Influence of the hole diameter in the perforated electrode on the parameters of electron beam generated by a forevacuum plasma electron source

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Abstract. We present experimental results on geometry optimization of the emission electrode in a plasma cathode electron source operating in the forevacuum range of pressure. For the 2-mm thick emission electrode, we have determined an optimal diameter of the emission aperture that provides the most efficient electron extraction from a hollow cathode glow discharge plasma in helium. At the working pressure of helium in the vacuum chamber 30 Pa, the beam power during emission from a single aperture can vary from 2 to 6 kW, while the beam diameter does not exceed 0.5 mm.

1. Introduction
Recent active developments of the beam-plasma treatment of materials demand an ongoing improvement of existing electron sources and plasma generators. One of the development trends of the electron beam sources is aiming at increasing the working gas pressure to the level of medium vacuum. Forevacuum plasma electron sources can operate in the pressure range from units to tens of pascals [1] and can be used for the electron-beam treatment of both conductive and dielectric materials without resorting to any auxiliary means to compensate the surface charge [2–3]. Stabilization of the emission plasma boundary in these sources is usually achieved by using a grid made of hard-melting materials [4–5] or a perforated electrode, less than 1 mm thick, with multiple holes in it [6]. The use of the grid improves the emission efficiency from hollow cathode plasma, but at the same time enhances the chances of the plasma collapse as a result of the accelerating gap breakdown. The use of the perforated electrode to a great degree excludes the collapse issue during the breakdown [7–9]. However, when the electron source operates under extreme regimes, i.e. when generating electron beams with power over 5–6 kW, the heat load on the perforated electrode increases, which eventually brings about its destruction. It should be noted that heating of the emission electrode is primarily caused by the reverse ion flow from the accelerating gap. The existence of such flow is one of the specific features of the plasma sources operating in the forevacuum. The heat load can be alleviated by improving the efficiency of the emission electrode cooling. The use of a water jacket proves cumbersome because it increases the size of the accelerating gap electrodes. Besides, inclusion of cooling circuitry will complicate the overall design of the plasma electron source. Other possible solution to the heat removal is increasing the emission electrode thickness. The purpose of the present work is to study the possibility of using a 2-mm thick perforated electrode for generation of a focused...
electron beam, as well as to search for an optimal diameter of the holes in the perforated electrode that will support a stable operation of the source.

2. Experimental setup

The experiments were carried out using a prototype model of a plasma electron source diagrammatically shown in figure 1.

![Figure 1. Experimental setup: 1 – hollow cathode, 2 – anode, 3 – perforated electrode, 4 – accelerating electrode (extractor), 5 – focusing system, 6 – deflecting system, 7 – electron beam, 8 – double-slit probe, 9 – collector, 10 – Faraday cup.](image)

The electron source sits on the upper flange of the vacuum chamber and includes cylindrical hollow cathode 1, plane anode 2, emission window, screened by perforated electrode 3, and accelerating electrode (extractor) 4. The thickness of the perforated electrode is 2 mm and the aperture diameter varies from 1.3 to 2 mm. The vacuum chamber is evacuated by a mechanical pump Edwards 80 E2M80 down to 3 Pa, then helium is puffed into the chamber to a pressure of 30 Pa. Electron acceleration and primary formation of beam 7 take place in the anode-extractor gap. The electron beam then enters the magnetic field of focusing system 5, where it is finally shaped. The electron beam is deflected by two deflecting coils 6. Applying an alternating sinusoidal current to the coils provides a linear beam sweep. The beam diameter is measured by a device located, at 20 cm from the extractor, which includes double-slit probe 8 with 0.2 mm wide slits perpendicular to the beam deflection line and collector 9. The current signal from the collector is delivered to an oscilloscope Tektronix TDS2024B. The total beam current is measured by Faraday cup 10.

![Figure 2. Typical collector current oscillogram.](image)
The collector current oscillogram (figure 2) allows one to determine the electron beam diameter as the width at half height of the current amplitude [10].

The sought diameter can be found from the formula:

\[
d = \frac{\tau \cdot L}{T},
\]

where \( L \) is the inter-slit distance; \( \tau \) is the time interval corresponding to the peak width at the amplitude half height; \( T \) is the time interval between the peaks.

3. Experimental results and discussion

Figure 3 shows dependence of the electron extraction efficiency on the accelerating voltage for various values of the hollow cathode current. The electron extraction efficiency was estimated as a ratio of the beam current, registered on the Faraday cup, to the discharge current. The results are given below for two characteristic values of the discharge current, 600 mA (figure 3a) and 1500 mA (figure 3b). For the discharge current over 1500 mA, there is a growing probability that the glow regime of the hollow cathode discharge will change to the arc mode. The experiments conducted previously showed that at the discharge current 100–300 mA the efficiency of the electron extraction from a single aperture is quite low, not exceeding 5% [11].

As seen from figure 3, with increasing hole diameter \( k \), the extraction efficiency, and hence the beam current, increase. Of the presented dependences, one should highlight curve 5, because at the discharge current 600 mA, the beam current was over 300 mA and the extraction efficiency exceeded 50%. Increasing the discharge current up to 1500 mA expectedly resulted in an increased beam current and extraction efficiency. However, increasing diameter \( k \) up to 2 mm results in a breakdown of the accelerating gap due to the plasma falling out of the emission aperture.

Figure 4 below shows the beam power on the collector.

From the plotted dependences, one can see that the maximum power of the beam that has reached the collector is about 5–6 kW at the discharge current 600 mA. Note that the indicated power was obtained during emission from a single 2-mm aperture and helium as a working gas. In the future, we plan to increase the beam total power by increasing the number of emission apertures.

For a single aperture emission at the accelerating voltage above 4 kV, we have managed to generate beams with a diameter less than 0.5 mm. Figure 5 below shows dependence of the beam diameter on the accelerating voltage for various values of the hole diameter in the perforated electrode.
Figure 4. The beam power vs. the accelerating voltage for various hole diameters in the perforated electrode: a – discharge current, 600 mA, b – discharge current, 1500 mA. 1 – \( k = 1.3 \) mm, 2 – \( k = 1.5 \) mm, 3 – \( k = 1.7 \) mm, 4 – \( k = 1.9 \) mm, 5 – \( k = 2 \) mm.

Figure 5. The beam diameter vs. the accelerating voltage for various hole diameters in the perforated electrode: a – discharge current, 600 mA, b – discharge current, 1500 mA. 1 – \( k = 1.3 \) mm, 2 – \( k = 1.5 \) mm, 3 – \( k = 1.7 \) mm, 4 – \( k = 1.9 \) mm, 5 – \( k = 2 \) mm.

From the above dependences, one can see that at the discharge current 600 mA and the accelerating voltage 18 kV, the beam diameter can vary from 0.25 to 0.5 mm. The beam diameter decreases as the accelerating voltage increases up to 18 kV.

4. Conclusion
It is possible to improve the operational stability of a plasma electron source in generating electron beams with power over 5 kW in the forevacuum range of pressure by employing a 2-mm thick emission electrode. The extraction efficiency thereby depends on both the hole size in this electrode and the processes taking place in the course of the electron beam transport. The maximal efficiency of over 50% has been attained for the diameter of emission electrode aperture 1.9 mm. The beam diameter in helium media at pressure 30 Pa does not exceed 0.5 mm, the beam current is over 300 mA and power over 5 kW. It is planned to increase the number of emission apertures to further increase the beam power.

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References

[1] Burdovitsin V A and Oks E M 2008 *Laser Part. Beams* **26** 619

[2] Klimov A S, Burdovitsin V A, Zenin A A, Oks E M, Khasanov O L, Dvilis E S and Khasanov A O 2015 *Technical Physics Letters* **41** (8) 747

[3] Goreev A K, Burdovitsin V A, Klimov A S and Oks E M 2012 *Inorganic Materials: Applied Research* **3** (5) 446

[4] Gavrilov N V, Emlin D R and Kamenetskikh A S 2008 *Technical Physics* **53**(10) 1308

[5] Gavrilov N V and Kamenetskikh A S 2007 *Technical Physics* **52** (3) 301

[6] Zenin A A, Bakeev I Y, Burachevskii Y A, Klimov A S and Oks E M 2016 *Technical Physics Letters* **42** (7) 712

[7] Oks E M and Schanin P M 1999 *Physics of Plasmas* **6**(5 II) 1649

[8] Zhirkov I S, Burdovitsin V A, Oks E M and Osipov I V 2006 *Technical Physics* **51** (6) 786

[9] Bakeev I Yu, Klimov A S, Oks E M and Zenin A A 2018 *Plasma Sources Science and Technology* **27** 075002

[10] Kaur A, Ribton C and Balachandaran W 2015 *Mater. Process. Technol* **221** 225

[11] Zenin A A, Klimov A S and Nikolaenko A N 2017 *Doklady TUSUR* **20** (2) 40