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Investigation of the stability of the electron source with a multi-aperture plasma emitter generating a large cross-section electron beam

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Abstract. An experiment was performed to investigate the electric strength of the high-voltage acceleration gap of an electron source with a multi-aperture plasma emitter generating a beam of large cross section (750 × 150 mm^2) extracted into the atmosphere through a thin metal foil. It has been shown that the use of a mask in the plasma emitter which partitions the overall emission region to produce a plurality of small-cross-section beamlets, so that the extracted beam is a superposition of beamlets formed by individual emission units whose plasma boundary is stabilized by a fine metal grid, increases the electric strength of the high-voltage acceleration gap. This is of critical importance in cases where the electron source is operated in a repetitive pulse mode at high average power of the beam. In addition, an increase in the electric strength of the acceleration gap is promoted by that the modernized cathode assemblies of the plasma emitter are arranged normal to the axis along which electrons are extracted into the acceleration gap.

1. Introduction

Increasing the electric strength of the acceleration gap in high-voltage electron sources is one of the main problems that must be solved in designing and using systems of this type [1–3]. It is well known that the use of plasma emitters where electrons are emitted only from certain sites bounded with an emission grid increases and stabilizes the parameters of the generated beam [4–7]. In systems of this type, called multi-aperture electron sources, large- cross-section beams are generated due to the superposition of individual beamlets, each being generated in the its own acceleration unit consisting of two or more electrodes with coaxial holes. The use of multi-aperture plasma cathodes allows additional stabilization of the plasma emission boundary, thereby providing a wide range of the electron beam parameters [4, 5].

It is also well known that the cathode spot operating on the surface of a cathode causes intense sputtering of the cathode material [8]. This not only leads to a considerable consumption of the cathode but also reduces the electric strength of the high-voltage acceleration gap, as the microdroplets of the molten cathode material, reaching, for instance, the emission grid and settling on it, cause a local increase in electric field, the occurrence of a cathode spot on the grid, and, consequently,

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electrical breakdown of the acceleration gap. The present study was carried out to investigate the electric strength of the high-voltage acceleration gap in an electron source with a multi-aperture plasma cathode in which the emission plasma is generated by a cathode assembly with a screened cathode spot initiated by electrical breakdown in a low-pressure gas.

2. Experimental procedure

The experiment was carried out on DUET, a modernized wide-aperture pulsed electron source with a grid plasma cathode (Fig. 1) capable of producing an electron beam with the following key parameters: an electron energy of up to 200 keV, emission current of up to 50 A, pulse duration of up to 100 μs, pulse repetition rate of 50 s^{-1}, and beam dimensions of 750 mm × 150 mm with the current density distribution over the beam cross section uniform to within ± 15% of the average current density.

It is well known [9] that the arrangement of the cathode assemblies in a plasma emitter normal to the axis along which electrons are extracted increases the electric strength of the high-voltage acceleration gap. This is probably due to a decrease in the number of the cathode material microdroplets formed as a result of the operation of the cathode spot [8] both on the emission grid and in the region of the acceleration gap.

To reduce the number of cathode material microdroplets falling onto the surface of the emission grid, a cathode assembly has been designed, fabricated, and experimentally investigated where the cathode spot is line-of-sight screened from both the hollow anode and the emission grid. The cathode assembly design and operating principle are described in detail elsewhere.

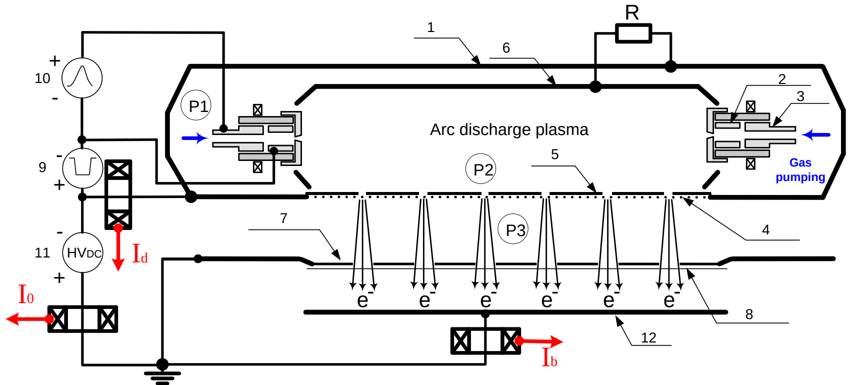

Figure 1. Schematic of a wide-aperture electron source: 1 – hollow anode, 2 – cathode, 3 – igniter electrode, 4 – emission grid, 5 – mask; 6 – screen 7 – support grid of extraction foil window, 8 – extracion foil, 9 - power supply of discharge, 10 – power supply of igniter, 11 – high voltage source, 12 – collector, P1, P2, and P3 – PMI-2 type manometric transducers.

A cathode assembly of this type has a constricting hole providing a pressure difference between the regions of electron beam generation and acceleration. This reduces the gas pressure in the acceleration region and thereby increases the electric strength of the high-voltage acceleration gap. This is especially important when operating the system at high average beam powers under the conditions of desorption of working and residual gases from the high-voltage electrode surfaces. When a metal mask is placed in the emitter, an additional pressure difference between the region of emission plasma generation and the acceleration gap should be attained due to the low geometric transparency of the mask. To check this assumption, three PMI-2 type manometric transducers were placed in the electrode system of the electron source (see Fig. 1): P1 downstream of the plasma emitter, P2 in the plasma emitter, and P3 in the acceleration gap. In the absence of a mask in the emitter, the readings of the transducers were approximately the same. When a mask of total geometric transparency ≈ 13% was placed in the emitter and the working gas pressure in the acceleration gap was 20 mPa, the pressure in the plasma emitter was a factor of 1.5 higher, equal to about 30 mPa. This provided stable operation of the plasma emitter at a slightly reduced working gas flow rate (from Q ≈ 0.1 $\frac{\mathrm{m}^3 Pa}{s}$ without a mask to Q ≈ 0.07 $\frac{\mathrm{m}^3 Pa}{s}$ with a mask). According to preliminary estimates, the stability of operation of the electron source, which is inversely proportional to the number of electrical breakdowns per 1000 beam current pulses, increased in inverse proportion to the geometric transparency of the mask placed in the plasma emitter. Thus, the stability was increased from 2 to 12.

3. Results and discussion

The mechanism of plasma generation in the plasma emitter electrode system is the following: The electrons produced due to the operation of the cathode spot are accelerated in the cathode layer and enter the space of the main discharge hollow anode with an energy roughly corresponding to the discharge voltage. The primary electrons interact with the atoms of the working gas, and the gas is ionized. The area of the anode in this case is much larger than the area of the cathode, and the electrons having higher mobility than the ions produced as a result of ionization of the working gas may arrive at the hollow anode if they have energies high enough to overcome the potential barrier induced by the positive charge of the plasma. Therefore, to maintain a balance of currents, the plasma reacts to the loss of electrons by increasing its potential [3]. This is, among other things, due to the lower potential barrier in the electron extraction region that should be overcome by the electrons when leaving the discharge gap toward the anode. However, the increase in plasma potential relative to the walls of the hollow anode is always limited. For instance, an increased plasma potential can be responsible for the formation of a cathode spot on the hollow anode surface, occurrence of the discharge current high-frequency noise, distortion of the discharge current waveform and amplitude, etc. The cathode spot formed on the hollow anode wall causes a local increase in plasma density and, as a consequence, an uncontrolled increase in discharge current accompanied by an increase in emission current. This, in turn, promotes the breakdown of the high-voltage acceleration gap [12]. It is also well known [12] that the increase in plasma potential can be significantly affected by the high-energy ions entering the plasma emitter from the acceleration gap through the emission grid, whose geometric transparency is always less than unity.

The presence of ions in the acceleration region is evidenced by the autograph of the ion beam left on emission grid 4 (Fig. 2) and on hollow anode 6 (not shown in Fig. 2). This experiment was carried out in the absence of a mask in the emitter. A somewhat smaller autograph of the ion beam on the emission grid and even smaller one on the hollow anode are probably due to the presence of a chamfer at the place of contact of the vacuum chamber with the support grid, causing the ion beam to focus. In this case, the ions can be produced, for instance, by ionization of the gas desorbed from the surfaces of the extraction foil and support grid both by the accelerated beam electrons and by the electrons reflected from the extraction window foil.

In addition, examination of the beam autograph shown in Fig. 2 suggests that each ion beamlet formed in the channel of the extraction window support grid always has a diameter less than the diameter of the holes in the support grid, which, probably, is also due to the focusing of each individual beamlet.

The ions accelerated in the high-voltage acceleration gap and arrived at the emission grid knock out secondary electrons from the grid. The number of these electrons is determined by the cathode material and the energy of the ions [13].

The absence of a mask in the emitter has the result that some portion of the ion flow reaches the emission grid, knocking out secondary electrons in accordance with the coefficient of secondary ion-electron emission. Another portion of the ion flow, determined by the geometric transparency of the emission grid, is injected into the emission plasma and partially reaches the hollow anode of the discharge. This results, first, in an increase in plasma potential and, second, in ejection of secondary electrons from the other electrodes of the plasma emitter, e.g., from hollow anode 6. All this adversely affects the electric strength of the high-voltage acceleration gap and leads to an increase in the potential of the emission plasma, to an uncontrolled increase in the emission current associated with the ion-electron emission, to charging of the dielectric inclusions that are always present on electrodes when a diffusion pump is used, etc. The decrease in electric strength of the high-voltage acceleration gap is accompanied by the loss of one of the main advantages of electron sources with plasma emitters with grid stabilization of the plasma emission boundary, namely the independence of the beam parameters from each other, as in this case, the processes occurring in the acceleration gap affect the processes occurring in the discharge gap.

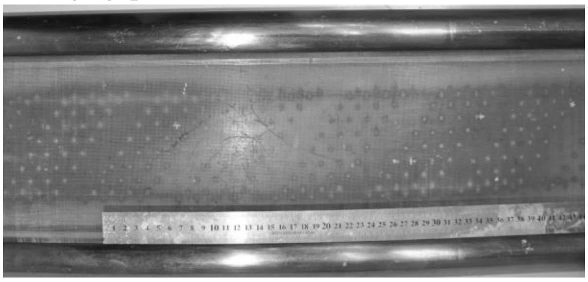

Figure 2. Ion beam autograph left on the emission grid on the side of the high-voltage acceleration gap in the experiment with no mask in the emitter.

Thus, it is of importance that the paths of the primary electrons emitted from the plasma emitter and accelerated mostly normal to the extraction foil window are substantially different from the paths of the desorbed gas ions accelerated, due to focusing, at an angle to the emission grid. Knowing this, one can significantly reduce the ion flow injected into the emission plasma that increases the plasma potential. This can also be achieved by using a low-geometric-transparency mask in the plasma emitter; in the case under consideration, the transparency was ≈ 13% (see Fig. 1). Assume that all electrons emitted into the acceleration gap are extracted into the atmosphere through the foil with no loss of the beam current at the support grid. At the same time, the interaction of the electron beam with the foil results in the occurrence of ions, as evidenced by the beam autograph shown in Fig. 2. However, in view of the geometric transparency of the emission grid equal to ≈ 50%, the total geometric transparency of the emission electrode makes only 7% (with no mask in the emitter, the geometric transparency of the emission electrode is ≈ 50%) and thus almost the entire ion flow is involved in ion-electron emission. This mechanism of electron beam generation makes it possible to significantly reduce the potential of the emission plasma and restore one of the major advantages of the plasma emitter, namely the possibility to control the electron beam parameters independently from each other.

In an experiment on the extraction of a beam from the acceleration gap into the atmosphere, it was shown that at an accelerating voltage U_0 = 200 kW, the beam current extraction efficiency β, which is the ratio of the beam current extracted into the atmosphere, I_b, to the current in the acceleration gap, I_0 ($\beta = I_b/I_0$), was no greater than 0.75. This indirectly confirms the presence of an ionic component in the acceleration gap, which is estimated to make about 10% of the total current in the acceleration gap.

4. Conclusion

The experiments have shown that the electric strength of the high-voltage acceleration gap in an electron source with a wide-aperture plasma emitter operating based on a low-pressure arc can be increased by using cathode assemblies with the cathode spot screened from the line of sight of the hollow anode and emission grid, which reduces the number of cathode material microdroplets, and by using a low-geometric-transparency mask in the emitter, which provides an additional pressure difference between the plasma generation and electron acceleration regions and reduces the potential of the emission plasma at a higher emission current density due to a reduced effect of the high-energy ion beam on the plasma and redistribution of the discharge current in the plasma emitter.

The presence of a mask in the emitter is a condition for stable operation of the electron source. With no mask, the average power of the beam in the acceleration gap was no greater than 3500 W, whereas with a mask placed in the emitter, it could be increased to 6500 W. Further increase in beam power in the experiment with a mask installed in the emitter was limited by the high-voltage power supply.

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