# NUMERICAL SIMULATION OF THE PROCESSES OF SMALL-DIAMETER HIGH-CURRENT ELECTRON BEAM SHAPING AND INJECTION

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With the aid of BEAM25 program there was carried out the numerical simulation of the non-stationary process of shaping a small-diameter (≤ 20 mm) high-current hollow electron beam in a diode with magnetic insulation, as well as of the process of beam injection into the accelerating LIA track. The diode configuration for the purpose of eliminating the leakage of electron flux to the anode surface was updated. Presented are the results of calculation of the injected beam characteristics (amplitude-time parameters of a current pulse, space-angle distributions of electrons etc.) depending on diode geometric parameters.
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## 1 INTRODUCTION

A possibility for injecting a hollow electron beam of a diameter up to 20 mm and current of 10-20 kA into an accelerating track is considered. As LIA injector it is supposed to use an accelerator with a system of formation of accelerating voltage pulse on the basis of stepped lines [1], whose prototype is a pulsed accelerator STRAUS-2 [2, 3]. Injection energy is about 2 MeV at voltage pulse duration at half-height equaling ~60 ns. To confine the beam from radial expansion under the action of space charge forces in the accelerating track, there will be created a pulsed uniform longitudinal magnetic field with 1.5÷2 T induction. In order to form the electron beam, it is supposed to use an unshielded coaxial magnetic insulated diode with explosive emission.

Below given are the results of numerical simulation obtained with the use of the program BEAM25 (developed at VNIIEF) based on the method of particles in a cell. This 2.5-dimensional program with a regular non-uniform grid provides a self-consistent joint solution of Maxwell equations and equation of charged particles motion at the assumption of axial symmetry.

## 2 CALCULATION SCHEME OF INJECTOR DIODE ASSEMBLY

The calculated scheme of the injector diode assembly is presented in Fig. 1. In the left upper part of the calculated area the gap between cathode 1 and anode electrode 7 is selected in such a way that the line impedance is equal to the output impedance of the system forming the pulses of accelerating voltage of 18 Ohm. To the boundary marked in the figure with dotted line there is applied a voltage pulse whose shape is shown in Fig. 2. The amplitude of voltage in the mode of running wave constitutes 2.25 MV that corresponds to the voltage in the mode of free running 4.5 MV. The pulse duration at half-height is ~ 60 ns.

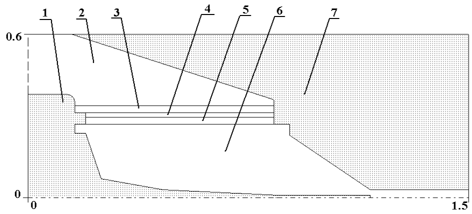



*Fig. 1. Calculated scheme of diode assembly.*

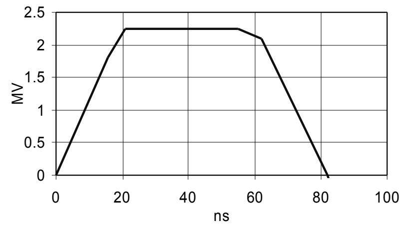



*Fig. 2. Shape of voltage pulse.*

The voltage pulse passes through volume 2 filled with transformer oil, accelerating tube and then achieves vacuum volume 6. The accelerating tube comprises a polyethylene tube 3 and sectioned insulator 5 and the layer of electrolyte 4 of 60 Ohm resistance being located between them. The electrolyte serves to equalize both the potential distribution along the sectioned insulator and the scattering of energy remaining in the injector after the work pulse is terminated. The axial size of the calculated area is 1.5 m while the radial one is 0.6 m. The anode cylindrical segment diameter constitutes 60 mm.

On the cathode surface inside the vacuum volume there was assigned the emission of electrons with a threshold strength of 200 kV/cm. The beam current and accelerating voltage is calculated in a self-constituent way following the condition of emission limitation by the space charge. The external magnetic field was superimposed on the calculated area. Fig. 3 presents the magnetic field inductance as a function of the longitudinal coordinate on the accelerator axis calculated in terms of selected design of solenoids.

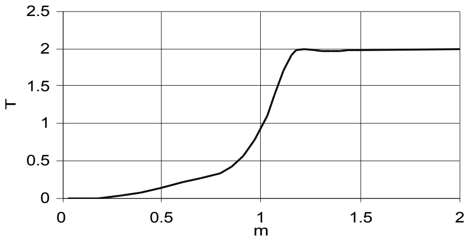



*Fig. 3. Magnetic field inductance versus longitudinal coordinate of the accelerator axis.*

Because of the electric field high strength the explosive emission of electrons takes place on a considerable part of the conical surface of cathode electrode. A series of calculations for cathode electrodes of different configuration was performed. In accordance with the results obtained, best conditions for small-diameter beam formation are realized for the case when the boundary of cathode electrode is directed along the magnetic field line. The calculated distribution of magnetic field lines near the cathode electrode is given in Fig. 4. In Fig. 5 the distribution of electrons in diode at the 40 ns time moment is presented that corresponds to the voltage pulse medium.

## 3 CALCULATION OF INJECTED BEAM CHARCTERISTICS

A simplified calculated scheme presented in Fig. 6 was used for detailed consideration of the effect to the electron beam characteristics of such parameters as anode-cathode gap and cathode radius. This made it possible to considerably increase the counting rate with getting practically the same results.

The radial gap of the transmission line in the left upper corner was selected in such a way that the impedance of the system of voltage pulses formation and the resistance of the connected in parallel electrolytic layer are simulated. The emission was assigned on the horizontal and face surfaces of the cathode. To the boundary marked by dotted line applied was the voltage pulse whose amplitude was determined in the calculation of the previous scheme (Fig. 1) for the case of electron beam absence.

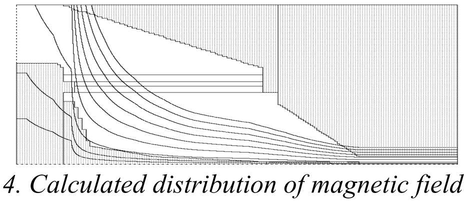


*Fig. 4. Calculated distribution of magnetic field lines near the cathode electrode.*

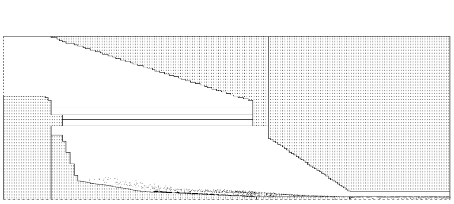


*Fig. 5. Distribution of electrons in the diode assembly at 40 ns time moment.*

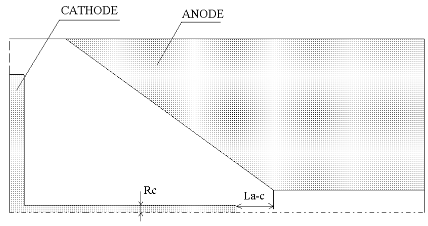
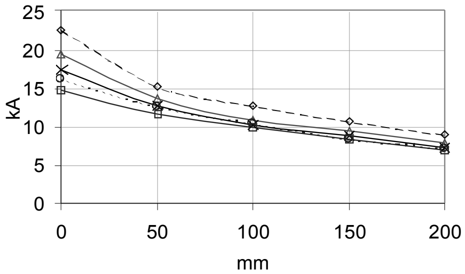


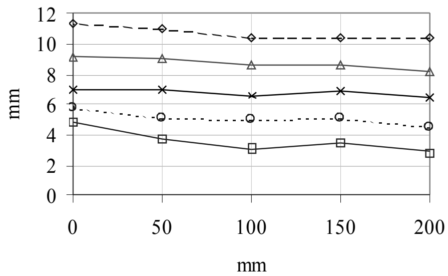

*Fig. 6. Geometry of the simplified calculated scheme of the injector diode.*

In the calculations the anode-cathode gap ($L_{a\text{-}c}$) was varied from 0 to 200 mm with a 50 mm step while the cathode radius ($R_c$) – from 2 to 10 mm with 2 mm step.

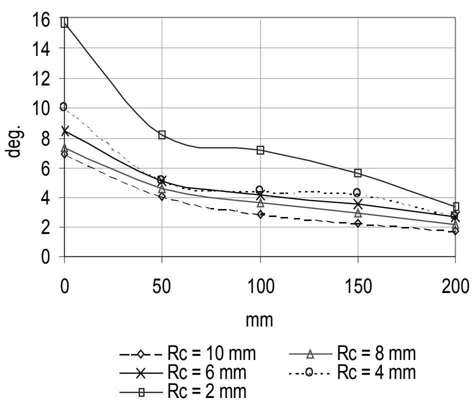
The results of calculations for the case of $B_z$= 1.5 T are presented in Fig. 7. Here shown are the dependencies of current amplitude (a), maximal beam radius (b) and module of pulse particles average angle (c) as related to the axis of symmetry on the right boundary of the calculated area depending on the anode-cathode distance at different cathode radii.




a

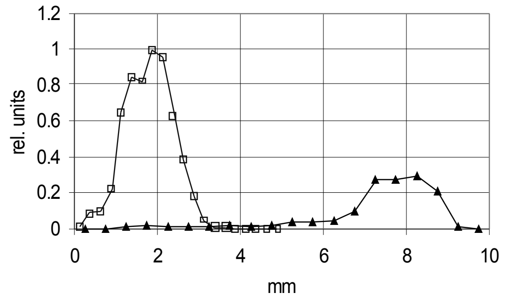



b

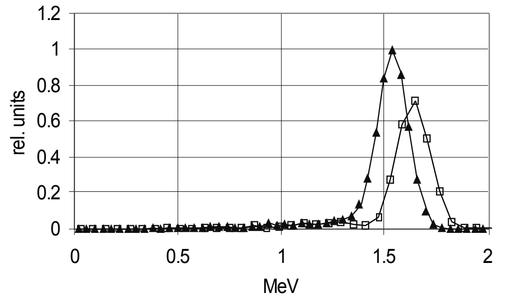



c

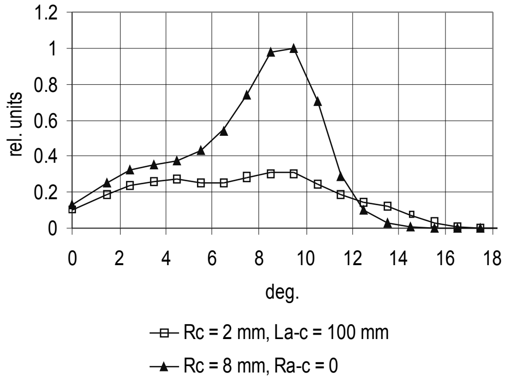
*Fig. 7. Current amplitude (a), beam radius in diode (b) and module of electron pulse average angle (c) versus anode-cathode distance at different cathode radii.*




a




b




c

*Fig. 8. Distribution of the charge density by radius (a), as well as distribution of particles by energy (b) and angle (c) for the cases of $R_c$ = 8 mm, $L_{a-c}$ = 0 and $R_c$ = 2mm, $L_{a-c}$ = 100 mm.*

When increasing the anode - cathode gap there take place the reduction of injected current, inconsiderable decrease of beam diameter and improvement of angular characteristics. To inject a beam with the external diameter ≤ 20 mm one should choose the cathode radius of ≤ 8 mm. The current amplitude of 20 kA is realized for the version of $R_k$ = 8 mm at the gap $L_{a-c}$ = 0, when the average relation of transverse and longitudinal pulse of particles constitutes $P_\perp/P_\parallel$ = 12.8% at the external beam diameter D = 18.5 mm. For the cathode of the specified radius the injected current decreases to 10 kA at $L_{a-c}$ = 130 mm when $P_\perp/P_\parallel$ = 4.4% and D = 17.5 mm. The current of 10 kA is achieved for the cathode of 2 mm radius at $L_{a-c}$ = 100 mm when $P_\perp/P_\parallel$ = 12.6% and D = 6.5 mm. The last version is of interest for the achievement on the target of the beam of minimal diameter.

For all the cases being considered the hollow beam is formed in the diode and injection energy for the voltage pulse peak varies inconsiderably and lies within the interval from 1.6 to 1.8 MeV. The calculated distribution of the charge density by radius (a) as well as the distribution of particles by energy (b) and angle (c) for the cases of $R_k$ = 8 mm, $L_{a-c}$ = 0 mm and $R_k$ = 2 mm, $L_{a-c}$ = 100 mm are presented in Fig. 8 by way of example.

Similar calculations for different values of magnetic field inductance were performed. The injected current grows as the leading magnetic field decreases that is explained by the rise of a limiting current caused by the increase of the electron flux diameter. The beam radius and the module of the average angle of the particle pulse grow quite slowly with the decrease of the magnetic field from 2 to 1.25 T and start growing quickly with further field reduction. The $B_z$ = 1.5 - 2 T range was selected to be optimal for accelerator.

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