SIMULATION OF THE EXTRACTION OF A STRONGLY FOCUSED ELECTRON BEAM FROM A PLASMA ELECTRON GUN

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Numerical simulation of the extraction of a strongly focused electron beam from a plasma electron gun with hollow cathode is performed. For this purpose, the methods of finite-difference and integral equations are used together with the direct trajectory analysis. The influence of a configuration of the magnetic field on the beam characteristics is investigated. It is shown that an additional axial magnetic field applied in the accelerating gap allows one to increase the beam current. The optimal values of the focusing current allowing one to obtain a small-diameter beam are determined.

1. Introduction

Strongly focused electron beams are used in many technological processes. Optimization of the source parameters, guaranteeing the beam stability, raising its power, and a decrease of losses represent the main tasks, whose solution will increase the efficiency of plasma electron sources. The basic mathematical methods used to solve these problems are numerical ones. The analytical solution of a nonlinear self-consistent problem, to which the investigation of the intense beams of charged particles is reduced, is possible only in the simplest cases. The modeling allows one to choose the optimal variant of the source construction and to estimate the influence of various parameters on the characteristics of a beam.

In the majority of works devoted to the computer simulation of electron guns, one describes the processes of formation of an electron beam with the help of the approximation of planar or spherical diode [1,2]. In the given paper, the generation and extraction of the electron beam from plasma, as well as its further transport, are simulated with the help of a modified three-dimensional cobra code [3], which is based on the finite-difference technique. It allows one to take into account both the geometry of a source and the accelerating gap and the physical conditions of the formation of a beam, by using the iteration algorithm to solve the self-consistent problem. The latter is solved with the help of one of the variants of the sweep method [4] in combination with the direct solution of the equations of motion for particles.

The previous papers [5,6] dealt with computer simulation for various geometries of both the extracting system and the accelerating gap with the purpose to optimize the system, to obtain a stable high-current beam with small divergence, and to minimize losses in the case where the beam passes through the accelerating gap and the drift space. A further improvement of the characteristics of a beam includes an increase of its current and a decrease of its diameter, i.e., an increase of the beam density. The performed experiments [7] have demonstrated that an attempt to raise the beam current by means of increasing the discharge current results in a breakdown between the hollow cathode and the accelerating electrode, due to which the electron beam disappears. In order to solve this problem, it was proposed to use an additional axial magnetic field in the accelerating gap, which allows one to limit the discharge current and to increase the beam current. Another possibility to raise the beam current consists in the extraction of the electron beam from plasma through a large number of emission orifices rather than through one of them. In this case, the problem lies in the focusing of the beam by the magnetic field and, consequently, the search for the optimal configuration of the magnetic field allowing one to obtain a stable beam with rather high current and small diameter.

2. Description of the Mathematical Model

We consider a collisionless fully ionized quasineutral plasma with uniformly distributed charged particles. In order to describe the plasma, we use the Poisson equation $\Delta\varphi = \frac{\rho}{\varepsilon}$, the charge conservation law $\nabla \cdot j = 0$, and the equations of motion $\frac{d\mathbf{v}_i}{dt} = \frac{q_i}{m_i}(\mathbf{E} + [\mathbf{v}_i \times \mathbf{B}])$, where φ represents the electric potential, ρ stands for the charge density; ε is the dielectric

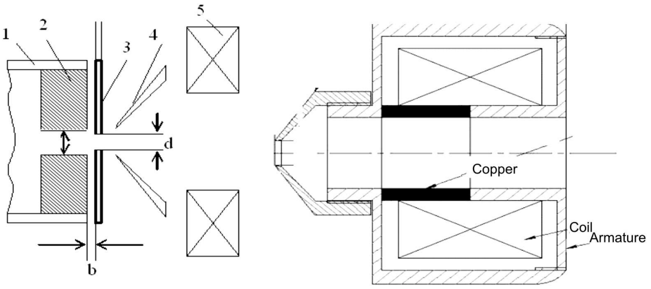

Fig. 1. From the left: the electrode subsystem of a electron source: *1* – hollow cathode; *2* – cathode insert; *3* – anode; *4* – accelerating electrode; *5* – focusing system; from the right: the scheme of an extractor (*4, 5*)

permittivity of the medium; $\mathbf{v}_i, q_i$, and m_i are the velocity, charge, and mass of particles of the sort i present in the plasma; $\mathbf{E}$ denotes the electric field intensity; $\mathbf{B}$ is the magnetic induction; and j is the current density. The space charge limits the current density j according to the Child–Langmuir law: $j = \frac{4\varepsilon_0}{9}\sqrt{\frac{2q}{m}}\frac{\varphi^{3/2}}{s^2}$, where s is the width of the emission slit. Due to the potential difference applied between the plasma and the accelerating electrode, electrons leave the cathode surface and are involved in the process of formation of the beam.

The computational procedures realizing the numerical solution of the considered self-consistent problem are as follows. The problem region is covered with a rectangular mesh with the nodes (i, j, k), i =1, ..., N; j =1, ..., M; $k = 1, \ldots, L$. At the first iteration, the space charge density ρ is assumed equal to zero, and the Laplace equation is solved. At the n-th iteration, the electrostatic potential $\varphi^n_{i,j,k}$ and its derivatives are calculated. At the boundary points of the region, the potential is calculated with the help of the method of integral equations, while at the internal ones – by means of the varying sweep method [5] using the 7-point difference scheme. At the n-th iteration, the minimum of the potential is found over all the points of the mesh (i, j, k), and the relaxation transformation of the mesh potential is performed for all $n \geq 2$ using the formula $\varphi^{n+1}_{i,j,k} = \alpha_n\varphi_{i,j,k} + (1-\alpha_n)\varphi^n_{i,j,k}$. Here, α_n is the value of the relaxation parameter at the $n-$th iteration, $\phi^n_{i,j,k}$ denotes the old value of the potential, $\phi^{n+1}_{i,j,k}$– the new one, $\phi_{i,j,k}$ is the correction for the node (i, j, k), calculating which one uses the values of the potential at the given point and at the neighbor ones.

After that, a manifold of electron trajectories is calculated depending on the position of an individual particle at the emitter, its initial energy, and the angles determining the orientation of the initial velocity vector. The electron trajectories are calculated by means of solving the Lorentz equations with initial conditions at the emitter surface. After that, the space charge density is calculated at the given mesh and the transition to the $(n + 1)$-th iteration is performed.

The relative error of the solution of the self-consistent problem with respect to the field at the n-th iteration is estimated, by basing on the formula $\delta_n = \frac{\Delta_n}{\alpha_n(\varphi_{n\max}-\varphi_{n\min})}$, where $\varphi_{n\max}$, $\varphi_{n\min}$ are the maximal and minimal values of the potential, respectively, Δ_n is the difference between two calculated values, and α_n is the value of the relaxation parameter at the n-th iteration.

In the general case, the magnetic field for high-current beams is calculated as a sum of external fields and the proper magnetic field of the beam generated by the current density $B = \mu_0\mu_r\frac{j}{r}$, where B is the magnetic induction; μ_0, μ_r is the magnetic susceptibility, and r is the normal to the trajectory.

3. Results Obtained and Discussion

The simulation was performed for a hollow-cathode electron source, whose schematic is shown in Fig. 1. Plasma in the setup is generated with the help of hollow-cathode discharge *1*. Electrons are extracted along the axis of the system through the central orifice in anode *3*. After it, accelerating electrode *4* is placed followed by the magnetic focusing system *5*.

The peculiarity of the focusing system consists in the fact that the coil is located in a ferromagnetic core that closes the magnetic flux on itself, and it comes out only through the window. Thus, the magnetic field is localized in a small region, where the beam is focused.

One of the basic problems in the improvement of a construction of electron guns is the increase of a beam current. In the previous papers [5,6], it was obtained that the current of an extracted beam increases with the diameter of the orifice in the emission electrode but, in the case where the diameter became too large, the electric breakdown occurred due to the penetration of plasma from the discharge region into the accelerating gap, and the electron beam is not extracted. However, in the case where an additional axial-symmetric magnetic field is applied in the accelerating gap, it will impede the radial motion of plasma and, due to this fact, maintain plasma along the axis of the system. Figure 2 demonstrates the variation of a form of the plasma boundary depending on the magnitude of the axial magnetic field.

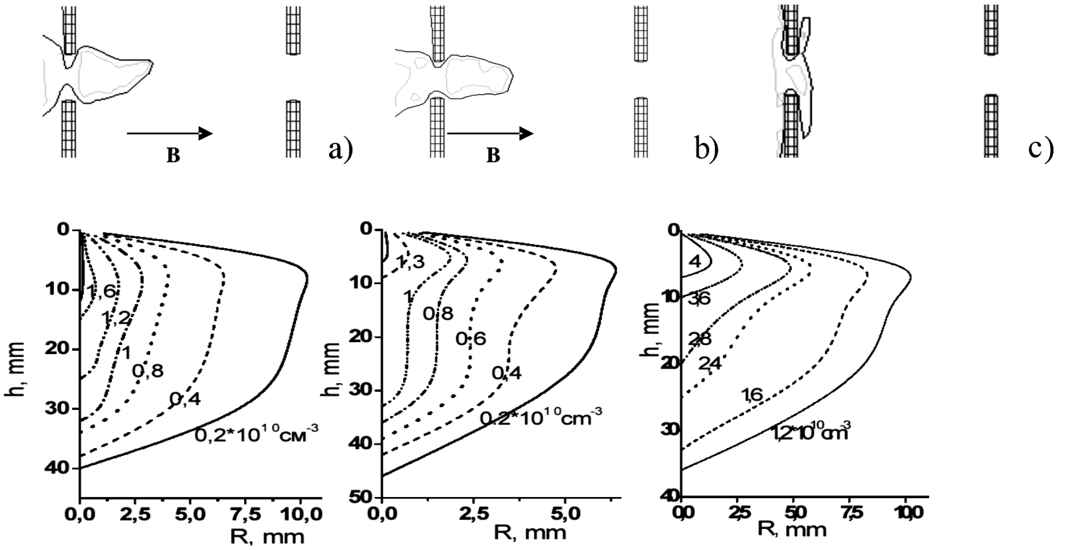

Fig. 2. From above – variation of the plasma configuration; from below –lines of equal concentration of plasma (h – axial coordinate, r – radial one) penetrating through the emission orifice into the accelerating gap depending on the magnitude of the magnetic field B, mT: a – 7, b – 15 c – no magnetic field

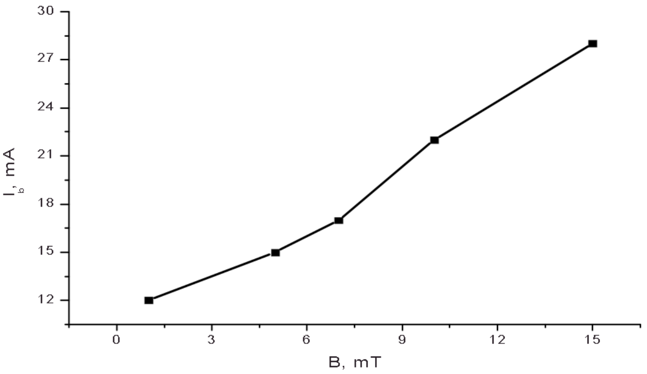

Fig. 3. Dependence of the beam current on the magnitude of the axial magnetic field (the orifice diameter equals 1.2 mm, and the accelerating voltage equals 1 kV)

Thus, the axial magnetic field in the accelerating gap can prevent the breakdown and promote the increase of the beam current. Figure 3 shows the dependence of the beam current on the magnetic field.

Using the focusing system presented in Fig. 1 from the right, one can match the optimal value of the focusing current allowing one to obtain a beam with a diameter lower than d at a rather large distance from the focusing system. The trajectories of separate particles of the beam for various magnitudes of the focusing current are given in Fig. 4.

Figure 5 presents the dependences of the beam diameter on the focusing current.

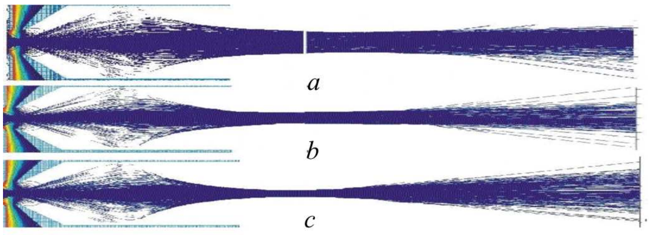

Fig. 4. Calculated trajectories of particles of the beam as a function of the focusing current (in A per loop) a – 900; b – 1000; c – 1100

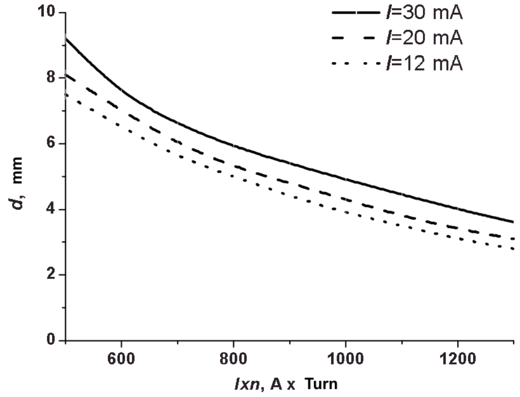

Fig. 5. Dependence of the beam diameter on the focusing current at the 15-cm distance from the center of the focusing system for various magnitudes of the emission current

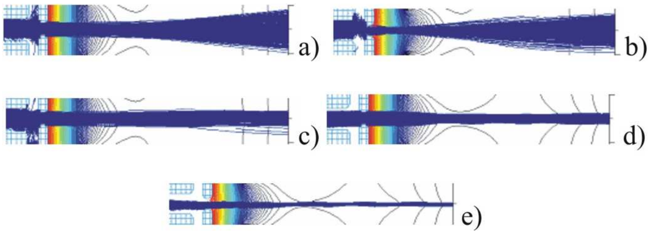

Fig. 6. Calculated trajectories of particles of the beam depending on the magnitude of the focusing magnetic field: a – no magnetic field, b – 1000 (A per loop); c – 10000; d – 50000; e – 100000. The beam current is equal to 95 mA, and the accelerating voltage is 20 kV

There exists another possibility to increase the beam current, namely to use an emission electrode with a collection of orifices rather than with a single one. Then the electron beam consists of a large number of beams. In this case, the total beam current is rather high, but the difficulty consists in the transport of the beam through the system of electrodes and the focusing of the beam so as to obtain a beam with small diameter and high current density. Computer modeling allows one to find the form of the emission electrode optimal for obtaining the beam with a current density of 10 A/cm^2 and a diameter of 3–4 mm. The trajectories of the beam electrons for various magnitudes of the focusing current in the case of a many-channel emission electrode are shown in Fig. 6.

Similar results were obtained experimentally for a many-channel tantalum emission electrode with the total number of orifices equal to 60 and the diameter of each of them of 0.6 mm [7].

4. Conclusions

Computer simulation of the generation and the transport of a strongly focused electron beam is performed. There exist two main problems in the projection of electron guns used for obtaining strongly focused beams. One of them is the breakdown arising in the accelerating gap, and the other is an increase of the current density of a beam. It is proposed to use the axial magnetic field in the accelerating gap, which will allow one to raise the maximum discharge current and, respectively, to increase the electron beam current. The influence of the axial magnetic field applied in the accelerating gap on the penetration of plasma through the emission slit into the accelerating gap is investigated, by using numerical methods. It is shown that the magnetic field impedes the penetration of plasma into the accelerating gap and maintains it along the axis of the system. The configuration of the magnetic field is optimized with the help of numerical modeling, and the optimal construction of the emission electrode is proposed.

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МОДЕЛЮВАННЯ ЕКСТРАКЦІЇ ГОСТРОСФОКУСОВАНОГО ЕЛЕКТРОННОГО ПУЧКА З ПЛАЗМОВОЇ ЕЛЕКТРОННОЇ ГАРМАТИ

І.В. Літовко

Резюме

Проведено чисельне моделювання формування гостросфокусованого електронного пучка з плазмової електронної гармати з порожнистим катодом. Для моделювання було використано чисельні методи оптики заряджених частинок, а саме спільно застосовувались методи скінченно-різницевих та інтегральних рівнянь, з одного боку, і прямий траєкторний аналіз – з іншого. Було досліджено вплив магнітного поля на характеристики пучка. Показано, що додаткове аксіально-симетричне магнітне поле, прикладене в прискорюючому просторі, дозволяє підвищити струм пучка. Були знайдені оптимальні значення фокусуючого струму, які дозволяють отримати пучок малого діаметра. Одержані результати можуть бути використані для оптимізації конструкції плазмових електронних джерел.