The reaction of arc discharge parameters to the selection of electrons from the emission plasma in an electron accelerator with a grid plasma cathode

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Abstract. In the electrode system of an electron source with a plasma cathode, which allows the generation of a pulse-periodic electron beam of a large cross section from vacuum to the atmosphere through the outlet foil window, investigations have been made of the effect of electron extraction from the emission plasma on the parameters of a low-pressure arc discharge in which this plasma is generated. The work of the plasma cathode in different modes of electron beam generation is compared, namely, with the use of both a wide-aperture two-electrode electron-optical system (EOS) characterized by high beam current losses on the ribs of the support grid and a multi-aperture two-electrode EOS, when a metal mask is installed on the emission mesh with a configuration of holes that repeats the configuration of the holes in the support grid, and the electron beam is a superposition of electron beamlets formed by separate emission structures, the plasma boundary of which is also stabilized by a fine-structure metal mesh. Under the experimental conditions, the selection of electrons from the emission plasma leads to an increase in the voltage in the interelectrode gap between the cathode and the hollow anode of the plasma emitter, whose "voltage-addition" depends on the conditions of generation of the emission plasma (pressure and type of working gas, the ratio of the anode area of the discharge to the emission area), the area of the emission structures and the cell size of the used emission grid.

1. Introduction
Among the various applications of electron beams, their use for electron irradiation of large surfaces of solids and significant gas volumes occupies a separate place [1-6]. At the same time, interest in this subject continues to grow, and to solve such problems, reliable and durable electron accelerators with stable parameters are still required. One of the most important elements of any source of charged particles is the type of cathode used which in many respects determines its design features, functional capabilities and performance characteristics. Plasma cathodes can be an alternative to thermo- [7, 8] and explosion-emission cathodes [9, 10]. It was shown in [11, 12] that the use of a multi-aperture two-electrode electron-optical system in accelerators with a grid plasma cathode at an accelerating voltage of 200 kV makes it possible to achieve beam efficiency of about 80% and to output into the atmosphere an electron beam with a cross section of 750×150 mm² average power of about 4 kW. It is possible to control the main beam parameters in accelerators based on a grid plasma cathode independently of one another in a wide range, which is difficult to realize or impossible in electron...
accelerators based on other types of emitters. However, a further increase in the average beam power by an increase in any of the beam parameters in practice is limited by the occurrence of an electrical breakdown of the high-voltage accelerating gap. In this case, the nature of the electrical breakdown with an increase in the magnitude of the accelerating voltage can be significantly different from the nature of the electric breakdown, for example, with the growth of the emission current or the beam pulse duration.

It should be noted that the presence of several mechanisms of electrical breakdowns [13–18] does not mean that electron guns with a plasma cathode are not capable of stably generating beams, but only shows the need to investigate the emission capacity of such cathodes and the mechanisms of electrical breakdowns of the accelerating gap for the further development of accelerator technology.

2. Experimental setup
The investigations were carried out on a modernized pulsed wide-aperture electron accelerator "DUET" [11] with a grid plasma cathode (figure 1). The plasma cathode of the accelerator is a hollow half-cylinder of stainless steel, on the ends of which two cathode assemblies on the basis of a low-pressure arc discharge are fixed [19]. Initiation of the cathode spot in this case occurs as a result of a "direct" electric breakdown in the gas, which excludes the intermediate electrodes and insulators needed to initiate the cathode spot and are subject to dusting by the cathode material. When a high voltage pulse of amplitude $\approx 3$ kV is applied from the transformer TV (figure 1) between a hollow cathode 3 and an igniting electrode 4 (hollow anode for a given discharge system) in a gas introduced through a hole in the ignition electrode, glow discharge is ignited. Since the power circuit of this cell is made without stabilizing the discharge current, this leads to an increase in the current density at the cathode and the initiation of a cathode spot on its internal surface. In this case, a sharp decrease in the burning voltage of the discharge is observed, and the glow discharge passes into a different stage of burning – the arc with a cathode spot.

![Figure 1. The scheme of the electron accelerator "DUET"](image)

After initiation of the cathode spot, using sources of main discharge $E_1$ and $E_2$ power supply having an inductive output, and in fact are current sources, the discharge is burned between the hollow cathode 3 and the hollow anode 1 and the emission grid 5, necessary for stabilizing the emission of the plasma boundary, generated by this discharge. To switch the discharge current toward the emission
grid 5 in the hollow anode circuit I sets the resistance of \( R_{HA} \) that is primarily needed to improve the efficiency of electron extraction from the emission plasma in the accelerating gap.

Under the action of a constant accelerating voltage of up to \( U_0=200 \text{ kV} \), provided by a capacitor bank \( (C=0.26 \mu \text{F}) \) and applied between the plasma cathode and the accelerating electrode 6, the distance between which is \( d=200 \text{ mm} \), through the cells of the emission grid electrons are selected and their acceleration is up to an energy corresponding to the applied accelerating voltage. Size mesh of emission grid is varied in the range \( h=(0.4÷1) \text{ mm} \). To study the emission capacity of a grid plasma cathode when operating in a two-electrode multi-aperture electron-optical system (EOS) [11], a metallic mask (not shown in figure 1) was perforated with round holes with diameter of 12 mm, which is welded to the emission grid by spot welding. The configuration of the holes in the mask repeats the configuration of the holes in a support grid of the output foil window (it is installed instead of the electrode 6 and in figure 1 it is not indicated). The support grid of the output foil window has a total geometric transparency of 56% and has the same number of coaxial holes as in the mask, but a slightly larger diameter equal to 15 mm. The foil 8 of aluminum-magnesium alloy AMg-2n with a thickness of 30 \( \mu \text{m} \) is placed on the support grid. When a multi-aperture EOS is used, a wide electron beam represents a superposition of elementary beams formed by separate emission structures whose plasma boundary is stabilized by a fine-structure metallic grid.

By installing additional loops with a high-voltage decoupling from ground potential in the power supply circuit and using the Rogowski coil, it is possible to measure the following currents: the currents in the cathode circuit \( I_{c1} \) and \( I_{c2} \), the total current in the hollow anode circuit \( I_{HA} \), the total discharge current \( I_d=(I_{c1}+I_{c2}) \), the voltage \( U_d \), and the current in the accelerating gap \( I_0 \). It is important to note that this solution makes it possible to measure these currents and voltages both in the absence of accelerating voltage and in its presence.

3. Results
In the absence of an accelerating voltage, as the resistance \( R \) is increased, the value of the current on the hollow anode \( I_{HA} \) decreases (figure 2a), which allows switching the discharge current toward the emission electrode area and thereby increasing the extraction coefficient \( \alpha=I_0/I_d \) of electrons from the plasma cathode into the accelerating gap. However, as can be seen from figure 3a, the introduction of resistance \( R \) leads to an increase in the voltage \( U_d \), which is most likely due to a decrease in the effective anode area of the main discharge. It can be seen from figure 2b that when the anode area is enlarged (by installing a mask), the current \( I_{HA} \) is close to the values obtained in experiments without a mask, and the voltage \( U_d \) in this case increases (figure 3b).

![Figure 2](image_url)

Figure 2. Dependence of the current on the hollow anode \( I_{HA} \) on the discharge current \( I_d \) for various resistances in the circuit of the hollow anode \( R \): 1 – \( R=0 \) Ohm; 2 – 1 Ohm; 3 – 5 Ohm; 4 – 10 Ohm.

The experimental conditions: \( p=40 \text{ mPa (Ar)} \), \( U_0=0 \text{ kV} \), \( h=0.4 \text{ mm} \):

- a – without mask, b – with the mask.
When the working gas pressure increases (figure 5), the extraction coefficient $\alpha$ is reduced (curves 1, 2), which is connected with the switching of the discharge current to the area of the hollow anode $I$ of the discharge, i.e. an increase in the current $I_{HA}$ (curves 3, 4). Also from figure 5 it can be seen that when the pressure increases, the increase in the voltage $U_d$ (curves 5, 6) occurs, which may be due to additional energy losses for ionization of the working gas.

![Figure 3](image3.png)

**Figure 3.** Dependences of the discharge voltage $U_d$ on the discharge current $I_d$ for various resistances in the hollow anode circuit in experiments with $h=0.4$ mm and the mask (a) and for different electron-optical systems (b): 1 – $h=1$ mm with the mask; 2 – $h=0.4$ mm with the mask; 3 – $h=0.4$ mm without mask. Experimental conditions: $p=40$ mPa, $U_0=0$ kV, $R=10$ Ohm.

![Figure 4](image4.png)

**Figure 4.** Dependence of the extraction coefficient $\alpha$ (1, 3) and the voltage $U_d$ (2, 4) on the accelerating voltage $U_0$. The experimental conditions: $R=5$ Ohm, $h=0.4$ mm with the mask: $p=40$ mPa. 1, 2 – $I_d=30$ A; 3, 4 – $I_d=10$ A.

![Figure 5](image5.png)

**Figure 5.** Dependence of the extraction coefficient $\alpha$ (1, 2), the current on the hollow anode $I_{HA}$ (3, 4) and the voltage $U_d$ (5, 6) on the accelerating voltage $U_0$ at different pressures of the working gas. Experimental conditions: $R=10$ Ohm, $I_d=50$ A, $h=0.4$ mm with the mask: 1, 4, 6 – $p=40$ mPa; 2, 3, 5 – $p=70$ mPa.

As noted earlier, regardless of the type of electron-optical system used in experiments in the presence of the accelerating voltage, the increase in the voltage $U_d$ occurs. However, when the discharge current was switched from the hollow anode to the emission electrode area, a decrease in the voltage $U_d$ was observed (figure 6). For example, in experiments without a mask with a grid mesh of
\( h = 0.4 \text{ mm at } U_0 > 0 \), the voltage \( U_d \) increased from 63 V to \( \approx 130 \text{ V} \), and when a resistance \( R = 10 \Omega \) was introduced into the circuit of the hollow anode, a decrease in the interelectrode voltage to \( U_d = 120 \text{ V} \) was observed. The decrease in the voltage \( U_d \) can be associated with an increase in the concentration of the emission plasma near the grid, a change in the position of the boundary of this plasma and, accordingly, with a change in the shape of the electric field in the grid meshes, that is, determined by the contribution of the serial connection of two power supplies: discharge and accelerating.

![Figure 6](image_url)

**Figure 6.** Dependence of the voltage \( U_d \) on the extraction coefficient \( \alpha \). Experimental conditions: \( I_d = 30 \text{ A}, p = 40 \text{ mPa}, U_0 = 20 \text{ kV (1)} \) and 100 kV (2) \( R = 0, 10 \Omega \); I – \( h = 0.4 \text{ mm with the mask (} U_{d0} = 81 \text{ V}) \); II – \( h = 1 \text{ mm with the mask (} U_{d0} = 83 \text{ V} \)); III – \( h = 0.4 \text{ mm without mask (} U_{d0} = 63 \text{ V}) \).

4. Conclusion
The carried out researches confirm the results obtained earlier on the influence of the processes occurring in the accelerating gap on the operation of the grid plasma cathode. Thus, when selecting electrons from the emission plasma it can be seen a sharp increase in the interelectrode voltage \( U_d \), presumably due to a decrease in the concentration of this plasma, can be observed. In this case, when the discharge is switched from the hollow anode to the emission electrode area, a certain decrease in the voltage \( U_d \) can be observed, however, in this mode of operation, the grid (layer) stabilization of the emission plasma can be violated, which can lead to an electric breakdown of the high-voltage accelerating gap. To reduce this effect, it is best to use emission grids with a smaller mesh size of the emission grid, which, however, leads to a decrease in the extraction coefficient \( \alpha \), and, correspondingly, to an additional current load on the cathode units decreasing their life.

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