# ULTRASAM - 2D CODE FOR SIMULATION OF ELECTRON GUNS WITH ULTRA HIGH PRECISION

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## *Abstract*

The program package UltraSAM intended for simulations of cylindrically symmetric electron guns and collectors is described. The package is the further development of the program package SAM and combines the boundary elements method, used in SAM, with curved meshes for the space charge description. Advanced models of electron emission and beam dynamics are developed. The thermal spread simulation of initial velocities of particles at a cathode is also added. Due to this the precision of high perveance gun evaluations is improved, and the scope of devices that can be simulated is essentially extended. The simulation results of several electron guns are presented.

## 1 INTRODUCTION

The SAM code package was designed in BINP for simulations of stationary axial-symmetric electron-optical systems and electron guns [1,2]. In SAM code the boundary elements method is used. A surface charge is distributed across surfaces of electrodes and dielectrics. The contours of these surfaces are simulated by segments (lines and arcs). A set of rectangular meshes is defined for the space charge distribution. A space charge density is considered to be constant within individual cells. The quasilaminar model of current pipes is used for the description of beam dynamics.

Several disadvantages of realised in SAM code space charge description by rectangular meshes and models of emission and beam dynamics were found while working with this package:

1. The piecewise constant space charge density distribution in a cell is a rough approximation of the real distribution.
2. Rectangular meshes can not be adjusted, in some cases, with geometry of electrodes and beam shape. For example in calculations of guns with spherical cathode part of space charge is inside the cathode creating additional numerical noise of electric field in this area.
3. Only one emitter can be described. Its form can be only simple – flat or spherical.
4. Reflections of particles are not allowed in the quasilaminar model of current pipes.

In this paper the development of the SAM package is described. This development is intended to improve the precision of calculations and to extend the scope of solvable electron guns and collectors by elimination of the disadvantages stated above.

## 2 METHODS AND ALGORITHMS IN USE

### *2.1 Curved mesh*

The most important step in the development of SAM code is the replacement of a set of rectangular meshes by a set of curved meshes. Contours of curved meshes can be adjusted with geometry of electrodes and beam shape (see Fig. 2). It is possible to specify several complex shape emitters. Each emitter is simulated by several segments. A set of curved meshes is defined for every segment describing electron flux from it (see Fig. 5). These measures increase the precision of a near-cathode area simulation and decrease numerical aberrations, which arise at trajectory analysis due to inaccurate description of the beam self field on its edge [2].

Every cell of curved mesh is defined by nine points – nodes of cell (see Fig. 1). The cell is treated as a quadrangular element, which is defined in the finite elements method. The cell is transformed into the square, which is situated in logical plane XY with nodes in vertexes, middles of sides and in the centre. In this square the interpolation of some function $f$ is built with help of basis functions $\psi_i(x,y)$:

$$f(x,y)=\sum_{i=1}^{9} f_i\cdot\psi_i(x,y), \qquad \textbf{(1)}$$

where $x$, $y$ – coordinates in logical plane, $f_i$ – value of function $f$ in node number *i*. The transformation between real and logical coordinates is defined by substitution in Eq. 1 as $f_i$ coordinates of cell nodes $(r_i, z_i)$.

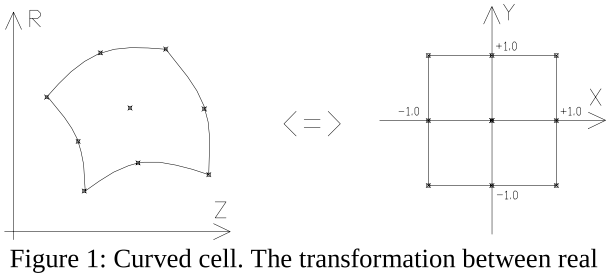

Figure 1: Curved cell. The transformation between real and logical coordinates.

### *2.2 Calculation of potential and field induced by space charge*

The potential induced by the beam space charge is equal to the sum of potentials induced by the space charges of individual cells. Using Eq. 1 the potential from one cell can be written as:

$$\begin{gathered}\varphi_{cell}(r_0, z_0) = \sum_{i=1}^{9} \rho_i \cdot M_i(r_0, z_0) \\ M_i(r_0, z_0) = \iint \psi_i(x, y) G(r_0, z_0; r, z) J(x, y) dxdy\end{gathered}, \quad \mathbf{(2)}$$

where $\rho_i$ – value of space charge density in the node number *i*; $r = r(x, y)$, $z = z(x, y)$ – transformation from logical coordinates into real; $J(x, y)$ – Jacobian of this transformation. Function $G(r_0, z_0; r, z)$ is the core of integral equations [2] and has the meaning of the potential induced in the observation point $(r_0, z_0)$ by charged ring with coordinates $(r, z)$, whose linear charge density is equal to one. The integration in logical coordinates is fulfilled in borders of the square, onto the cell is transformed. When the set of observation points is fixed, coefficients $M_i$ are depended only from the cell geometry and are calculated only once before space charge iterations. The calculation of these coefficients is embarrassed by the logarithmic singularity of function *G* in the observation point $(r_0, z_0)$. To keep the high precision of potential calculation when this point is situated near the cell or in it the singularity is separated analytically by the same method as described in [2].

The calculation of electric filed is fulfilled the same by replacement $G(r_0, z_0; r, z)$ with $\vec{\nabla} G(r_0, z_0; r, z)$.

### *2.3 Models of emission and beam dynamics*

To find the emitted current density the special surface is introduced. This surface is parallel to the cathode and is situated on the small distance $\delta$ from it. Knowing electric field $E_0$ on this surface the current density can be found using Child-Langmour low. The approximation of plane, cylindrical or spherical diode is used depending on the shape of the cathode and its position. The usage of electric field instead of potential improves significantly the convergence of space charge iterations due to sharp rise of field near the cathode.

The new beam model was developed to overcome the limitations of the quasilaminar model of current pipes. A beam is represented as a set of particle trajectories each currying its own part of full current. The charge induced in the node number *i* by particles flying through the cell can be written as:

$$Q_i = \sum_k \int I_k \cdot \psi_i(x_k(t), y_k(t)) dt, \quad \mathbf{(3)}$$

where $x_k(t)$, $y_k(t)$ – logical coordinates of particle number *k*, $I_k$ –current curried by this particle trajectory, integration is fulfilled by the time when the particle is in the cell. The charge density in the node is calculated from the induced charge as:

$$\rho_i = \frac{Q_i}{V_i}, \; V_i = \iint 2\pi \cdot r(x, y) \cdot \psi_i(x, y) \cdot J(x, y) dxdy \,. \quad \mathbf{(4)}$$

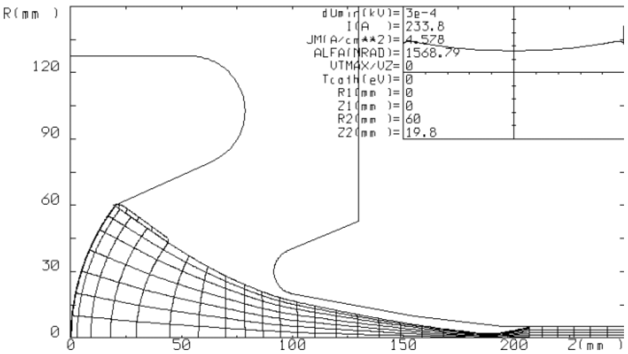

Figure 2: The electron gun of RF magnicon amplifier: the mesh used and the current density on the cathode.

In some systems the heating of a cathode has significant influence on the beam dynamics. The transversal thermal spread of initial velocities of particles is simulated to consider this effect. From every start point of trajectories (in the case of cold cathode) the calculation of several trajectories starts each having different additional transverse thermal velocities (see Fig. 6). These velocities are defined by the division of the plane of transverse velocities to radial and azimuthal layers. The number of these layers is defined by user.

## 3 EXAMPLES OF CALCULATIONS

One of the first tests of UltraSAM code was the calculation of the RF magnicon amplifier electron gun [3]. This gun with electrostatic beam area compression $C_s \approx 1000$ is intended for production of the uniform electron beam with high density (up to several thousands A/cm$^2$), high energy (430 KeV) and low emittance. The gun geometry, the mesh used and the emitted current density are shown on Fig. 2. To estimate the calculated emitted current accuracy one should consider the electric field on the cathode. In the space charge limitation regime the filed must be equal to zero. Due to the disadvantages of rectangular meshes the field calculated by SAM code is very noisy, while using the curved meshes for near-cathode area description the amplitude of filed oscillations is significantly closer to zero (see Fig. 3). Calculated perveance of this gun is $P_\mu = 0.829$, while its experimental value is $P_\mu = 0.83$. The trajectories and the electric field module distribution along the axis are shown on Fig. 4; the output beam profile and phase picture are shown in the top-right corner.

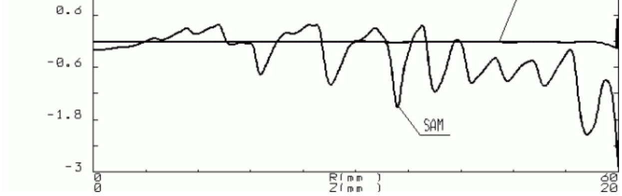

Figure 3: Electric field on the cathode of the magnicon electron gun obtained by SAM and UltraSAM.

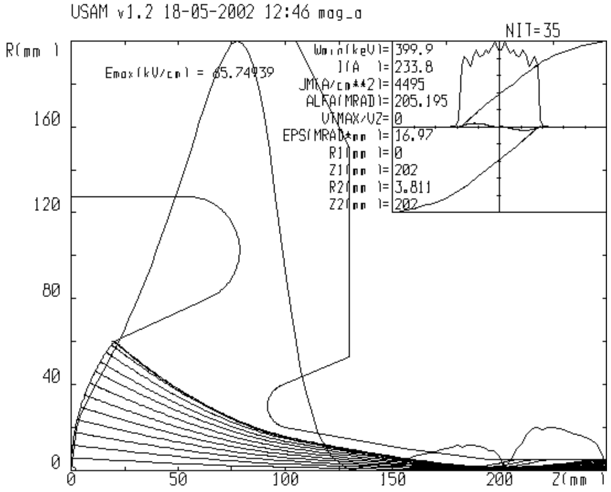

Figure 4: The electron gun of RF magnicon amplifier: the trajectories, the electric field module along the axis, the output beam profile and phase picture.

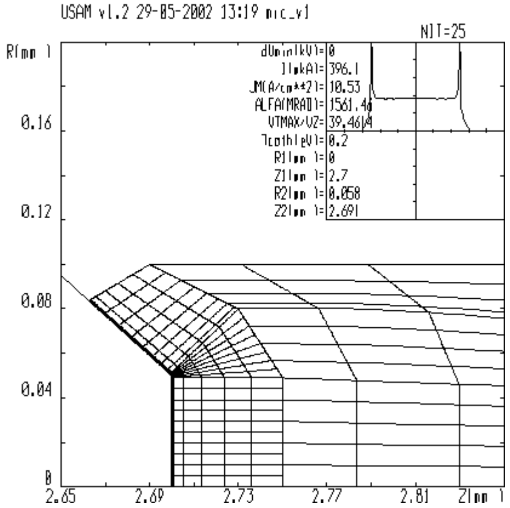

Figure 5: The electron gun for lithography: the mesh used and the current density distribution on the cathode.

The possibility of complex shape cathode simulations with the consideration of thermal effects is demonstrated by the simulation of the electron gun used in a lithographic device. On Fig. 5 the mesh used and the current density distribution on the cathode are shown. The trajectories with the thermal spread of transverse velocities, the output beam profile and phase picture are shown on Fig. 6.

Figure 7 illustrates the possibilities of UltraSAM package in calculations of systems with reflections of particles. This is the collector of Electron Beam Ion Source installation [4]. Central electrons reflect from the extractor, which is under negative potential with respect to the cathode potential.

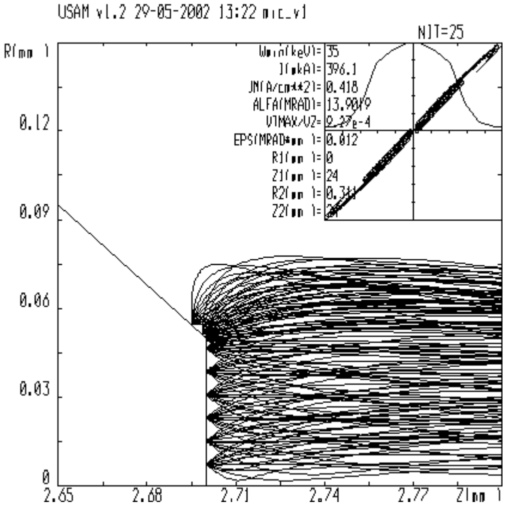

Figure 6: The electron gun for lithography: trajectories with thermal spread of velocities, the output beam profile and phase picture.

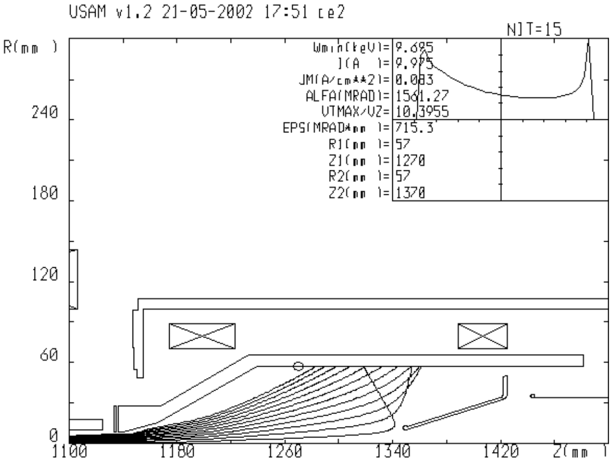

Figure 7: Collector of EBIS installation; current density on the surface of collector.

## 4 CONCLUSION

The introduction of curved meshes into the SAM package as well as the development of the new models of emission and beam dynamics increase the precision of calculations and extend the scope of solvable tasks of the UltraSAM package.

## 5 REFERENCES

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