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SIMULATION OF ELECTRON-OPTICAL SYSTEMS OF ELECTRON COOLERS

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Abstract

To provide successful operation of electron coolers one need thorough simulation and development of electron-optical system. In this paper simulations of electron gun, accelerating structure and collector are discoursed. Particular attention is paid to obtaining high perveance electron beam with a small transversal temperature and controlled profile, and collector with low flux of secondary electrons. Bends of electron beam are also considered.

Main program for simulations is SAM code. This code is based on boundary integral method, its main advantage is precision and speed of calculations.

INTRUDUCTION

At the development of such large facilities as electron coolers, it is necessary to perform an initial numerical simulation of all the important parts. In this paper, we focus on numerical calculations and optimization of the electron-optical system of electron coolers and the dynamics of electron beams in them. Since the coolers created in BINP use magnetized beams, the following tasks can be distinguished: first, it is necessary to build and optimize the magnetic system in the region of the electron gun and the collector. The second task is the numerical development of the electron gun itself as well as the collector. The third task is the development of a magnetic system for bends and matching system and optimization the beam motion in these regions.

To solve these problems, SAM [1, 2] and MAG3D [3] packages are mainly used in BINP. These programs were developed at the Institute; their main peculiarity is the use of integral methods for calculations, which ensures good accuracy and speed of calculations. The SAM program is intended for simulation of axially symmetric electron optical systems with space charge consideration. These systems can include electrodes, dielectrics, coils, permanent magnets, linear ferromagnetics. Tasks with space charge can also be simulated with help of the SAM program, that allows calculation of electron guns and collectors. MAG3D program is used to solve problems of nonlinear 3D magnetostatics.

SIMULATION OF ELECTRON GUNS

The specificity of electron cooling makes the following requirements for electron guns used in coolers:

- required perveance;
- independent current and energy control;
- low (< 1 eV) transverse temperature of the beam;
- independent adjustment of the current density distribution across the beam.

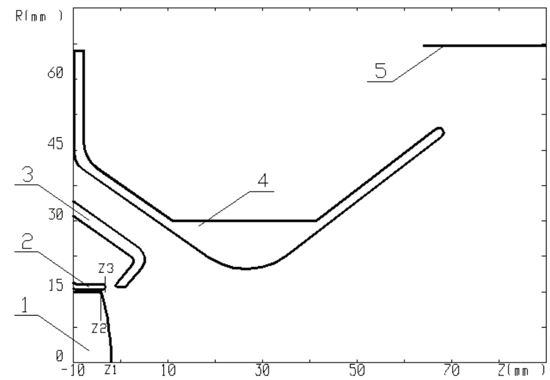

Figure 1: Geometry of electrodes of the electron gun with variable beam profile.

To meet these requirements, an electron gun was developed in the Institute, the drawing of which is shown in Fig. 1. The convex cathode 1 immersed into longitudinal magnetic field is used. To form the electron beam control electrode 3 is used together with anode 4. The control electrode is placed near the cathode edge and influences the emission from this area. By applying different potential on this electrode the beam with radial current density distribution from parabolic to hollow can be obtained.

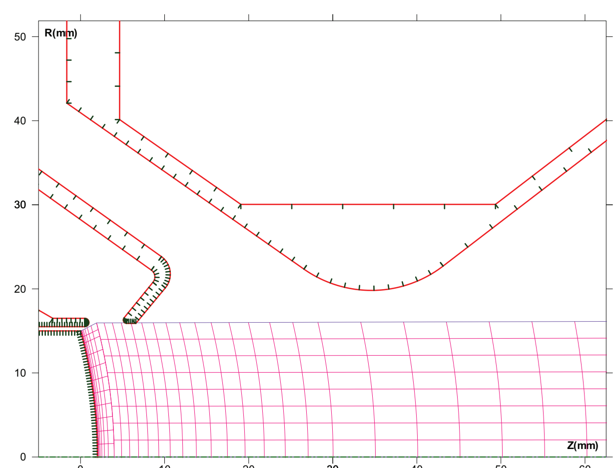

Figure 2: The mesh used for calculation of the electron gun.

The calculation and optimization of this gun was performed using the SAM package, the mesh used for the calculations and the collocation points are shown in Fig. 2. The total number of collocation points is less than 200, total number of cells in mesh – less than 500. With such a number of nodes calculation takes little time – less than 1 minute, even on a relatively low-power personal computer. However, the ability of the SAM complex to

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describe the emission from cathodes of complex shape and the ability to thicken the cells allowed not only to achieve high accuracy of calculations, but also to describe the emission from the very edge of the cathode.

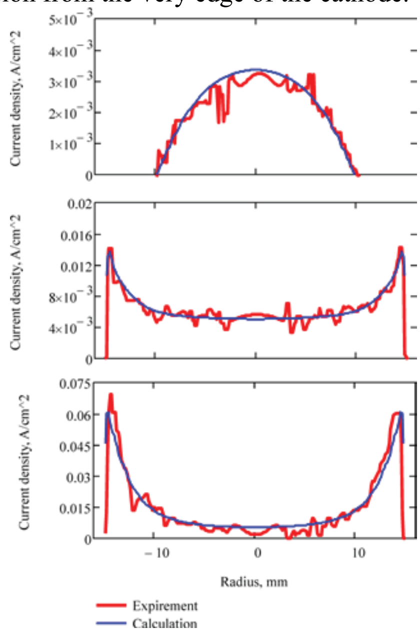

Figure 3: Calculated and experimentally obtained beam profiles at various potential of control electrode.

Experimental studies had confirmed [4] all the main parameters of the gun obtained previously in numerical simulations, including its perveance, the threshold of the virtual cathode, and the dependence of the beam profile on the voltage ratio of the control electrode and anode (see Fig. 3).

SIMULATION OF COLLECTORS

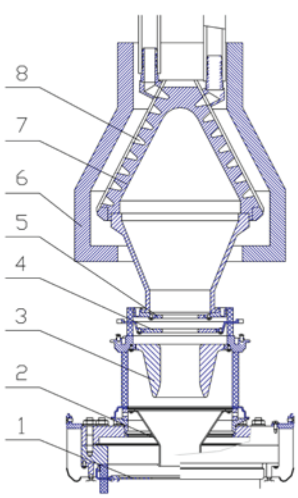

Figure 4: The collector of electron coolers for CSR and LEIR rings.

In electron coolers, when the electron beam moves from the electron gun to the cooling solenoid, it passes one or more bends. In the accompanying magnetic field, this movement is accompanied by centrifugal drift, which must be compensated. In the electron coolers created in the BINP for CSR (IMP, China) and LEIR (CERN) rings, this compensation is carried out by creating a transverse electrostatic field in the bends. Such electrostatic compensation works equally well for both the primary electron beam and the secondary beam moving from the collector in the opposite direction. In such a system, it is not necessary to provide a very small secondary collector emission factor to ensure low total losses. In the coolers for COSY (Jülich, Germany) and NICA (JINR, Russia) rings, the electrostatic compensation is replaced by a magnetic one, with a strong transverse displacement of the secondary beam after cornering. In this case, a very small collector secondary emission factor ($< 10^{-5}$) is required to ensure stable operation of the entire cooler.

The collector of electron coolers for CSR and LEIR rings is shown in Fig. 4. The massive magnetic shield 6 weakens the magnetic field inside the collector, the electron beam expands and comes to the cooled inner surface 7 with an acceptable current density. This reduced field also forms a barrier – a magnetic plug – on the path of secondary electrons that try to leave the collector following the magnetic field lines. The second barrier to the way of this secondary flow is the electrostatic barrier formed by the suppressor electrode 4.

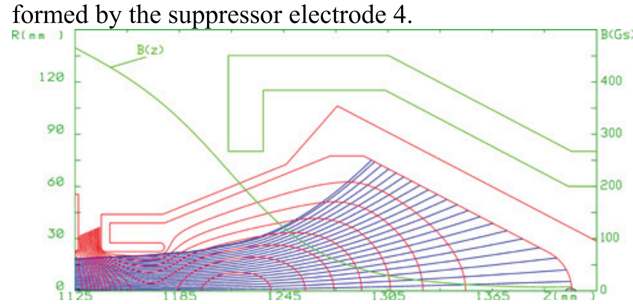

Figure 5: Equipotentials and trajectories of electrons in the collector for CSR ring.

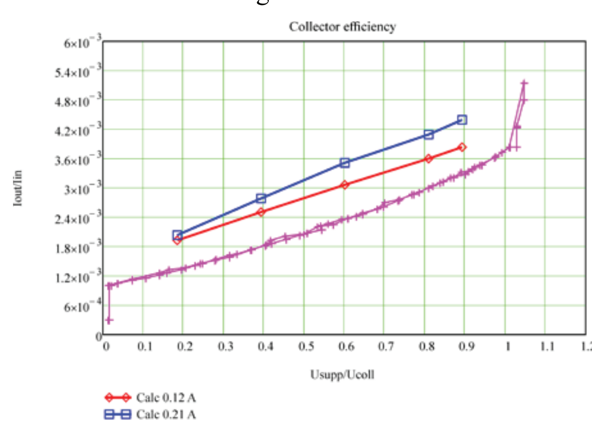

Figure 6: Dependence of collector efficiency from the suppressor potential.

The SAM program was also used to calculate and optimize this collector taking into account the space charge of both primary beam and secondary electrons. The electron beam was calculated from the Neumann boundary located in front of the collector, the calculation time is also insignificant. The results of collector calculation are shown in Fig. 5.

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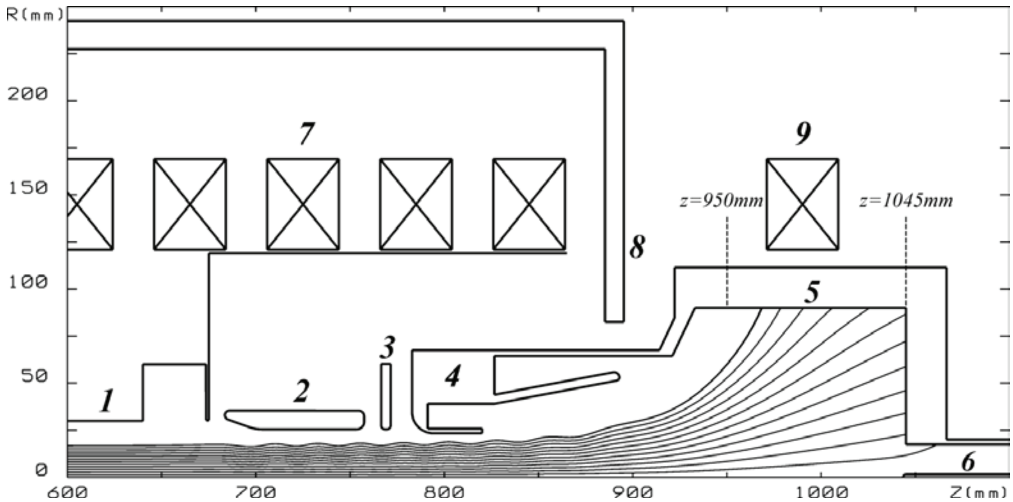

Figure 7: The collector for COSY ring and the electron beam trajectories.

The secondary emission model integrated into the SAM complex was used in the calculations. This model considers all three types of secondary electrons – true secondary electrons, rediffused and backscaterred electrons. Their total coefficients, angle and energy distributions are taken into account. Several generations of secondary electrons are also considered. These calculations allowed us to estimate the output flow of secondary electrons from the collector (see Fig. 6), subsequent measurements confirmed the dependence obtained in numerical simulations [5].

In COSY and NICA coolers to reduce secondary coefficient of collector, a Wine filter is placed between the collector itself and accelerating column. In this filter, additional electrodes create a transverse electric field, and a set of permanent magnets create a transverse magnetic field. These fields for the primary beam compensate each other, and for the secondary beam that goes in the opposite direction, they reinforce each other. As a result, the primary beam passes this filter without noticing these fields, and the secondary beam experiences a strong transverse displacement and goes to the diaphragm. Calculation of the Wine filter was performed with help of MAG3D program. This system showed the efficiency several orders of magnitude better than the efficiency of a single collector [6].

Due to the presence of Wien filter, the collector itself can have a simpler design (see Fig. 7), without the need for a massive magnetic screen. To reduce the magnetic field in the collector region, it was enough to put a magnetic wall 8 that divides the collector from main magnetic system, and for further decrease of magnetic field one standard coil 9 with the opposite direction of current can be used.

SIMULATION OF ELECTRON MOTION IN BENDS

As mentioned above, when the magnetized beam moves in bends, the centrifugal drift of electrons is compensated by either the force from the electrostatic field in CSR and LEIR coolers, or Lorentz force in NICA and COSY coolers. To maintain the beam orbit in the same plane, these forces must compensate for each other on average, but it is impossible to achieve their complete mutual compensation at each point of the beam path. An uncompensated transverse force appears; this force is especially big at the entrance to the bend and at the exit from it, causing a significant transverse motion of electrons. It is necessary to choose the dynamics of the particles in bends in such a way that these two impacts will compensate for each other.

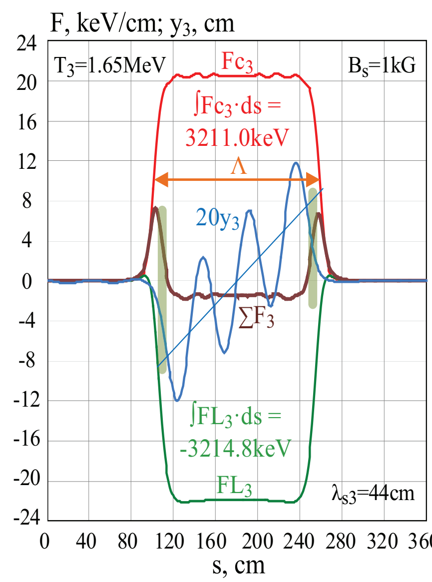

Figure 8: Centrifugal and Lorentz force in bends in COSY cooler and y-coordinate of the central electron.

The results of the calculation of the forces acting on central electrons in the turns and the results of the trajectory analysis of these particles in the optimized system are shown in Fig. 8. These calculations were performed with help of MAG3D program. Less than 3,000 elementary volumes were required to model the magnetic elements of the transport system, and the total calculation time was less than one hour [7].

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CONCLUSION

Software packages SAM and MAG3D, developed at BING, are successfully used in the development of electron coolers at the Institute. With the help of the SAM package, an electron gun with high perveance, low transverse temperature and a controlled beam profile was created, as well as two electron beam collectors with the required perveance and secondary emission coefficient. The MAG3D complex was used to calculate the transport system of our coolers with a longitudinal magnetic field and to optimize the motion of the electron beam in them. Test measurements confirmed the calculated parameters of these systems, which ensured the successful commissioning and operation of coolers.

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