.8\) kV, the arc voltage \(U_d\) and normalized voltage \(U_d/I_d\) almost linearly decrease with increasing \(U_a\). However, at \(p > 15\) Pa, when the voltage \(U_d\) reaches a certain minimum value \(U_{d, \text{min}}\), the arc voltage \(U_d\) is almost independent on the accelerating voltage \(U_a\). This value \(U_{d, \text{min}}\) is on average, 1.5–2 times higher than operation voltage of the cathodic arc (i.e., arc discharge operating without the intermediate electrode) at the same discharge current \(I_d\). The minimum voltage \(U_{d, \text{min}}\) of the constricted arc is mainly depended on the current \(I_d\) regulated by \(U_0\).

Figure 4a shows the dependences of \(I_d, I_e\) and \(U_d\) on the pressure \(p\), and figure 4b shows the dependence of \(U_d/I_d\) on \(p\) for \(U_0 = \text{const}\). The electron emission current \(I_e\) increases with increasing pressure \(p\), which provides a decrease in the arc voltage \(U_d\). In turn, this decrease in \(U_d\) causes an increase in current \(I_d\) at \(U_0 = \text{const}\). The emission current \(I_e\) increases more than the discharge current \(I_d\) as pressure \(p\) rises due to the effect of “switching” of the electron current (i.e., flow of electrons from discharge plasma) from the anode into the e-beam [23]. In case of the forevacuum plasma electron sources, this effect is caused by ion flow from beam-produced plasma [24]. Therefore, the coefficient of efficiency of electron emission \(\eta = I_e/I_d\) from constricted arc plasma increases with increasing \(p\). In case of \(p \leq 15\) Pa, an increase in pressure \(p\) and, accordingly, an increase in the current \(I_e\) lead to a decrease in the arc voltage \(U_d\) and normalized voltage \(U_d/I_d\) of the constricted arc. At pressure \(p > 15\) Pa minimum voltage \(U_{d, \text{min}}\) is reached, and the voltage \(U_d\) and, accordingly, normalized voltage \(U_d/I_d\) are almost independent on pressure \(p\).

![Figure 3](image-url)

**Figure 3.** Dependencies of arc operation voltage \(U_d\), discharge \(I_d\) and emission \(I_e\) currents on accelerating voltage \(U_a\) (a); and dependence of normalized voltage \(U_d/I_d\) on \(U_a\) (b). Pressure \(p = 8\) Pa.

The obtained dependancies show significant influence of the processes occurring during electron emission on the constricted arc discharge operating in the pulsed forevacuum plasma electron source. The decrease in the constricted arc voltage \(U_d\) is most likely caused by the back-streaming ion flow, which arises from the beam-produced plasma and moves in opposite direction to the electron beam. These back-streaming ions are accelerated by \(U_d\) and move towards the emission electrode. Some part of these accelerated ions penetrates into the hollow anode through the cells of the emission mesh (anode mesh). The accelerated back-streaming ions, penetrated into the hollow anode of the discharge system, change the operation conditions for the constricted arc discharge and contribute to formation...
of the arc plasma in the hollow anode, and thus provide a lower arc voltage $U_d$. An increase in emission current $I_e$, an increase in pressure $p$ and an increase in accelerating voltage $U_a$ provide an increase in current density of back-streaming ions [24, 25]. Therefore, an increase in $p$ and an increase in $U_a$ lead to an increase in the quantity of back-streaming ions penetrated into the hollow anode, which provides a decrease in the operating voltage $U_d$ of the constricted arc (figure 3 and figure 4).

![Figure 4](image-url)  
**Figure 4.** Dependencies of arc operation voltage $U_d$, discharge current $I_d$ and emission current $I_e$ on pressure $p$ (a); and dependence of normalized arc voltage $U_d/I_d$ on pressure $p$ (b). Accelerating voltage $U_a = 4$ kV.

4. Conclusion
The influence of electron emission and processes associated with the generation of the pulsed large-radius electron beam on operation of the constricted arc discharge, which forms emission plasma in the forevacuum plasma-cathode electron source, has been investigated. In case of generation of e-beam, a decrease in the operation voltage of the constricted is observed. The constricted arc voltage decreases with rising gas pressure and increasing the accelerating voltage. However, at pressure more than 15 Pa, arc voltage decreases until a certain minimum value is reached. When this value is reached, the arc voltage is almost independent on pressure and accelerating voltage. The minimum voltage of the constricted arc is on average 1.5–2 times higher than operation voltage of the cathodic arc at the same discharge current. A decrease of arc voltage provides an increase in the current of the constricted arc discharge. The observed influence accelerating voltage and pressure on the constricted arc voltage is most likely caused by accelerated back-streaming ions, which move toward the emission electrode from beam-produced plasma. These accelerated ions partially penetrate into the hollow anode through the cells of the emission mesh (anode mesh) and change operation conditions for the constricted arc discharge. Thus, back-streaming ions, penetrated into the hollow anode of discharge system, contribute to formation of the arc plasma and provide lower voltage of the constricted arc discharge.

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