Formation of pulsed large-radius electron beam in the forevacuum pressure range by a plasma-cathode source based on arc discharge

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Abstract. The research on generation and propagation of large-radius low-energy (up to 10 keV) electron beam with millisecond pulse duration by the plasma-cathode electron source in the forevacuum pressure range (3–30 Pa) is presented. An arc discharge with cathode spot has been used to generate emission plasma with millisecond pulse duration. Large hollow anode and ball-shaped redistributing electrode have provided formation of arc plasma with emission surface of 100 cm²; emission plasma boundary has stabilized by metallic mesh. It is established, that gas type and gas pressure affect the parameters of the arc discharge. In case of gases with greater ionization cross section (argon, nitrogen), an increase of gas pressure has led to a decrease of arc voltage and to an increase of emission plasma density. Gas with small ionization cross section (helium) had weak effect on the arc discharge parameters. An increase of emission window in the anode has provided an increase in radius of the electron beam and an increase of efficiency of electron extraction from the arc plasma; on the other hand it has led to an increase of influence of back-streaming ion flow on the electron emission and led to a decrease of maximal operating gas pressure. Reducing the geometric transparency of the emission mesh, as well as the use of gas with small ionization cross section have provided an increase in the maximal operating pressure of the source of large-radius electron beam. It is established, that in the forevacuum pressure range, large-radius electron beam is efficiently generated in the investigated range of distances from the extractor up to 35 cm.

1. Introduction
Pulsed plasma-cathode sources of large-radius electron beams are used for modification of material surfaces [1–3], gas laser pumping [4, 5], and other applications [6–9]. The low-energy (usually not exceeding 30 keV) electron beams being generated in the pressure range \( p = 10^{-3}–10^{-1} \) Pa, which is standard for plasma-cathode electron sources, are mostly applied to modify metals and other conductive materials [1, 3]. The electron sources with plasma-cathodes have number of advantages over the sources with hot cathodes [10–12]. In particular, the plasma-cathode sources are able to operate at higher working gas pressure and in the presence of active gases (O₂, N₂ and others) [10–12]. Further development of this advantage has led to creation of forevacuum plasma-cathode electron sources that generate electron beams in the pressure range 3–100 Pa [13–15]. The forevacuum plasma-
cathode sources are advantageous in that they can be used to treat dielectric materials (ceramics and polymers) without resorting to the use of auxiliary equipment [16–18]. In the forevacuum pressure range this possibility is provided by the fact that the negative potential created on the dielectric surface by an electron beam is compensated by ions from beam-produced plasma and by non-self-maintained discharge occurring between the charged surface of dielectric and the grounded vacuum chamber walls (or other grounded units) [16].

Some applications of pulsed large-radius electron beams in the forevacuum pressure range, for example treatment of high-temperature ceramic, require increased energy per pulse. Since in the forevacuum pressure range increase of the electron emission current (current density) is limited by the breakdown of the accelerating gap [19], the required energy per pulse can be attained by using pulse durations longer than 1 ms. At such pulse durations, stable generation of the emission plasma with density of the order of $n \sim 10^{17}–10^{18} \text{m}^{-3}$ can be supported by an arc discharge with cathode spot. It has been previously demonstrated a possibility to generate a low-energy electron beam with millisecond pulse duration in the forevacuum pressure range [20]. The present work aims to study features of plasma generation with a developed emission surface of an area of about 100 cm$^2$, and research influence of the working gas pressure on the electron beam generation and propagation in order to obtain a large-radius electron beam with millisecond pulse duration in the forevacuum pressure range.

2. Experimental setup and techniques

The researches were carried out on the experimental setup schematically shown in figure 1. The plasma electron source was mounted on a vacuum chamber flange 1. The plasma-cathode source includes cylindrical copper cathode 2 with a diameter of 6 mm enclosed in ceramic insulator 3, which limits the cathode working surface. The cathode 2 and the ceramic insulator 3 are mounted on an insulator 4 with vacuum current input leads 5. A hollow cylindrical anode 6 with height of 150 mm and inner diameter of 114 mm is made of stainless steel. The arc discharge is initiated by an auxiliary discharge over dielectric surface 3 between the copper cathode 2 and an ignitor electrode 7 made of stainless steel. The arc initiation occurs in “triggerless” mode [21], i.e., without using a trigger pulse generator. Opposite to the cathode unit, on butt-end of the anode 6, there is cut out an emission window covered by fine mesh (emission mesh electrode) 8 of stainless steel. Cells of anode mesh 8 have dimensions 0.3×0.3 mm$^2$ and geometric transparency of 60% or 30%. The distance between the cathode 2 and emission mesh 8 is 80 mm. A redistributing electrode 9 is installed in the discharge gap of the source. The use of redistributing electrodes in the discharge gaps of plasma-cathode sources enables formation of sufficiently uniform plasma [1, 2], and thus smoothing the current density distribution across the electron beam. With the given geometry of the discharge gap, the ball-shaped redistributing electrode with a diameter of 28 mm, isolated from other electrodes, provides formation of plasma with inhomogeneity in the electron extraction region no more than 15–17%. The source accelerating gap is formed by the mesh emission electrode 8 and a grid accelerating electrode 10 with the cell dimensions 2.4×2.4 mm$^2$ and geometric transparency of 70%. A high-voltage insulator 11 ensures electrical separation of the accelerating gap electrodes.

The vacuum chamber was pumped out by a forevacuum mechanical pump that provided minimal gas pressure $p_{min} = 2.5$ Pa. The working pressure $p$ was controlled by rate of gas flow into the vacuum chamber. Nitrogen (N$_2$), argon (Ar), and helium (He) were used as working gases. The plasma-cathode electron source operated in isobaric mode, i.e. pressure in the vacuum chamber and in the plasma source was equal. The source was fed by a pulsed arc discharge power supply unit 12 and by a high-voltage source of DC accelerating voltage 13 with a capacitor bank of 150 µF. The arc discharge power supply unit 12 provided the discharge current $I_d$ up to 60 A at the pulse duration $\tau_p$ up to 10 ms. The pulse repetition rate $\nu$ was 0.2–2 Hz. The high-voltage source 13 provided DC voltage $U_a$ on the accelerating gap up to 10–11 kV.

The plasma density $n$ was measured by using a single Langmuir probe (not shown in figure 1). Negative potential $U_p = –90$ V was applied to the probe by DC voltage source, which enabled the probe measurement in the regime of the ion current saturation. The discharge current $I_d$ and the
emission current $I_e$ were measured by current transformers with sensitivity 20 A/V. The electron beam current $I_{b-F}$ was measured by Faraday cup 14 and a current transformer (sensitivity 10 A/V). The electron beam current $I_{b-c}$ was also measured by a calorimeter 15. The Faraday cup 14 and the calorimeter 15 were placed on a linear manipulator 16 that provided vertical movement. The voltages were measured using high-voltage probes TESTECH HVP-15HF (1000:1). A small Faraday cup 17, encased in a grounded protective shield 18 with a collimating hole with a diameter of 5 mm, was used to measure the electron beam current density $j_e$ distribution. This Faraday cup was placed on a two-coordinate manipulator (not shown in figure 1).

Figure 1. Schematic of the experimental setup: 1 – vacuum chamber; 2 – cathode; 3 – ceramic insulator; 4 – insulator; 5 – vacuum current input leads; 6 – anode; 7 – ignitor electrode; 8 – emission mesh electrode (anode mesh); 9 – redistributing electrode; 10 – grid accelerating electrode (extractor); 11 – high-voltage insulator; 12 – arc discharge power supply unit; 13 – high-voltage source of DC accelerating voltage; 14 – Faraday cup; 15 – calorimeter; 16 – linear manipulator; 17 – small Faraday cup; 18 – grounded protective shield; 19 – converter.

3. Experimental results and discussion

Figure 2 shows typical pulse shapes of the current $I_d$ and the voltage $U_d$ of the arc discharge with cathode spot operating in the discharge gap of the forevacuum plasma-cathode source of the large-radius electron beam. For the given discharge gap geometry dependence of the arc voltage $U_d$ on the current $I_d$, i.e. current–voltage characteristic of the arc discharge, has an increasing behavior and practically does not depend on the pulse duration (in figure the values of $U_d$ and $I_d$ are averaged over pulse). Changing the geometry of the discharge gap of the plasma-cathode source in order to form the electron beam with bigger cross section (radius) resulted in increase of the arc voltage $U_d$ by a factor of about two as compared to the discharge gap configuration used in ref. [20]. The working gas pressure $p$ affects the arc discharge voltage $U_d$ (figure 4). When using argon and nitrogen, increasing
gas pressure $p$ results in decreased voltage $U_d$, and this effect is stronger for argon. While for helium, slight growth of $U_d$ is observed with increasing pressure $p$. The different influences of gases on the arc discharge voltage are due to their different ionization and recombination cross-sections [22]. The ionization and recombination processes affect the arc plasma potential, which in turn lead to change of the arc voltage $U_d$. 

![Figure 2](image2.png)  
**Figure 2.** Pulse shapes of the arc current $I_d$ and the arc discharge voltage $U_d$. 

![Figure 3](image3.png)  
**Figure 3.** Current–voltage characteristic of the arc discharge at $p = 4$ Pa (N$_2$).

In the near-cathode region, the gas pressure $p$, as should be expected, does not have any effect on the density $n$ of the arc discharge plasma. At distance from the cathode $h > 20$ mm, the type of gas and its pressure $p$ begin to affect the plasma density $n$. In the electron extraction region ($h > 70$ mm) an increase of the gas pressure $p$ leads to significant growth of the plasma density $n$. Figure 5 shows dependence of the plasma density $n$ on time $t$ in the electron extraction region ($h = 75$ mm). The density $n$ is calculated from the ion saturation current on the probe, on the assumption that the electron temperature does not change during the pulse. It follows from figure 5 that at pressure $p > 12$ Pa the growth time for the plasma density $n$ in the electron extraction region can reach about 1 ms (curve 4). Since the time of the density change does not exceed 1 ms, at $\tau_d > 1$ ms the arc discharge operates in the discharge gap of the forevacuum plasma-cathode electron source in quasi-continuous mode. The
use of a gas with greater ionization cross-section (for example, Ar) results in greater increase of the plasma density $n$.

![Figure 4](image1.png)

**Figure 4.** Dependence of the arc discharge voltage $U_d$ on the gas pressure $p$ for different types of working gases. Discharge current $I_d = 40$ A, pulse duration $\tau_d = 5$ ms.

![Figure 5](image2.png)

**Figure 5.** Dependence of the plasma density $n$ on time $t$ in the electron extraction region ($h = 75$ mm) for various gas pressures $p$ ($N_2$) at $\tau_d = 3$ ms: 1 – $p = 4$ Pa; 2 – $p = 8$ Pa; 3 – $p = 12$ Pa; 4 – $p = 20$ Pa.

Figure 6 shows pulse shapes of the discharge current $I_d$, the emission current $I_e$, and the beam current $I_{b,F}$ measured by the Faraday cup. The dependence of the emission current $I_e$ on the accelerating voltage $U_a$ (the current-voltage characteristic of the electron-beam source) has shape typical for the plasma-cathode electron-beam sources (figure 7). The discharge current $I_d$ and the pulse duration $\tau_d$ do not significantly affect on the current-voltage characteristic of the electron source. Increasing the diameter of the anode emission window increases the electron beam radius (cross section) and the efficiency of the electron extraction from the arc discharge plasma $\eta = I_e/I_d$. However, increasing the diameter of the anode emission window also results in growing influence of the back-streaming ion flow on the electron emission from the arc plasma. In the forevacuum pressure range this ion flow occurs from the electron beam acceleration and propagation regions. As shown previously in ref. [23], in the forevacuum pressure range, the back-streaming ion flow penetrates into the discharge gap and induces the effect of “switching over” the discharge current to the emission...
Current density of the back-streaming ion flow increases with increasing gas pressure $p$, which leads to increase of the efficiency $\eta$ of the electron extraction from the arc plasma. When the efficiency reaches $\eta \approx 1$, a further pressure increase causes considerable disturbance of the arc discharge plasma, and eventually causing a breakdown of the accelerating gap. Thus, for example, in case of nitrogen, at the diameter of the emission window equal to that of the hollow anode and with the emission grid geometric transparency $\beta = 60\%$, the electron extraction efficiency reaches $\eta \approx 1$ at pressure $p = 8$ Pa. Therefore, in order to increase the maximal operating pressure $p_{\text{max}}$, when using gases with high ionization cross-sections (Ar, N$_2$), it is advisable to decrease the geometric transparency $\beta$ of the emission electrode (table 1). At low pressure $p$, decreasing $\beta$ predictably decreases the electron emission efficiency $\eta$, while the shape of the current-voltage characteristic remains the same. For any geometric transparency $\beta$, increasing the pulse duration $\tau_d$ decreases the electric strength of the accelerating gap, which results in decreased maximal working pressure $p_{\text{max}}$. The use of a gas with lower ionization cross-section (such as helium) provides stable electron beam generation up to the pressure $p_{\text{max}} > 30$ Pa, even for the geometric transparency of the emission electrode $\beta = 60\%$ (table 1).

![Figure 6](image_url)

**Figure 6.** Pulse shapes of the discharge current $I_d$, the emission current $I_e$, and the beam current $I_{b-F}$ measured by the Faraday cup.

![Figure 7](image_url)

**Figure 7.** Dependence of the emission current $I_e$ on the accelerating voltage $U_a$ for various arc discharge current $I_d$. Pressure $p = 4$ Pa (N$_2$), geometric transparency of emission mesh $\beta = 60\%$: $1 - I_d = 20$ A; $2 - I_d = 27$ A; $3 - I_d = 34$ A.
Table 1. Maximal operating pressure $p_{\text{max}}$ for various geometric transparencies $\beta$ of the emission electrode at $\tau_d = 2 \text{ ms}$.

| Gas  | $\beta = 60 \%$ | $\beta = 30 \%$ |
|------|----------------|----------------|
| Ar   | 5 Pa           | 9 Pa           |
| N$_2$| 8 Pa           | 15 Pa          |
| He   | > 30 Pa        | > 30 Pa        |

Investigations of the electron beam propagation in the drift region by the Faraday cup and the calorimeter have shown that the beam current $I_b$ is always smaller than the emission current $I_e$. Both measurement methods indicate that the beam current increases with increasing pressure $p$ at invariable arc discharge current $I_d$ (figure 8). The beam current $I_{b,c}$ measured by the calorimetric method is smaller than the current $I_{b,F}$ measured by the Faraday cup, and the measurement difference between the two methods grows bigger as the working gas pressure $p$ increases (figure 8). The current $I_{b,F}$ measured by the Faraday cup is apparently greater than the current $I_{b,c}$ measured using the calorimetric method because of the beam-produced plasma that is formed along the electron beam propagation path at high pressure. The beam-produced plasma is a source of additional low-energy charged particles, which arrive at the walls of the Faraday cup. For the experimental distance range from the extractor to the calorimeter $L = 5$–35 cm, the electron beam transport has proved to be efficient.

Figure 8. Dependence of the emission current $I_e$, the beam current $I_{b,F}$ measured by the Faraday cup, and the beam current $I_{b,c}$ measured by the calorimeter on the working gas pressure $p$. The working gas is nitrogen (N$_2$), distance from the extractor $L = 35 \text{ cm}$, $\tau_d = 4 \text{ ms}$, $U_a = 8 \text{ kV}$.

Figure 9 gives normalized radial distribution of the plasma density $n$ in the electron extraction region ($h = 75 \text{ mm}$) and radial distribution of the current density $j_e$ of the electron beam in the drift region. The use of the redistributing electrode and the emission electrode with lower geometric transparency $\beta$ improves homogeneity of the current density $j_e$ distribution over the electron beam cross-section. In particular, the redistributing electrode provides formation of rather uniform emission plasma, while decreased geometric transparency $\beta$ of the emission electrode diminishes the influence of the back-streaming ion flow on the emission plasma. Without these changes, the current density distribution $j_e$ of the electron beam has shape close to the Gaussian (normal) distribution.
Figure 9. Radial distributions of the normalized plasma density \( n/n_{\text{max}} \) in the electron extraction region \((h = 75 \text{ mm})\) and the normalized current density \( j_e/j_{e\text{-max}} \) of the electron beam at distance \( L = 12 \text{ cm} \).

4. Conclusion
It has been established that the working gas pressure affects the parameters of the arc discharge with cathode spot, which forms the emission plasma in the discharge gap of the forevacuum large-radius electron-beam source. When using the working gasses with greater ionization cross-sections (argon, nitrogen), increasing pressure results in decreased voltage of the arc discharge, while gas with small ionization cross-section has weak effect. Increased gas pressure provides the growth of the emission plasma density in the electron extraction region. At the pressure over 12 Pa, there can be observed growth of the plasma density during 1 ms. Thus, for the pulse durations over 1 ms, the arc discharge operates in the discharge gap of the forevacuum source in quasi-continuous mode. Increasing the radius of the anode emission window increases the electron beam diameter and the efficiency of the electron beam extraction from the arc plasma, whereas increasing the influence of the back-streaming ion flow on the electron emission and stability of the electron source operating in the forevacuum pressure range. In particular, increase of the radius of emission window causes decrease of maximal working pressure. Decrease of the geometric transparency of the emission electrode, as well as the use of gas with smaller ionization cross-section increase the maximal operating gas pressure of the forevacuum plasma-cathode electron source. Investigations of the electron beam propagation in the forevacuum pressure range have shown that the electron beam generation and propagation prove to be efficient for the experimental distances from the extractor up to 35 cm. The use of the redistributing electrode and decrease of geometric transparency of the emission electrode improve the uniformity of the current density distribution across the electron beam generated in the forevacuum pressure range.

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