Profile formation of emission current of grid plasma cathode in a longitudinal magnetic field

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Abstract. The paper presents a gas discharge system for a grid plasma cathode which provides the generation and transport of an intense pulsed (20–250 µs) electron beam with an energy of up to 25 keV and current of up to 500 A (against its nominal value of 300 A) in a longitudinal magnetic field of 20–50 mT. The main feature of the plasma-cathode discharge system is its stable operation with no discharge constriction in an inhomogeneous magnetic field (5–30 mT) which penetrates in the system from the beam transport region. The system shows stable initiation and operation of its main discharge without current cutoffs at an argon pressure of (2–8) × 10⁻² Pa, which has been attained by optimizing the geometry of its electrodes as well as the position and orientation of its permanent magnets. When transported in a magnetic field, the beam current reaches its maximum at the beam center. For controlling the cross-sectional beam homogeneity, the initial distribution of the emission current from the plasma cathode is varied by varying the magnetic field penetrating in the discharge system and the current flow at its redistributing electrode. Such corrections of the initial current from the cathode provides a more homogeneous (±10%) energy distribution over the beam cross-section after transport to a distance of 300 mm.

1. Introduction
Intense electron beams find application in various fields of science and technology such as electron beam welding, heat treatment, generation of high-power electromagnetic radiation (from X rays to microwaves), high-temperature plasma heating for controlled thermonuclear fusion, and pulsed electron beam surface modification. It is often required that intense electron beams, in particular low-energy ones, be transported in a guide magnetic field of tens to hundreds of milliteslas and even several teslas, as in MHD flow control and electron beam plasma heating. For such transport of an electron beam, its source is completely immersed in a magnetic field or the beam is injected into an increasing magnetic field which can penetrate in the electron source from the beam transport region.

Depending on the use of electron beams, they can be formed by electron guns based on thermionic [1, 2], explosive emission [2–7], and plasma cathodes [1, 2, 7–18]. In electron sources immersed in a strong magnetic field, these are normally thermionic and explosive emission cathodes. The use of a plasma cathode in such sources is problematic because of the strong effect of a magnetic field on gas discharges which produce emission plasmas. The major problem is that the magnetic field disturbs the discharge current homogeneity in the region of a plasma emission boundary, which is particularly adverse when the electron component of the discharge current is distributed over small cathode areas, as in arc discharges with cathode spots. The presence of a longitudinal magnetic field can result in...
current filaments operating lengthwise the field lines. For example, in experiments [12], ribbon beams with a pulse duration of up to 100 µs, current of up to 40 A, and energy of up to 10 keV were generated using a plasma-cathode electron source based on a multi-arc low-pressure discharge at a magnetic field of 0.1–0.35 T. With six cathodes in the source, a beam comprising six hardly overlapping beams was extracted through an emission grid of 15×65 mm². The experiments suggested that for better cross-sectional homogeneity of the beam current, one should either increase the number of cathodes in the discharge system or decrease the magnetic field.

Another method to improve the discharge current density distribution at the emission grid of a plasma-cathode electron source was proposed elsewhere [13]. With a magnetic field of no more than 35 mT in its discharge system, the current density distribution was controlled by switching the discharge to multichannel operation with a proper channel diameter and relative position. Such a system was used in an electron source for producing a ribbon beam with an aperture of ~ 4×60 mm, pulse duration of 200 µs, current of 300 A, and energy of 15–20 keV [14].

Here we describe a plasma cathode with a single-channel low-pressure arc discharge system for producing an electron beam of initial diameter up to 50 mm. The discharge system is equipped with an additional electrode which allows one to increase the initial beam diameter and to control the current density distribution over the beam cross section by varying the external magnetic field penetrated in the plasma cathode.

2. Experimental setup

The electron source was based on a grid plasma cathode [17, 18] with a modified two-stage gas discharge system (figure 1). First, a trigger discharge with a current amplitude $I_{tr} = 14$ A is ignited in the circuit of anode 2 by power supply $U_{tr}$ with a no-load voltage of $\approx 12$ kV. Within 10 µs after its ignition, a main arc discharge is initiated by power supply $U_d$. The arc discharge, showing cathode spots mostly at Mg insert 4 (inner diameter $D_{in} = 10$ mm, length $L = 35$ mm), takes its path through channel 6 ($D = 10$ mm, $L = 12$ mm) to emission grid 10 ($D = 50$ mm) and partly through resistance $R_a$ to anode insert 7 ($D = 80$ mm, $L = 80$ mm). The discharge current density over the emission grid surface is corrected by redistributing electrode 9 ($S = 0.5$ mm, $D_r = 15–40$ mm). The electrons extracted through the emission grid (mesh size 0.15 mm, transparency 40–50 %) are accelerated by the field of grounded electrode 11, and after gas ionization in the beam drift space, by the electric field between the emission grid and plasma anode boundary. High-voltage power supply 14 provides an accelerating voltage of up to 25 kV. The gas (Ar) pressure in the vacuum chamber is $p = (2–8)\times10^{-2}$ Pa. The pressure is controlled by varying the gas flow rate to the plasma-cathode discharge system. The discharge current amplitude $I_d$, ranging from 20 to 500 A, determines the beam current amplitude $I_b$. The electron beam is transported to collector 13, spaced by 300 mm from emission grid 10, in longitudinal magnetic fields $B_1$ and $B_2$ produced by solenoids 15 and 16, respectively.

3. Results and discussion

The plasma-cathode discharge system was designed to extend the range of discharge and beam currents $I_d$, $I_b$. Initially, the diameter of its cathode insert 4 and cathode channel 6 was $D = 6$ mm, allowing long-term stable operation with discharge currents of up to $\approx 200$ A. Increasing the maximum discharge current to $\approx 500$ A required that the diameter of the two elements be no less than 10 mm. However, while the system with this diameter provided stable discharge operation with no current cutoff, the discharge ignition was impaired due to a decrease in the pressure in the trigger discharge region. The problem was solved by equipping the system with additional permanent magnets 3, 5 and electrode 2. The best conditions for stable arc ignition are attained when the axial field of magnets 1, 3 is oriented in one direction, and that of magnets 3, 5 in the opposite one. Besides, the axial field of magnet 5 should coincide in direction with the field of solenoids 14, 15.
Figure 1. Experimental setup: 1, 3, 5 – permanent magnets (0.1 T), 2 – trigger discharge anode, 4 – Mg cathode insert, 6 – cathode channel, 7 – anode insert, 8 – main discharge anode, 9 – redistributing electrode, 10 – emission grid, 11 – drift tube, 12 – magnetic screen, 13 – collector, 14 – high-voltage power supply, 15, 16 – solenoids. \( U_{tr} \) – trigger discharge power supply, \( U_d \) – arc power supply.

Figure 2 shows the trigger discharge voltage \( U_{tr} \) versus the pressure in the vacuum chamber \( p \). The trigger discharge is ignited beginning with \( p \approx 2 \times 10^{-3} \) Pa. The main arc discharge is ignited at much higher pressure but its ignition is stable throughout the operating pressure range of the electron source. This range is bounded below by the pressure in the plasma-cathode discharge system sufficient for the ignition of a main arc discharge and by the conditions of the formation of a plasma in the beam transport channel and plasma anode of the high-voltage diode. Its upper bound is determined by breakdowns of the acceleration gap. Figure 3 shows typical waveforms of the trigger discharge and arc currents \( I_{tr}, I_d \) and arc voltage \( U_d \) at \( I_d = 500 \) A.

The use of magnets 3, 5 in the cathode unit provides more stable attachment of cathode spots to the inner surface of Mg insert 4 and more stable operation of the discharge due to additional gas ionization in cathode channel 6 and its adjacent discharge region. This result becomes particularly important with increasing the discharge current because the discharge operating voltage with a hollow cathode is higher than that with a plane one. In case of discharge current cutoffs, new cathode spots may arise on the outer side of the cathode unit and if a magnetic field along with them is present in the discharge system, the emission plasma can lose its axial homogeneity. Besides, if the discharge voltage is decreased to \( U_d \approx 20 \) V or the discharge current takes the path around the emission grid, a decrease in the emission plasma density is possible and so is a change in the grid stabilization of its boundary. In several experiments, the emission current dropped to 50% in response to such changes in the discharge operation.

Figure 2. Trigger discharge voltage \( U_{tr} \) vs vacuum chamber pressure \( p \).

Figure 3. Trigger discharge and arc currents \( I_{tr}, I_d \) and arc voltage \( U_d \). Scale: 40 V/div, 10 A/div (\( I_d \)), 100 A/div (\( I_d \)), 50 \( \mu \)s/div.

The discharge stability allowed the use of a large redistributing electrode in the system to mitigate the problem of limited initial beam diameters typical of single-channel plasma-cathode discharge systems operating in a magnetic field. Figure 4 shows the energy density distributions over the beam...
cross section in the system with a redistributing electrode of diameter $D_r = 15$ mm (figure 1, electrode 9). The energy density was measured per beam current pulse by heat sensors located with a step of 7 mm downstream of holes of diameter 3 mm. It is seen that the initial distribution (measured at $\approx 6$ mm from the emission grid) depends strongly on the magnetic field. Noteworthy also is that the diameter of the emitted beam is much smaller than the grid diameter. The relative distributions of $J/J_{\text{max}}$ for $D_r = 25$ mm in figure 5 demonstrate an increase in the initial beam diameter with the possibility to efficiently control the distribution by varying the magnetic field in the plasma cathode.

The change in the profile of an intense low-energy electron beam during transport in a magnetic field necessitates that the initial current density from the emission grid has its minimum in the grid center to provide the most homogeneous final state of the beam after its transport to the collector. Such a distribution of the initial beam and its maximum final diameter at the collector can be attained by using a redistributing electrode comparable in size to the emission grid ($D_r = 40$ mm).

Figure 6 shows the relative energy density distributions at the collector with a redistributing electrode of diameter 40 mm for different magnetic fields. The data in the figure demonstrates the possibility to provide a homogeneous energy distribution by slightly varying the field of solenoid $B_1$ (curves 1, 2) and to efficiently focus the beam (curve 3). The magnetic screen (figure 1, screen 12), which decreases the on-axis magnetic field in the emission grid region by a factor of $\approx 1.8$, can serve for addition distribution correction when it is needed to increase the field for beam transport.

**Figure 4.** Initial distributions of energy density $J$ over beam cross section at $D_r = 15$ mm, $I_d = 200$ A, $U = 8$ kV for $B_1 = B_2 = 15$ mT (1) and $B_1 = B_2 = 50$ mT (2).

**Figure 5.** Initial distributions of $J/J_{\text{max}}$ at $D_r = 25$ mm, $I_d = 200$ A, $U = 10$ kV for $B_1 = 7$ mT, $B_2 = 14$ mT (1), $B_1 = B_2 = 14$ mT (2), $B_1 = B_2 = 30$ mT (3), and $B_1 = B_2 = 50$ mT (4).

**Figure 6.** Relative distributions of $J/J_{\text{max}}$ at collector at $D_r = 40$ mm, $I_d = 250$ A, $U = 12$ kV for $B_1 = 65$ mT, $B_2 = 14$ mT (1), $B_1 = 60$ mT, $B_2 = 14$ mT (2), and $B_1 = 20$ mT, $B_2 = 55$ mT (3).

**Figure 7.** Currents $I_d$ (2, 4) and $I_b$ (1, 3) in modes with nominal (1, 2) and maximum beam currents (3, 4). Scale: 100 A/div, 50 $\mu$s/div.
From the oscillograms of \( I_b \) and \( I_c \) in figure 7 it is seen that in the mode of electron beam generation, the beam current \( I_b \) becomes unstable when it goes above \( \approx 300 \) A, which is likely due to oscillations of the boundary of the plasma anode formed by the electron beam.

4. Conclusion

The proposed plasma-cathode gas discharge system based on a single-channel low-pressure arc in an inhomogeneous magnetic field of up to 30 mT provides the generation of a pulsed (20–250 µs) electron beam with a current amplitude of up to 500 A at an accelerating voltage of 5–25 kV. The initial beam diameter is \( \approx 50 \) mm.

The discharge system, which is equipped with an additional redistributing electrode of relatively large diameter \( (D_r = 40 \) mm), allows one to control the cross-sectional energy density distribution of the electron beam emitted from the plasma cathode by varying the magnetic field which penetrates in the plasma cathode.

The diameter of the beam transported to a distance of 300 mm is 35 mm with a cross-sectional energy density nonuniform to \( \pm 10\% \) of its average value.

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