Electron source with a multi-apertured plasma emitter

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Abstract. In the present study, we investigated the energy efficiency of an electron source with a multi-aperture plasma emitter where the generated beam is extracted into the atmosphere through a thin metal foil. The boundary of the plasma produced in this type of emitter is stabilized with a fine metal grid. To prevent the loss of electrons at the circle-holed support grid of the extraction foil window, a metal mask with holes of smaller diameter arranged coaxially to the support grid holes is put on the emission grid. Thus, the electron beam is a superposition of beamlets formed by individual electron emitting units with the plasma boundary stabilized by the fine metal grid. The efficiency of current extraction from the acceleration gap into the atmosphere reached 75% with respect to the gap current, making possible to increase the average power of the extracted electron beam. With a 200-kV accelerating voltage, a 16-A current in the acceleration gap, and 40 μs FWHM pulse duration, 4 kW of the average beam power was extracted into the atmosphere from the acceleration gap. With the geometric transparency of the support grid of the extraction foil window equal to 56%, this made 65% of the beam power in the gap. Further increasing the beam power was limited by the power of the high-voltage power supply.

1. Introduction

The electron sources using cathodes of any type to produce large-cross-section beams extracted into the atmosphere through a foil window are widely used in industry, medicine, environmental protection, processing of agricultural products, etc. [1–4]. With the relatively high average beam power provided by these electron sources, special attention is given to minimization of the loss of electrons both at the support grid of the extraction foil window and in the foil. The foil material is chosen so that, on the one hand, it would have a low density for more current could be extracted at a given beam energy and, on the other hand, it should be as mechanically strong as possible at the smallest thickness.

As the support grid of an extraction foil window typically has a geometric transparency less than 90% and part of the electron beam is dissipated as heat at the grid edges, the large-cross-section electron beam extracted into the atmosphere consists of a plurality of beamlets whose cross-section shape and area are determined by the design of the support grid. Therefore, to reduce the beam current losses at the support grid edges, it is necessary to eliminate the electron flow toward the edges. To do this requires that the large-cross-section beam consist of a plurality of small-cross-section beamlets even upon generation and during acceleration [5–7].

2. Experimental procedure

The wide-aperture electron source used in the experimental study under consideration has a plasma emitter operating based on a low-pressure arc with a grid-stabilized plasma emission boundary. The electron source is capable of generating electron beams of specified structure. Electron sources of this type are rather indifferent to vacuum conditions and feature a long service life, mutually independent basic parameters of the beam, and a reasonably uniform current density distribution over the beam cross section.

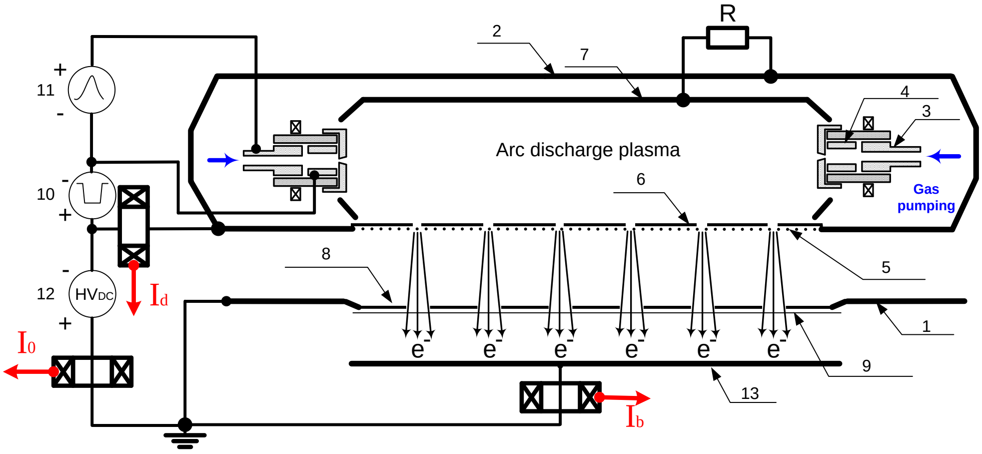

Figure 1. Schematic of the wide-aperture electron source: 1 – vacuum chamber, 2 – plasma emitter, 3 – igniter, 4 – cathode, 5 – emission grid, 6 – mask, 7 – hollow anode, 8 – support grid, 9 – extraction foil, 10 – discharge power supply, 11 – igniter power supply, 12 – high-voltage power supply, and 13 – collector.

Measurements of the efficiency of electron extraction from the plasma emitter into the acceleration gap, α, equal to the ratio of the current flowing through the gap, I_0, to the discharge current I_d ($\alpha = I_0/I_d$) and the efficiency of current extraction from the acceleration gap into the atmosphere, β, equal to the ratio of the extracted beam current I_b to the gap current I_0 ($\beta = I_b/I_0$), were carried out on DUET, a modernized wide-aperture pulsed electron source with a grid plasma cathode (Fig. 1) [8, 9].

The plasma emitter (2) of the source is a hollow stainless-steel half-cylinder of dimensions 750 mm × 150 mm with two low-pressure-arc cathode units (3, 4) fixed on the ends [10]. A stainless-steel mask (6) of thickness 200 μm is put on the emission grid (5), which serves as the anode for the arc. There are 344 round holes of diameter 8–12 mm in the mask, which are individual emission units of the plasma emitter. The hollow anode (7) is electrically connected via a resistor to the emission grid (5), which is necessary to facilitate the discharge ignition, switching, and operation in the region of the emission grid. Electrons are extracted from the plasma surface of the emission units under the action of a dc accelerating voltage of up to 200 kV applied to the 120-mm gap between the emitter (2) and the extraction foil window (8, 9). The aligned holes in support grid 8, having a total geometric transparency of 56%, are of the same number as those in mask 6, but of larger diameter (15 mm). Alignment of the holes in mask 6 and in support grid 8, and thereby attainment of a coaxial plane-parallel geometry of the acceleration gap, minimizes the beam losses in the support grid of the extraction foil window. Thus, the electron beam produced is a superposition of beamlets formed by individual emission units with the plasma boundary stabilized by the fine metal grid. Support grid 8 is covered with 30-μm-thick foil 9 made of AlMg–2n alloy. The beam current Ib extracted from the acceleration gap into the atmosphere was measured in the circuit of a collector (13) of dimensions 800 mm × 200 mm using a Rogowski loop.

3. Results and discussion

When electrons were extracted from the plasma emitter into the acceleration gap using a 0.4 mm × 0.4 mm mesh grid of total geometric transparency 44% in the absence of mask 6, the maximum electron extraction efficiency, $\alpha \approx 0.6$, was achieved with the resistance of the resistor connected in the hollow anode circuit $R \geq 10\ \Omega$ (Fig. 2a). The electron extraction efficiency α also increased with accelerating voltage and discharge current. In the first case, this was due to the penetration of the electric field in the emission grid meshes and to the switching of the discharge current electronic component to the meshes. In the second case, an increase in discharge current, and, hence, plasma density, reduced the thickness of the near-electrode ion layer, which in turn increased the area of the open plasma emission surface and, hence, the extraction efficiency α [10]. As the geometric transparency of the emission grid was lower than the extraction efficiency α, the mechanism of the discharge current switching into the emission grid meshes becomes apparent. This method of current switching was demonstrated to be very efficient, as in this case, the discharge voltage varied slightly (Fig. 2b) and the extraction efficiency increased more than twice (Fig. 2a). Additionally, when a resistor of resistance $R \geq 10\ \Omega$ was connected in the circuit of hollow anode 7, the emission current pulse had a sharper leading edge and a more pronounced flat top.

Figure 3 (curve 1) shows the efficiency of extraction of the beam current from the accelerating gap into the atmosphere, β, as a function of accelerating voltage for the case of no mask in the emitter. It can be seen that the beam extraction efficiency β increases with accelerating voltage. It can be stated that in the absence of the mask, the increase in β with accelerating voltage is only due to the increase in transparency of the foil [11]. Thus, in the investigated range of beam electron energies, the percentage of the current losses at the edges of support grid 8 weakly depends on accelerating voltage. This can be accounted for by the small angular divergence of the generated electron beam associated with the relatively low temperature of the electrons extracted from the plasma emitter. The weak dependence of β on the time point within the pulse duration for which it was determined (see Fig. 3, curve 3) is evidence of the source stable operation throughout the range of beam current pulse durations with a time-invariable efficiency of electron beam extraction into the atmosphere, even supposing that the parameters of the emission plasma varied in time.

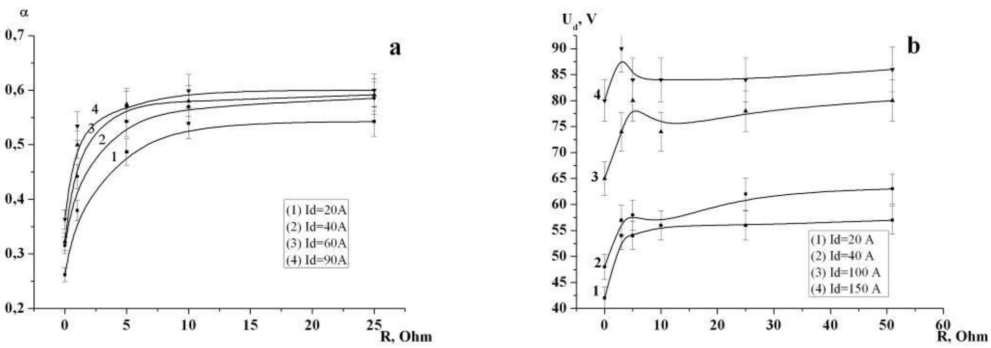

Figure 2. The extraction efficiency αin the absence of a mask at U0 = 160 kV (a) and the discharge voltage Ud (b) as functions of the resistance R of the resistor connected in the hollow anode circuit. An emission grid of mesh size 0.4 mm × 0.4 mm was used.

The data of an experiment on minimization of the electron losses in the support grid of the extraction foil window covered with a mask having 12-mm diameter holes are also plotted in Fig. 3 (curves 2 and 4). In this case, at an accelerating voltage of 200 kV, the current losses in the support grid of the extraction foil window were reduced to 30%. According to the data given in Ref. 12, about 12% of the electron current was lost in 30-μm thick aluminum foil at an accelerating voltage of 200 kV. It can be supposed that the remaining 18% included the losses due to high-energy electrons reflected from the foil and ions produced by the interaction of the reflected electrons with the desorbed gas and the beam losses at the support grid of the extraction foil window due to nonideal alignment of the holes in mask 6 and in support grid 8.

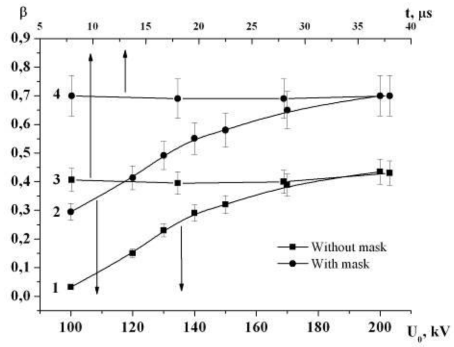

Figure 3. Beam extraction factor β as a function of accelerating voltage and of the time of β determination within the pulse duration. The data were obtained without a mask on the support grid (curves 1, 3) and with a mask having 12-mm dia holes aligned with the support grid 15-mm dia holes (curves 2, 4).

When a metal mask with 12-mm diameter holes and ~30% total geometric transparency was put on the emission grid of mesh size 0.4 mm × 0.4 mm, the extraction efficiency α decreased in direct proportion to the mask geometric transparency to α ≈ 0.6 × 0.3 ≈ 0.2. Using such an emission grid at discharge currents of 10–100 A, a discharge current pulse duration of 40 µs, an acceleration gap spacing of 70–200 mm, and a working gas pressure of 20–60 mPa, we could not obtained the extraction efficiency α greater than the geometric transparency of the mask.

To facilitate the alignment of the holes in the mask and in the plasma emitter support grid, the mask holes were made 8 mm in diameter. Obviously, using a grid with meshes 0.4 mm × 0.4 mm in size and decreasing the mask hole diameter to 8 mm, with the mask geometric transparency equal to about 13%, should reduce the extraction efficiency to α ≈ 0.6 × 0.13 ≈ 0.08 if additional measures are not taken. Therefore, to facilitate the switching of the discharge current to the emission grid meshes, and thereby increase α, the emission grid was replaced by a grid of mesh size 0.6 mm × 0.6 mm.

With the grid of mesh size 0.6 mm × 0.6 mm used in the emitter, but in the absence of a mask, the electron source operation was extremely unstable. When the accelerating voltage was high and a discharge was ignited, a high-frequency (1–2 MHz) modulation occurred on the pulse waveforms of both the discharge and the emission current (Fig. 5a). It was found that the high voltage affected the discharge current waveform and amplitude, the electric strength of the acceleration gap decreased, and the operation of the plasma emitter power supply became unstable to the extent that some components of its electric circuits could fail. Nevertheless, a pronounced increase in extraction efficiency α was observed: at a discharge current I_d = 20 A, an accelerating voltage of 160 kV, and an acceleration gap spacing of about 120 mm, we had α = 0.75 (see Fig. 4a). This can be accounted for by the increased area of the open plasma emission surface at the same wall layer as with the grid of 0.4 mm × 0.4 mm mesh size, as the measurements were carried out at the same discharge current and the same working gas pressure in the chamber.

When a mask with 8-mm diameter holes and 13% geometric transparency was put on the emission grid of 0.6 mm × 0.6 mm mesh size, all high-frequency modulations on the discharge current pulses were ceased and the accelerating voltage ceased to affect the shape and amplitude of the discharge current pulse (Fig. 5b). Thus, one of the main advantages of using a plasma emitter was realized, namely the possibility of independent control of the beam current parameters (pulse amplitude, duration, and repetition frequency) by varying the discharge current.

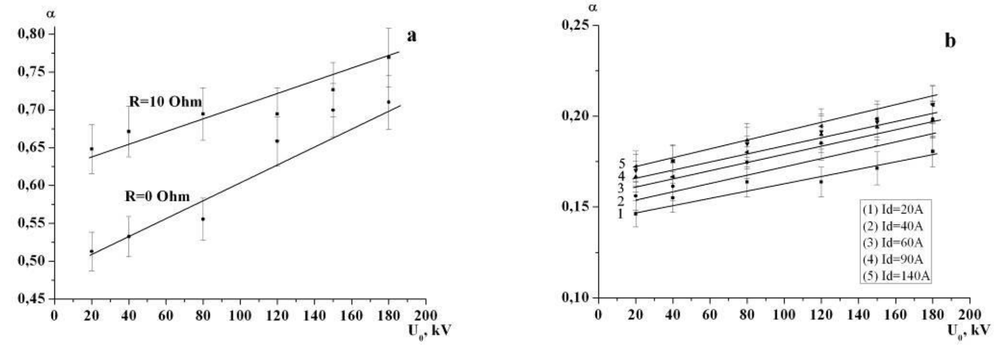

Figure 4. Extraction efficiency αas a function of accelerating voltage U0 in the absence of a mask (a) and with a 8-mm diameter hole mask of geometric transparency 13% (b). The emission grid mesh size was 0.6 mm × 0.6 mm.

For this case, the extraction efficiency α was estimated and plotted as a function of accelerating voltage U_0 (Fig. 4b). For the discharge current I_d = 100 A, U_0 = 160 kV, and 13% geometric transparency of the mask, α = 0.21 was obtained. The emission current pulse waveform had a slightly rising flat top at an invariable discharge current. This is well consistent with the model of the discharge current switching to the emission grid meshes under the action of the applied accelerating voltage [11], and the current rise may indicate an increase in plasma density during the discharge current pulse and a gradual decrease in thickness of the wall layer in the grid meshes.

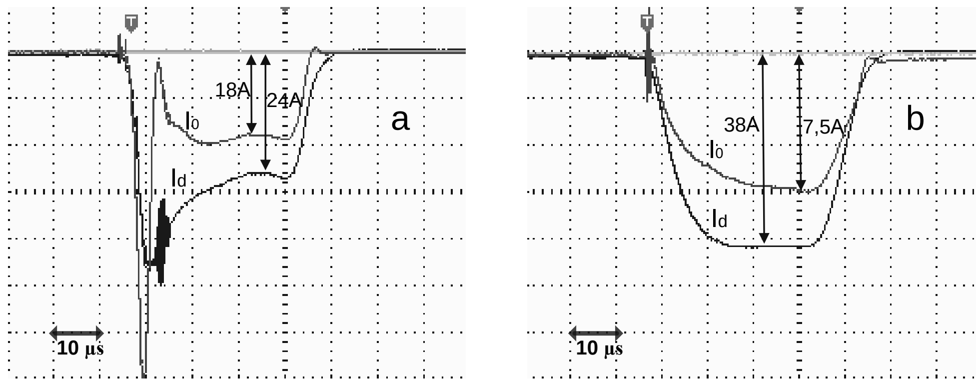

Figure 5. Typical waveforms of the discharge and emission currents at U_0 = 150 kV in the absence of a mask (a) and with a 8-mm diameter hole mask of geometric transparency 13% (b). The emission grid mesh size was 0.6 mm × 0.6 mm.

Using a multi-aperture system of electron extraction from the plasma emitter and a plane-parallel geometry of the mask aligned with the support grid of the extraction foil window, about 75% of the emission current and more than 60% of the beam power were extracted into the atmosphere from the acceleration gap. Thus, at an accelerating voltage U_0 = 200 kV, acceleration gap current I_0 = 16 A, pulse duration t = 40 µs, pulse repetition rate f = 50 s^{-1}, and an about 6.4 kW average beam power in the gap, about 4 kW of the average power were extracted from the acceleration gap through the foil window. Further increasing the beam power was limited by the power of the high-voltage power supply.

4. Conclusion

The study performed has shown that the proposed and investigated simple method of minimization or even, with precision alignment of the equipment, almost complete elimination of the beam current losses at the support grid of the extraction foil window makes it possible to substantially increase the efficiency of the electron source. In addition, its operation can be made more reliable while retaining all of its key advantages, such as the mutual independence of the main beam parameters (energy, current, duration, pulse repetition frequency) and the possibility of varying them over wide limits, the energy homogeneity of the beam, the high pulse repetition frequency of the beam current, and the weak dependence of the beam parameters on vacuum conditions. This opens new prospects for both scientific and technological use of electron sources of this type.

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