SIMULATION OF FORMATION OF AN INTENSIVE ELECTRON BEAM IN BIPOLAR ELECTRON-OPTICAL SYSTEM WITH THE PLASMA ANODE

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The algorithm of numerical simulation of electrons sources in base of the high-voltage glow discharge with the anode plasma, taking into account change of the form and the location of a surface of anode plasma, that renders essential influence on formation of an ion stream, which at hit on the cold cathode as a result of secondary ion - electronic emission forms an electron beam, is offered. As against other algorithms the offered physics-mathematical model takes into account influence on distribution of potential not only an ion space charge, but also a space charge of beam electrons, distribution of potential in turn defines as a trajectory the beam electrons and a stream of ions, and position of plasma edge which movement is considered during formation of a beam according to Stefan's condition.

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In sources of electrons on the basis of the high-voltage glow discharge emission of electrons from the cold solid-state cathode occurs as a result of its bombardment by the ions injected by the plasma anode [1]. Acceleration of electrons in the area of cathode fall of potential and their formation in a beam occurs in a back ion stream. In this connection extent of area of cathode fall of potential and the form of a surface of anode plasma are defined by properties of bipolar electron-optical system (a voltage between the cathode and the plasma anode and density ion and electron currents). The density of a beam electron current depends on characteristics of ion stream and factor of secondary ion-electron emission. Formation of an ion stream is determined in turn by an arrangement and the form of a plasma surface.

As against other algorithms [2] offered physics-mathematical model takes into account influence on distribution of potential not only an ion space charge, but also a space charge of electrons of a beam, distribution of potential in turn defines as a trajectory of electrons of a beam and a stream of ions, and position of plasma edge which movement is considered during formation of a beam according to Stefan’s condition. Thus boundary conditions (an arrangement and the form of a surface of plasma) have time to change during flight of ions up to the cold cathode, hence mathematically the task of calculation of formation an ion beam is a non-stationary task. Therefore in the offered algorithm of numerical simulation of electrons sources of the high-voltage glow discharge with anode plasma the ion stream is calculated by a method of large particles. The electronic stream is calculated by a method of a current tubes on each step of calculation of the equations of movement of large particles (ions). It is defined by that electrons speed on some orders is more than speed of ions, and it is possible to believe, that electrons for a time step have time to reach the plasma anode, hence their movement can be described by the equation of a trajectory, instead of the equation of movement in the form of the Newton’s law.

The algorithm of numerical modelling consists of the following stages:

1. The setting of geometry of calculation region, parameters of grid area of large particles, potentials of electrodes, density of a current of an ion beam and initial position of plasma edge; the density of a current of the ions emitted by anode plasma, was defined by the Bom’s formula in view of speed of movement of a surface of plasma:

$$j_i = en_i(0.61\sqrt{kT_e / M_i} - dS/dt),$$

   where $\mathbf{n_i}$ - density of ions of plasma, $\mathbf{T_e}$ - electron temperature of plasma, **e** - a charge of an ion, $\mathbf{M_i}$ - mass of an ion, **k** – Boltzmann constant, **S** - displacement along a normal to boundary of division plasma – ion beam from an initial condition. Ions are emitted on a normal to a surface of plasma.

2. The decision of Laplace’s equation for calculation of distribution of potential **φ** at the initial moment of time and calculation of intensity of a field $\bar{\mathbf{E}}$:

$$\Delta\varphi = 0, \quad \vec{E} = -\nabla\varphi$$

   For difference approximation of Laplace’s equation the five-point scheme was used, for the decision the difference equation the method of variable directions (Pisman-Racford’s method) was used. For calculation of the components of intensity of an electric field formulas of numerical differentiation were used.

3. Start from boundary of plasma of group of large particles

$$N_{inj.l} = \frac{j_i}{eN_{enl.}}\Delta m,$$

where $\mathbf{N_{inj.l}}$ - number simultaneously injected large particles, $\mathbf{\Delta\tau}$ - time of emission of the next set of large particles, $\mathbf{eN_{enl.}}$ - density of a charge of a large particle, $\mathbf{N_{enl.}}$ - parameter of enlargement.

4. The decision of system of the equations of movement of large particles:

$$\frac{d\overrightarrow{r_j}}{dt} = \overrightarrow{v_j}\ ,\ M_i\frac{d\overrightarrow{v_j}}{dt} = \frac{e}{V}\int \vec{E}d^3r\ ,$$

where $\overrightarrow{\mathbf{r_j}}$, $\overrightarrow{\mathbf{v_j}}$ - - radius-vector a large particle and its speed accordingly, $V = \int d^3r$ - volume a large particle. At numerical integration of the equations of movement of large particles Runge-Kutta method was used.

5. Definition of net density of space ion charge $\boldsymbol{\rho_i}$ and distributions of density of an ion current on the cathode $\mathbf{j^{cath}_i}$:

$$\rho_i = \sum_j eN_{enl.}\ ,\ j_i^{cath} = \sum_j eN_{enl.}v_j^{cath}\ ,$$

where $\mathbf{v^{cath}_j}$ - speed a large particle at the cathode, summation is conducted on number of large particles, past the given cell of a grid.

6. On the found density of ion current on the cathode there is a density of an electrons current $\mathbf{j^{cath}_e}$ emitted by the cathode as a result of secondary ion-electronic emission

$$j_e^{cath} = \gamma j_i^{cath}\ ,$$

where $\boldsymbol{\gamma}$ - factor of secondary ion-electronic emission. The electrons are emitted along a normal to a surface of the cathode.

7. Trajectories of electrons by a method of a current tubes are determined. For this purpose the area of the cathode is broken into parts by area $\mathbf{S_0}$, borders between which represent the beginning of a current tubes. Tubes of a current are formed to trajectories boundary electrons. The equation of a trajectory were it is received by the combined decision of the equation of movement of electrons in the form of Newton's law and law of conservation of energy:

$$\frac{d^2r}{dz^2} = \left(\frac{\partial\varphi}{\partial r} - \frac{\partial\varphi}{\partial z}\cdot\frac{dr}{dz}\right)\left(1 + \left(\frac{dr}{dz}\right)^2\right)\left(\frac{m_e\vartheta_{0e}^2}{|e|} + 2U\right)$$

where **r** and **z** - radial and axial coordinates, $\mathbf{m_e}$, $\mathbf{v_{0e}}$ – mass of electron and its exit speed from the cathode, **U** - a potential difference between the cathode and the plasma anode. For calculation of function **r(z)** formulas of numerical differentiation were used.

8. The space electron charge in each point of grid of calculation region $\boldsymbol{\rho_e}$ is defined as:

$$\rho_e = \frac{j_e^{cath}S_0}{S_z\vartheta_e}\ ,$$

where $\mathbf{S_z}$ - the area of section of a current tube by a plane **z**. Speed of electrons in point is determined according to the law of conservation of energy:

$$\frac{m_e\vartheta_e^2}{2} = \frac{m_e\vartheta_{0e}^2}{2} + eU$$

9. The distribution of potential by the decision of Poisson's equation with the account both ion and electron space charges is defined as:

$$\Delta\varphi = -\frac{\rho_i - |\rho_e|}{\varepsilon_0}$$

10. The finding of new position and the form of a surface of the plasma anode according to Stefan's condition:

$$\frac{dS}{dt} = \left(\frac{\varepsilon_0}{M_i n_i}\right)^{1/2}\left(\frac{\partial\varphi}{\partial n} - \left(\frac{2n_i kT_e}{\varepsilon_0}\right)^{1/2}\right)$$

where **S** - displacement along a normal **n** to boundary of division plasma – ion beam from an initial condition. $\partial\varphi/\partial n$ - the module of intensity of a field.

11. Passage to injection of new group of large particles and recurrence of all calculations up to the moment of an establishment of boundary of plasma and the finishing of change of values of potential and density of a space charge within the limits of the given accuracy.

Thus, we shall receive the established cathode fall of potential, an arrangement and the form of a surface of the plasma anode, a trajectory of ions and electrons of a bipolar stream, distribution of density ion current on the cold cathode, distribution of density of a current of an electron beam on cross section.

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