Forevacuum plasma source of ribbon electron beam with a multi-aperture extraction system

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Abstract. The article presents the results of modernization of the accelerating interval of the forvacuum plasma electron source. The source generates an electron beam in the form of a sheet at pressures of 10–30 Pa. To increase the homogeneity, a multi-aperture extraction system was used. The optimal distances between the anode and the extractor, as well as the ratio between the cell sizes of the multi-aperture system, allowing to obtain a homogeneous electron beam width of 30 cm are determined.

1. Introduction

The sources of low-energy wide-aperture electron beams have found their application in surface treatment technologies of materials. As a rule, such sources operate in a pulsed mode and generate electron beams with a cross-sectional area of more than 10 cm² and pulse energy more than 20 j/cm² [1]. The high energy density combined with the short pulse duration allows such beams to concentrate energy in a thin near-surface layer of the irradiated material. As a result, there is melting, and even evaporation of the material, which can significantly change the structure and properties of the surface layers and improve the characteristics of products. High-energy wide-aperture electron beams emitted into the atmosphere or high-pressure gas are used for processing polymers, sterilization of water and gases [2], medical instruments [3], as well as in plasma chemistry and pumping of high-power lasers, etc. [4–7]. One of the types of wide-aperture electron beams is the so-called ribbon or sheet-like electron beams. Sources generating such beams can operate both in pulsed and continuous modes. The cross section of the ribbon beams is a rectangle with an aspect ratio of more than 10:1. When a band electron beam propagates in the gas, a large-area beam plasma is formed – about 1 m². [8–9]. Such plasma is nonequilibrium and attractive for plasmochemical reactions and etching of a thin atomic layer of materials [10–11]. As a rule, to increase the beam plasma density, it is necessary to inject the electron beam into the gas at a pressure much higher than the pressure in the electron source. This situation complicates the electron-beam installations and increases the demands on the vacuum chambers and the pumping devices. In this case, the use of so-called forvacuum plasma electronic sources capable of operating at pressures up to 100 Pa [12] is preferred. The sources are a three-electrode system – cathode, anode and accelerating electrode. This electrode system allows to independently regulating the current and energy of the electron beam. The special design of the accelerating gap allows such sources to operate at pressures from 5 to 100 Pa. For the sources of ribbon beams, there are problems of homogeneity of the current density distribution as in the case of the generation of wide-aperture electron beams. In addition, when working in conditions of high...
pressures of the forevacuum, the thermal load on the grid located in the anode is significantly increased. The grid is necessary to stabilize the plasma boundary and can bend and even burn out at electron emission at pressures of 10–100 Pa. One way to increase the resource of the emission grid can be the use of a multi-aperture extraction system. This system traditionally uses in ion and electron beam sources. In multi-aperture extraction systems [13], an electron beam forms by adding individual beams. Such beams form in elementary accelerating cells, which are two or more electrodes with coaxial holes. In such systems, the beam losses on the electrodes are minimal and usually do not exceed a few percent. In addition, the thermal load on the grid reduces, since it is sandwiched between flat electrodes, the heating of which is much less [14]. The aim of this work was to study the influence of the parameters of a multi-aperture system on the formation of a homogeneous electron beam in the forevacuum pressure region.

2. Experimental setup
A forevacuum plasma electron source was used for the experiments. The electrodes of electron source are shown in figure 1. The main electrodes of the source cathode 1, anode 2 and extractor 3 were made of stainless steel.

![Figure 1. The scheme of the source of the ribbon electron beam and the location of the measuring probe in the chamber: 1 – Extended hollow cathode, 2 – anode, 3 – extractor, 4 – perforated electrode, 5 – emission holes, 6 – plate in extractor, 7 – trajectories of edge electrons, 8 – current probe.](image)

The cathode was a cavity with internal dimensions of 320×70×30 mm and had a water-cooling jacket. The anode was flat with the possibility of installing a perforated electrode 4 1 mm thick with holes located along one line 5. The number of holes in the perforated electrode was 54. A perforated electrode with the holes diameter of 3.5 mm was used. The distance between the centers of the holes was 6 mm. The extractor also contained a removable insert 6 with holes. The holes in the extractor and anode were arranged coaxially to each other. Three replaceable plates in the extractor with different hole diameters of 3.5 mm, 4.5 mm and 5.5 mm were used in the experiments. The distance between the perforated electrode in the anode and the plate of the extractor varied from 2.5 mm to 10 mm. The experiments were carried out in an air atmosphere at a pressure of 7 Pa. The accelerating voltage in the experiments varied from 2 to 8 kV, the discharge current varied from 200 to 800 mA. It was possible to measure the current to the extractor to determine the beam losses on it. To do this, the extractor was connected to the ground through a current device 9.

The current density distribution was investigated by means of a movable collector 8 located at a distance of 30 cm from the extractor. The collector had a narrow slit width of 1 mm and allowed to measure the transverse distribution of the beam current density. Both experimental and numerical experiments were carried out to determine the optimal geometry of the accelerating gap.
3. Experimental results and discussion

A typical distribution of the current density of the electron beam at different accelerating voltages and different distances between the anode and the extractor is shown in figure 2.

![Figure 2](image)

**Figure 2.** The density distribution of the electron beam current when the distance between the anode and the extractor: 1.2–2.5 mm, and 3.4–5 mm, 5.6 to 10 mm. Accelerating voltage: 1, 3, 5 – 2 kV, 2, 4, 6 and 8 kV. The size of the holes in the anode and the extractor is 3.5 mm.

From presented in figure 2 dependences it can be seen that by increasing the anode-extractor distance from 2.5 to 5 mm, there is a slight improvement in the homogeneity of the beam current density distribution, compare the curves 1, 2 and 3, 4. The average value of the current density decreases almost twice. A further increase in the distance between the anode and the cathode to 10 mm adversely affects both the homogeneity of the current density distribution and the average value of this current (curves 5, 6). The accelerating voltage regardless of the anode-extractor distance influences the homogeneity of the distribution. As the accelerating voltage increases, the inhomogeneity increase.

The decrease in the average beam current with increasing anode-extractor distance is most likely due to the electron beam hitting the extractor. The anode-extractor distance increasing leads to a change in the distribution of the electrostatic field in the accelerating gap. This leads to a change in the trajectory of the accelerated electrons and their interception by the extractor. Measurement of the current per extractor and beam current shown in figure 3, confirm this.

![Figure 3](image)

**Figure 3.** The dependence of the current to the extractor (1, 2 and 3) and the beam current (4, 5 and 6) on the accelerating voltage. Anode-extractor distance is: 1, 4 – 2.5 mm, 2, 5 – 5 mm, 3, 6 – 10 mm.
As shown in figure 3 as the anode-extractor distance increases, the current losses on the extractor increase. At a distance of 10 mm between the anode and the extractor, beam current losses reach 15 mA, which is almost half of the beam current. The operation of the electron source in this mode leads to heating of the plate in the extractor and its curvature. This adversely affects the homogeneity of the extracted beam current, and can lead to the shortening of the accelerating gap and loss of efficiency of the source.

To verify the findings, a simulation of the accelerating system in CST Studio Suite 2019 performed. The program creates a simulation of the trajectory of charged particles in electric and magnetic fields, while using the configuration of step-by-step update of momentum and coordinates.

The results of modeling one cell of the accelerating system with a diameter of 3.5 mm holes in the anode and extractor and an anode-extractor distance of 2.5 and 10 mm are shown in figure 4.

![Figure 4. Electron trajectories at the anode-extractor distance of 2.5 mm (a) and 10 mm (b), the diameter of the holes in the anode and extractor 3.5 mm.](image)

The simulation results showed that, from the point of view of the beam passing through the extractor, the minimum distance between the electrodes is optimal. Increasing the diameter of the holes up to 5.5 mm in the extractor practically does not affect the uniformity of the electron beam. However, the number of electrons entering the extractor decreases, which is confirmed by the simulation results, figure 5.

![Figure 5. Electron trajectories at the anode-extractor distance of 2.5 mm (a) and 10 mm (b), the diameter of the holes in the anode 3.5 mm, the diameter of the holes in the extractor 5.5 mm.](image)

As you can see, the simulation results confirm the assumptions made earlier. At a minimum anode-extractor distance the beam divergence is maximum. A further increase in the length of the accelerating gap leads to an increase in the electron beam losses on the extractor. Minimum losses are observed at a distance between the anode and the extractor 2.5 mm. Increasing the accelerating voltage leads to a decrease in current losses, but leads to an increase in the inhomogeneity in the distribution of the beam current density.

4. Conclusion
As a result of experimental research and numerical modeling, the optimal geometry of the accelerating interval of the source of the ribbon electron beam is obtained. The lowest current losses on the
extractor at the minimum possible distance between the anode and the extractor are observed. In the case of a ribbon electron beam source, this distance is 2.5 mm. The value of the accelerating voltage affects both the electron beam current transmission and its homogeneity. The greatest homogeneity of the electron beam is observed at a small accelerating voltage of about 2 kV. The uniformity is reduced with increasing accelerating voltage; however, decrease the loss of current on the extractor of the source of electrons.

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