Generation of focused high-current electron beam with millisecond pulse duration by a forevacuum plasma-cathode electron source based on cathodic arc

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Abstract. We describe our work on the generation of low-energy (up to 10 keV) pulsed high-current electron beams with pulse duration up to 7 ms, compressed (focused) by a magnetic field in the forevacuum pressure range (3–30 Pa). We show that the focusing system, consisting of two coaxially arranged coils, provides effective compression of the beam. In the forevacuum pressure range, the gas pressure and type of gas affect the focusing of the beam at fixed emission current, accelerating voltage and magnetic field. Increased pressure leads first to increased beam current density, but beyond a certain optimal value further pressure increase leads to a decrease in the current density of the electron beam. The use of gas with greater ionization cross-section results in stronger compression of the beam at lower gas pressure, but also leads to decreased maximal operating gas pressure of the plasma-cathode electron beam source. Variation of magnetic fields provides control of the beam current density and the position of the beam crossover (focus). A low-energy electron beam with current density up to 15 A-cm² and pulse duration up to 7 ms is obtained in the forevacuum pressure range. The use of the focused beam for evaporation of high-temperature ceramics is demonstrated.

1. Introduction
Plasma-cathode sources of pulsed low-energy (up to 25–30 keV) electron beams in the pressure range 10⁻³–10⁻¹ Pa have been used mainly for processing various electrically conductive materials [1–3]. Pulsed forevacuum-pressure plasma-cathode sources, which generate large-radius electron beams in the pressure range 3–30 Pa [4, 5], provide direct surface treatment of various dielectric materials (ceramics and polymers) [6–8]. In the forevacuum pressure range, direct electron beam processing of dielectrics is feasible because the negative charge that is built up on the dielectric surface by the e-beam is neutralized by ions from the beam-produced plasma and from the non-self-sustained plasma that is generated between the charged dielectric surface and the grounded walls of the vacuum chamber [6]. As well as application for material modification over rather large surface areas, other applications are associated with local material treatment – surface cleaning, surface hardening, evaporation of material, etc. For these uses, high energy density beams (per pulse) are needed for processing of high-temperature materials. For processing electrically conducting materials by low-energy e-beams in the traditional pressure range, one of the methods for producing the required
electron beam energy density is to use electrostatic or magnetic fields in the beam propagation region [9, 10]. At the same time, high-energy (up to 1 MeV) ion beams [11], laser beams [12, 13] and abrasive tools [14, 15] are used for local treatment of high-temperature dielectric materials. The generation of a focused (compressed) pulsed electron beam with high energy density in the forevacuum pressure range can provide local treatment of high-temperature dielectric materials. The use of compressed electron beams for the treatment of dielectrics in the forevacuum pressure range can be more energy-efficient than with high-energy ion beams and laser beams.

In the forevacuum pressure range, the use of electrostatic focusing systems is problematic because of the ignition of discharges between the electrodes of the focusing systems. Thus magnetic focusing systems are used to focus continuous electron beams in the forevacuum pressures range [16]. This approach can also be used to focus pulsed low-energy electron beams. The maximum current density in the accelerating gap of plasma-cathode sources is constrained (the current density is limited by breakdown in the accelerating gap) [17], and so the required energy density per pulse for low-energy (up to about 10 keV or so) electron beams is achieved by extending the pulse duration to 1 ms or more.

In prior work we have demonstrated the generation of focused pulsed electron beams, and explored the influence of magnetic field on the emission of electrons from a cathodic arc plasma at pulse duration of up to 5 ms in the pressure range 4–30 Pa [18]. The purpose of the work described here was to investigate the features of focusing of the pulsed beam by a magnetic field, and to study the influence of gas pressure on the focusing of the low-energy electron beam with millisecond pulse duration in the forevacuum pressure range.

2. Experimental setup and techniques

A schematic of the experimental setup is shown in figure 1. In the forevacuum pressure range, increase of gas pressure and of pulse duration lead to a decrease in the maximum current density in the beam accelerating gap due to decrease in the electrical strength (maximum hold-off voltage and emission current) of the gap [17]. Therefore, to allow generation of narrow high-current electron beams with millisecond pulse duration, electrons are extracted from relatively large plasma boundary, which is stabilized by a mesh electrode, and then the beam is compressed by appropriate magnetic fields. To generate the electron beam we use a forevacuum-pressure, pulsed, plasma-cathode electron source utilizing a cathodic arc discharge [5]. The plasma-cathode electron source consists of a copper cathode 1 enclosed in a ceramic insulator 2, a hollow anode 3 with an emission window covered by a stainless steel mesh (emission electrode) 4, an ignitor electrode 5, an accelerating electrode (extractor) 6, and a high-voltage insulator 7. The diameter of the emission window, which is covered by a metal mesh, is 90 mm. The design of the source has been modified to provide generation of a narrow (small diameter) beam. The distance between the working surface of the cathode 1 and the emission mesh electrode 4 was shortened to 3 cm in order to ensure generation of emission plasma 8 with a more pronounced normal (Gaussian) distribution in the region of electron extraction.

The electron source is positioned on a flange of the vacuum chamber 9, which is pumped out by a mechanical pump to a base pressure $p_{\text{min}} = 2.5$ Pa. The working gas pressure $p = 4–30$ Pa is regulated by the gas flow rate into the vacuum chamber. Argon (Ar), nitrogen (N$_2$) and helium (He) were used as working gases. The source is powered by a pulsed power supply for the arc discharge 10 and a high-voltage source of DC accelerating voltage 11. The power supply unit for the arc plasma provides a discharge current $I_d$ up to 40 A with pulse duration $\tau_d$ up to 7 ms and pulse repetition rate $\nu$ up to 2 Hz. The high-voltage source provides DC voltage $U_a$ to the accelerating gap up to 10 kV. Compression (focusing) of the pulsed electron beam 12 is effected by the magnetic field produced by two coaxially located coils (No. 1 and No. 2) 13 and 14. The optimal location of the focusing coils was determined empirically; coil No. 1 is located at a distance of 7 cm from the extractor and provides a magnetic field $B_1$ up to 0.7 mT, and coil No. 2 is located a distance of 16 cm from the extractor and provides a magnetic field $B_2$ up to 5.5 mT.
Measurement of the discharge current $I_d$ and emission current $I_e$ was by current transformers. The current $I_b$ of the electron beam was measured by Faraday cup 15 and by a current transformer. The DC voltage $U_a$ on the accelerating gap was measured by a high-voltage probe type TESTEC HVP-15HF. To measure the average current density $j_e$ on the axis of the electron beam, a small Faraday cup 16 enclosed in grounded protective shield 17 with a collimating orifice of diameter 3.5 mm was used. The distribution of energy density $J_e$ over the cross-section of the electron beam was measured using a thermal imaging method [19]. A stainless steel plate 18 with thickness 1.5 mm was installed on the beam propagation path. The choice of plate thickness and material is determined by a compromise between the resolution of the thermal imaging method and the rate of destruction of the plate by the electron beam. To prevent rapid destruction of the plate by the beam, the pulse duration was limited to 1 ms and the pulse repetition rate to 0.05 Hz. The back side (not irradiated by the e-beam) of the plate 18 was coated with a high-temperature black paint with greyness coefficient about 0.95. Thermal radiation 19 from the plate was observed using an infrared (IR) silver mirror 20 and an IR-transparent glass window 21. The temperature distribution on the metal plate (thermogram) was recorded by a thermal imager (Fluke 200Ti) 22. The thermal imager worked in video mode at 9 frames per second, and the e-beam thermogram was obtained by subtracting the background thermogram (before irradiation) from the thermogram recorded after the plate was irradiated by the electron beam.
3. Experimental results and discussion
The pulse shapes of the arc discharge current $I_d$, emission current $I_e$ and beam current $I_b$ during generation of the electron beam focused by the magnetic fields are close to rectangular (figure 2). Figure 3 shows the dependence of the beam current $I_b$ on accelerating voltage $U_a$ (the current-voltage characteristic of the electron source) for different gas pressures. When the pulsed electron beam is compressed by the magnetic field, the dependence of the current $I_b$ on the voltage $U_a$ has a classic shape typical for plasma-cathode electron sources. The pulse duration $\tau_d$ does not have any significant influence on the shape of the current-voltage characteristic. Increase in the gas pressure $p$ leads to increase in the emission current $I_e$ and, accordingly, in the beam current $I_b$. The influence of gas pressure on electron emission, as for e-beam generation in the forevacuum pressure range without magnetic fields, is mainly caused by the “switching” of discharge current to emission current [20]. In the forevacuum pressure range, this effect is induced by back-streaming ion flow from downstream beam-produced plasma [21].

![Figure 2. Typical pulse shapes of discharge current $I_d$, emission current $I_e$ and beam current $I_b$.](image1)

![Figure 3. Dependence of beam current $I_b$ on accelerating voltage $U_a$ (current-voltage characteristic of the plasma-cathode electron source) at arc current $I_d = 25$ A and different N$_2$ pressures: 1 – $p = 4$ Pa, 2 – $p = 5$ Pa, 3 – $p = 8$ Pa.](image2)
The configuration of the discharge gap of the plasma-cathode source ensures generation of emission plasma with a density distribution close to normal (Gaussian) in the electron extraction region. This in turn ensures the formation of a pulsed electron beam with current density distribution over the beam cross section that is also close to normal (Gaussian) in the absence of external magnetic fields. The external magnetic fields, created by coils No. 1 and No. 2, provide compression (focusing) of the millisecond electron beam in the beam propagation region. Increase in the magnetic field, as expected, leads to increased beam compression, which increases the on-axis current density $j_e$. At fixed distance $L$ from the extractor when the magnetic fields $B_1$ and $B_2$ exceed some optimal values, depending on the emission current $I_e$, the accelerating voltage $U_a$ and gas pressure, further increase in $B_1$ and $B_2$ leads to a decrease in the current density $j_e$ of the electron beam (figure 4). This decrease is due to beam crossover (focus) then occurring closer to the accelerating electrode (extractor) of the electron source.

**Figure 4.** Dependence of the electron beam current density $j_e$ on the magnetic field $B_2$ for $U_a = 8$ kV, $p = 4$ Pa (N$_2$), $I_e = 18$ A, $B_1 = 0.36$ mT.

For constant emission current ($I_e = \text{const}$), increased gas pressure $p$ leads first to increased current density $j_e$ of the electron beam, but when some maximum value is reached, further increase in gas pressure $p$ leads to a decrease in current density $j_e$ (figure 5). This decrease of beam current density is due to the movement of the beam crossover. The use of working gas with greater ionization cross-section (for example, Ar) provides stronger beam compression (greater $j_e$) at lower gas pressure (figure 5a). At fixed distance $L$ from the extractor and constant magnetic fields $B_1$ and $B_2$, the value of the optimum pressure $p$ which provides maximum beam current density $j_e$, depends on the emission current $I_e$, the accelerating voltage $U_a$ and the type of gas. The influence of the type of gas and gas pressure on the compression (focusing) of the pulsed beam is apparently caused by the interaction of the electron beam with the beam-produced plasma. The influence of the beam-produced plasma is confirmed by the fact that for gas with greater ionization cross-section, i.e. for the case of denser beam-produced plasma, a greater beam current density $j_e$ is achieved at lower pressure $p$. However, the use of working gases with greater ionization cross-section leads to a decrease in the maximum operating pressure $p_{\text{max}}$ for which stable generation (without breakdown of the accelerating gap) of the focused electron beam occurs. The use of helium (a gas with low ionization cross-section) ensures stable generation of the focused electron beam over the pressure range investigated, $p = 3$–30 Pa (figure 5b). The influence of plasma, including beam-produced plasma, on the propagation and compression of electron beams was also observed in the more-traditional (lower) pressure range [22–24]. Depending on the electrode configuration of the electron source, beam parameters (current density, electron energy) and gas pressure, the presence of plasma in the beam propagation region can lead to both compression (focusing) or defocusing (dissipation) of the beam [22–24]. An increase of
the emission current $I_e$ leads to additional compression of the e-beam and causes movement of the beam crossover closer to the extractor, which is caused by the self-magnetic field of the electron beam. Changing the magnetic fields $B_1$ and $B_2$ provides control of the current density $j_e$ of the millisecond beam at a chosen distance $L$ from the source extractor.

Figure 5. Dependence of electron beam current density $j_e$ on pressure $p$ for different working gases for distance from the extractor $L = 35$ cm, $B_1 = 0.46$ mT, $B_2 = 3.6$ mT, $I_e = 18$ A, $U_a = 8$ kV.

Figure 6 shows the radial distribution of energy density $J_e$ of the pulsed electron beam. Variation of the magnetic fields $B_1$ and $B_2$ provides control of the diameter of the electron beam and the position of the beam crossover. Figure 7 shows imprints of the pulsed electron beam with millisecond pulse duration on a stainless steel plate of thickness 1.5 mm. For pulse duration $\tau_d = 4$ ms and an emission current of $I_e = 20$ A, 7 pulses are enough to pierce the plate (figure 7b). The electrode configuration of our plasma-cathode source and focusing system afford generation of a pulsed high-current electron beam with diameter 10–12 mm (at half-maximum, FWHM). Compared with the current density (energy) directly behind the extractor, the two-coil focusing system provides increased current density and, accordingly, electron beam energy density greater by a factor of 18–20 at distances from the extractor $L$ up to 40 cm. The current density $j_e$ reaches 15 A·cm$^{-2}$ with pulse duration up to $\tau_d = 7$ ms.

Figure 6. Radial distribution of electron beam energy density $J_e$ for $U_a = 8$ kV, $I_e = 18$ A for different magnetic fields: 1 – $B_1 = 0.36$ mT, $B_2 = 1$ mT; 2 – $B_1 = 0.36$ mT, $B_2 = 5$ mT.
The millisecond pulse duration focused electron beam was used for evaporation of high-temperature alumina and zirconia ceramic targets in the forevacuum pressure range. Figure 8 shows the dependence of the average mass \( m_c \) of alumina ceramic evaporated by the beam per pulse on pulse duration \( \tau_d \). Increase of the pulse duration \( \tau_d \) leads to increased mass removed \( m_c \). However, at an emission current \( I_e = 18 \) A or greater, for pulse duration \( \tau_d > 6 \) ms, the ceramic evaporation is accompanied by the formation of large droplets and fragments of the ceramic target; i.e. exposure of the ceramic to electron beam irradiation then leads to thermal explosion.

**Figure 7.** Imprint of the electron beam on the stainless steel plate of thickness 1.5 mm, for \( I_e = 20 \) A, \( U_a = 9 \) kV, \( \tau_d = 4 \) ms, \( B_1 = 0.36 \) mT, \( B_2 = 5 \) mT: (a) – 1 pulse, (b) – 7 pulses. Ruler scale is millimeters.

**Figure 8.** Dependence of the average ceramic mass \( m_c \) evaporated per pulse on pulse duration \( \tau_d \), for \( I_e = 18 \) A, \( U_a = 9 \) kV, \( p = 6 \) Pa, \( B_1 = 0.46 \) mT, \( B_2 = 5 \) mT.

### 4. Conclusion

The features of a magnetically-compressed (focused) low-energy (up to 10 keV) electron beam with pulse duration up to 7 ms in the forevacuum pressure range 4–30 Pa have been explored. The beam current density is up to 15 A-cm\(^{-2}\). The focusing system consisting of two coaxially arranged coils provides effective compression of the electron beam in the beam propagation region. Magnetic field variation allows control of the electron beam current density and the position of the beam crossover. At constant emission current, accelerating voltage and magnetic field, the gas pressure and type of gas
affect the focusing of the electron beam. Increase in gas pressure leads first to increased beam current density, but after a certain optimum value is reached, further increase in pressure leads to decrease in current density. The use of gas with greater ionization cross-section provides stronger compression of the beam at lower gas pressure, but reduces the maximum operating pressure of the plasma-cathode electron source. Use of the focused, pulsed electron beam for evaporation of high-temperature ceramic targets in the forevacuum pressure range was demonstrated.

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