Numerical model of EOS with large-area plasma cathode with mesh stabilization of the emission plasma boundary

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Abstract. The source of electrons that generates a beam of a large cross section (BLCS) with the beam release into the atmosphere through a thin metal foil has been developed in the IHCE SB RAS. The electronic BLCS in this case is a superposition of elementary beams formed by separate emission structures. Their plasma boundary is stabilized by a fine-grained metal mesh, covered by a mask with round holes. The configuration of holes repeats the configuration of the holes in the support grid of the outlet foil window having a slightly larger diameter. In preliminary experiments, the maximum current-to-atmosphere output coefficient reached ~70% of the current in the accelerating gap. The objective of this paper is to select a numerical model of the electron-optical system (EOS) for computer simulation and analysis of the characteristics of the formed elementary beams for further optimization of the source and increase the efficiency of beam extraction into the atmosphere.

1. Introduction

Irradiation of large surfaces and gas volumes by electron currents is widely used for scientific and technological purposes. It is used, in particular, in plasma chemistry, radiation chemistry, product sterilization, high-power electro ionization lasers, etc. In the sources under consideration, plasma cathodes are used to form such streams. They have a number of advantages over thermionic cathodes and cathodes with explosive emission.

An electron accelerator with a large-area plasma cathode “Duet” [1] with an accelerating voltage of up to $U_{ac}=200$ kV and a beam current of $I_{ac}$~50 A has been developed at the IHCE SB RAS. The electron beam is generated by pulses of up to 100 μs with a frequency of up to 50 Hz. Emission (cathode) plasma in the volume of a plasma emitter, which has the form of a hollow half-cylinder, is created by two plasma generators on the basis of an arc discharge in argon or nitrogen located at its ends. On the flat side of the volume there is an emission window of 150×750 mm, which is closed with a woven mesh of stainless wire of $d_w=0.2$ mm in diameter with square cells of 0.6×0.6 mm increments and geometric transparency $\alpha$~0.445 stabilizing the emission plasma boundary. A mask of stainless steel with a thickness of 200 μm is laid over the mesh, in which $N_{op}=344$ holes with a diameter $d_c=12$ mm, defining the diameter of each individual elementary beam, are made. The anode electrode, consisting of an outlet foil and a 20 mm high support grid, is located at a distance...
$d=120\div140$ mm from the cathode and also contains $N_{op}=344$ holes of diameter $d_{a}=15$ mm in the support grid located coaxially with the holes in the mask. Thus, there are 344 emission structures in the diode gap that form elementary electron beams with currents $I_{1}=I_{a}/N_{op}=0.145$ A released through the foil into the atmosphere.

Tests of the accelerator showed that a significant part of the emission current leaving the cathode plasma is lost on the support grid. By adjusting the position of the holes in it, the selection of the diameters of the cathode and anode holes, and the parameters of the cathode plasma generator, the beam output from the accelerating gap to the atmosphere was increased to 75% in current and up to 62% in beam power. Further increase in the efficiency of the output can be associated with optimization of the geometry of the emission structure. For this purpose, at this stage, a numerical two-dimensional simulation of the formation of an elementary electron beam in a structure with a plasma emitter is carried out for comparison with experiment. The numerical code POISSON-2 [2] was used for simulation.

Let us estimate the position of the plasma surface in the fine-scale mesh cells. The shape of the surface of the plasma emitter will be determined by the equality, obtained from the continuity equation, of the electron current density freely emanating from the plasma and of the current density in the region of electron acceleration in the regime of current limitation by space charge. Taking into account that, as a rule, in gas discharges, the ion temperature is less than the electron temperature, we can assume that in equilibrium the electric field at the plasma surface is close to zero. Since the thermal energy of the electrons is small in comparison with $eU_{a}$ ($e$ is the elementary charge), the plasma can be considered as cold and the density of the emission current should be described fairly accurately by the Child law. Based on this, we estimate the average current density, which is passed through the accelerating gap in the simulated emission structure:

$$j_{CL} \approx 2.33 \cdot 10^{-5} U_{a}^{3/2} / d^{2} \approx (0.76\div1.03) \text{ A/cm}^2.$$

(1)

In the experiment, the beam current $I_{1}$ per one hole in the cathode mask is $I_{1}=I_{a}/N_{op}=0.145$ A. Hence, the average current density in the mesh cell (assuming that only the plasma emits) is equal to

$$j_{g} = 4I_{1} / \left(\alpha \pi d_{c}^{2}\right) = 0.29 \text{ A/cm}^2,$$

(2)

which is less than the current density according to the Child law (1) by a factor of $\sim$3. In order to pass a current of magnitude $j_{g} < j_{CL}$ through the accelerating gap, the emitting plasma surface must be moved away from the anode and placed in the electric “shadow” of the wires, forming concave wells. In this case, the electric fields in the wells are much less than the inhomogeneous fields between the wires of the cells on the side of the anode, which, in general, will determine the transverse velocities when the electrons move in the acceleration region. It can be expected that in this case the angular characteristics of the electrons in the beam will be weakly dependent on the shape of the surface of the cathode plasma. This circumstance would make it possible to simplify its modeling, considered below. One of the purposes of this paper is to verify the correctness of this assumption.

2. Emission structure models

The main problem in the numerical solution of the self-consistent problem for the EOS under consideration is the strong multiscale of its elements. Even within the framework of an individual emission structure, the ratio of the length of the accelerating gap and the wire mesh radius is $2d/d_{w}=1400$. Additionally, inside each mesh cell, the shape of the emitting plasma surface must be found, for each element of which it is required to calculate the density of the emission current with analytic accounting of the space charge singularity on a small distance from the surface of the emitter (another scale factor is $\sim$10). For this reason, the solution of the complete problem with available codes for the emission structure is impossible because of the lack of suitable algorithms for it. The complexity of the problem is aggravated by the three-dimensionality of the problem geometry.
The proposed modeling process consists of solving three approximate problems. The first one examines a single emission structure under the assumption of homogeneous emission from a flat emitter (replacing the plasma cathode with the mesh) closing the hole in the cathode mask with a current equal to the experimental value. A self-consistent solution for the potential and trajectories of the electrons would be found for it.

The second problem in the approximation of axial symmetry considers the fragment of the accelerating gap adjoining the mesh. The fragment uses the solution of the first task, and includes in the transverse direction three cells of the cathode mesh and has a length about 8 cell sizes along the axis. In this problem a self-consistent form of the plasma boundary is calculated, that emits the currents in the central cell with space charge limitation and in the adjacent cells corresponding to the experimental currents. The boundary is described by a cubic spline passing through its points. When solving, the trajectories of electrons and their transverse velocity distribution at the exit from the fragment are calculated.

In the third problem for the same structure fragment, the previously obtained plasma boundaries are approximated by arcs of circles with minimal deviation from the spline with the same currents as in the second problem. The distribution of beam electrons over transverse velocities is calculated and compared with the results of the second problem. It is concluded how the form of the plasma surface affects the characteristics of the beam.

3. Results of modeling

All problems are solved in a two-dimensional axis-symmetric approximation in cylindrical coordinates \((r, \phi, z)\). Problem No. 1 is solved for a separate structure which forms an elementary electron beam emitted from the plasma surface. Because it is surrounded on all sides by the same structures with a spatial period \(2r_0=17\) mm, we single out the structure under consideration by lateral boundaries in the interval \([0, r_0]\). At these boundaries, we set the condition \(\partial \phi/\partial r = 0\) for the potential and the condition of elastic reflection for the electrons. At the ends the structure is limited by electrodes with given potentials. An anode electrode with a potential \(U_a=160\) kV is formed by the surface of the outlet foil and the support grid. A cathode electrode with a potential \(U_c=0\) contains a part of mask with an aperture covered with a fine-scale mesh. The geometry of the structure is shown in figure 1.

![Figure 1](image_url)

**Figure 1.** Geometry of a separate structure. 1) – the cathode mask; 2) – the fine-scale mesh; 3) – emission plasma; 4) – anode foil; 5) – support grid. The fragment of the model No.2 is marked with dashed lines.

In the problem No.1, we replace the mesh and plasma with a flat emitting electrode with a current \(I_1\) and a uniform current density \(j_1=4I_1/\pi d_c^2\sim 0.128\) A/cm\(^2\), assuming that the electrons are emitted with zero initial energy inside the area \(r\leq 6\) mm. This formulation corresponds to the classical problem with current limitation by the cathode emission capacity. The solution of this problem for the separate structure allows us to find the potential distribution in the accelerating gap, including area near the cathode surface. The distribution of the potential and trajectory of electrons is shown in figure 2. Under these conditions, due to the inhomogeneity of the electric field in the region of the anode, the
beam electrons acquire transverse velocities, so that the angular divergence of the velocities increases to 0.016 rad. The beam passes through the anode foil without losses.

Figure 2. The electron trajectories and the potential distribution in a separate structure, in the approximation of model No.1. Equipotent lines are plotted with interval of 1 kV and 10 kV.

The solution region of the problem No.2 is the paraxial fragment of problem No.1 with the boundaries [0<r<0.9 mm], [0<z<3 mm]. To determine the boundary conditions, we use the potential distribution obtained in the model No.1. On the lateral surface r=0.9 mm, a condition is set for the potential, and at the end (z=3 mm) serving as the anode for this model, the potential is set equal to $\varphi \approx 3.88$ kV.

Evidently, the metal mesh with square cells, which stabilizes the plasma surface, is a three-dimensional object. To model one cell of mesh in the axis-symmetric approximation, we select the Z-axis of the coordinate system at the center of the cell. The cells adjacent to it will be modeled by an annular gap bounded by mesh wires with centers $r_1=0.4$ mm and $r_2=0.9$ mm. The geometry of problem No.2 is shown in figure 3. Inside the cells the plasma surfaces emit the electron fluxes. To calculate the equilibrium plasma boundary, the following optimization conditions were used: the current from the central cell in the space charge limited mode should become equal to $i_1=j_1 \cdot \pi r_1^2=0.364$ mA, and the current from the annular gap was set equal to $i_3=j_1 \cdot \pi (r_2^2-r_1^2)=2.893$ mA. So, the average current density in the fragment will be equal to $j_1$, as in the whole structure. The position of the plasma boundary was varied by the displacement of its points along the Z-axis. Obviously, the central cell simulates the square mesh cell much better than the annular gap. The angular characteristics of the beam were determined for the trajectories emitted from the central cell. It was obtained that the maximum angle of trajectories with the Z axis in the beam at the exit from the calculated region is 0.06 rad, which corresponds to the transverse electron energy ~14 eV.

Figure 3. Geometry of the fragment (model No.2) with trajectories and equipotent lines with intervals of 0.1 kV and 0.5 kV.

Figure 4. Geometry of model No. 3. The plasma surfaces are approximated by arcs of circles.
The model No.3 differs in that the shape of plasma boundaries is represented by arcs of circles with a radius of ~0.26 mm, which describes quite well their shape obtained in the model No.2. In the central cell, the emission current density was also limited by the space charge, and in the annular surface it was set constant so that the total beam current is, as in the model No.2. The result of the calculation is shown in figure 4. Here the maximum angle of trajectories with the axis was 0.065 rad, which agrees well with the model No. 2.

4. Conclusion
The assumption of the weak influence of the shape of the plasma boundary on the angular characteristics of the beam at the operating parameters of the EOS under consideration with a large-area plasma cathode with mesh stabilization of the emission plasma boundary is confirmed. In general, the angular divergence of beam velocities is determined by the electric fields of the cathode mesh. This allows us to further simulate and optimize this system with a description of the shape of the plasma boundary by circular arcs, determining the parameters of the arcs from the total current limited by the space charge of the beam. It also makes it possible to use the ERA-DD code [3] for modeling such a problem, which uses more detailed computational mesh and special algorithms for separating the cathode singularity.

Another possibility to improve the beam parameters may be as the following. In order to exclude the influence of the 3D grid form factor on the angular characteristics of the beam, change the emission grid to, for example, a thin metal sheet with holes, which repeats the configuration of the mesh cells position in the cathode. These holes of about 0.5 mm diameter may be done by laser cutting. Of course, this new configuration requires a separate experimental verification and numerical simulations.

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