BINP
SB RAS

Simulation of electron-optical systems of electron coolers

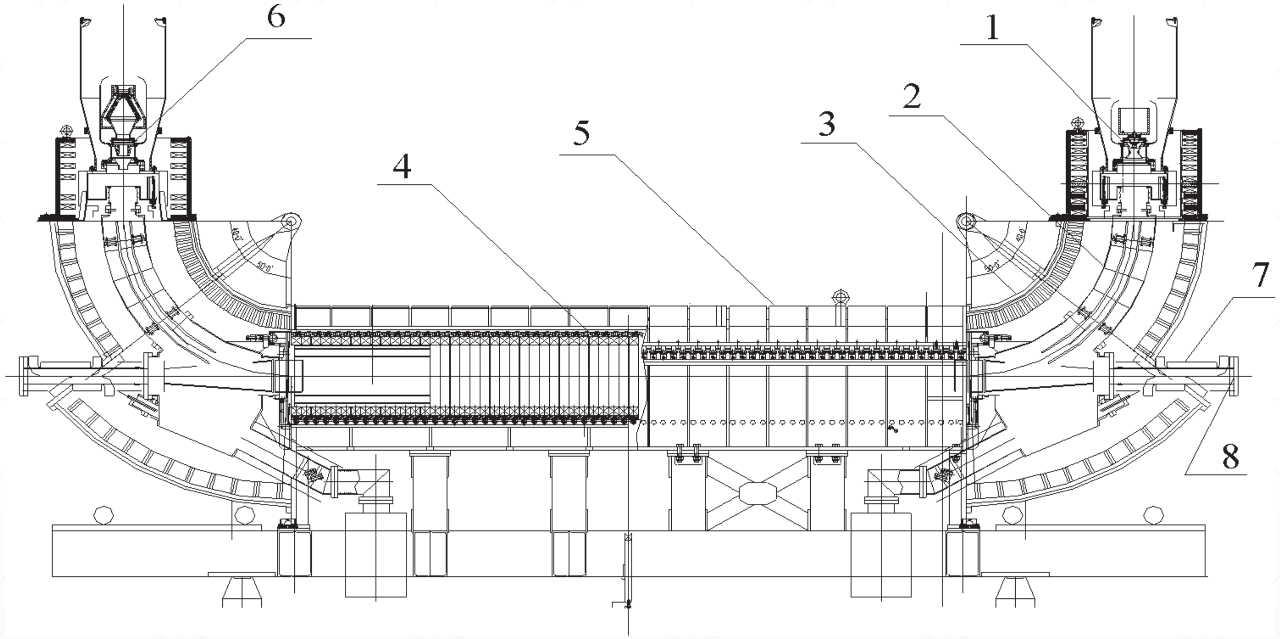
A.V. Ivanov, M.I. Bryzgunov, V.M. Panasyuk, V.V. Parkhomchuk, V.B. Reva
(BINP SB RAS, Novosibirsk)
COOL19 Workshop

Outline

- Tasks to be solved;
- Programs for calculations;
- Numerical methods;
- Calculations of electron guns, collectors, transport system.

Problems to be solved at the development of electron coolers

- Development of the magnetic systems of electron gun, accelerating system and collector
- Development of electron gun, collector and accelerating system
- Development of the magnetic system of toroids, bends and matching system
- Simulation of beam dynamics in bends

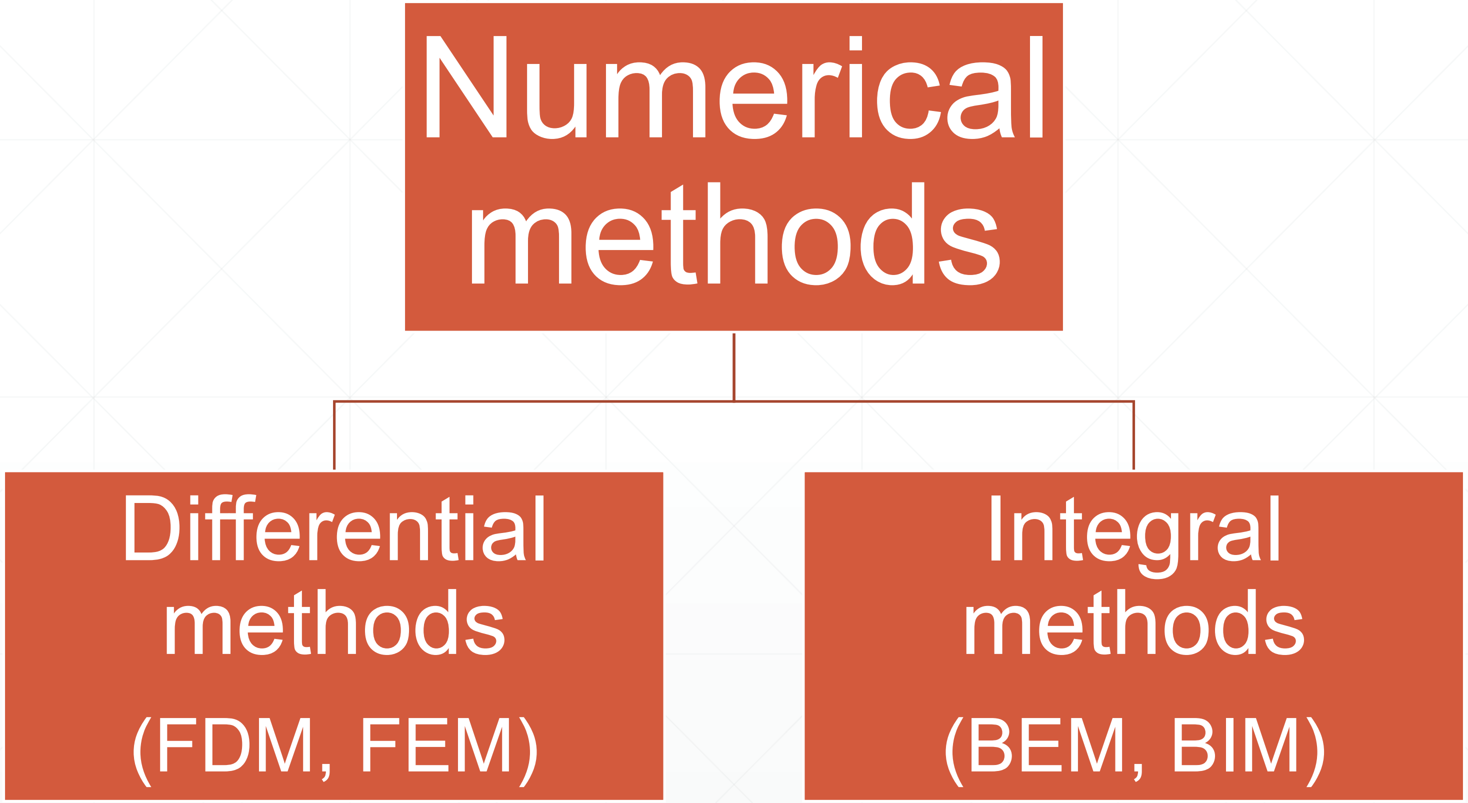


Commercial programs

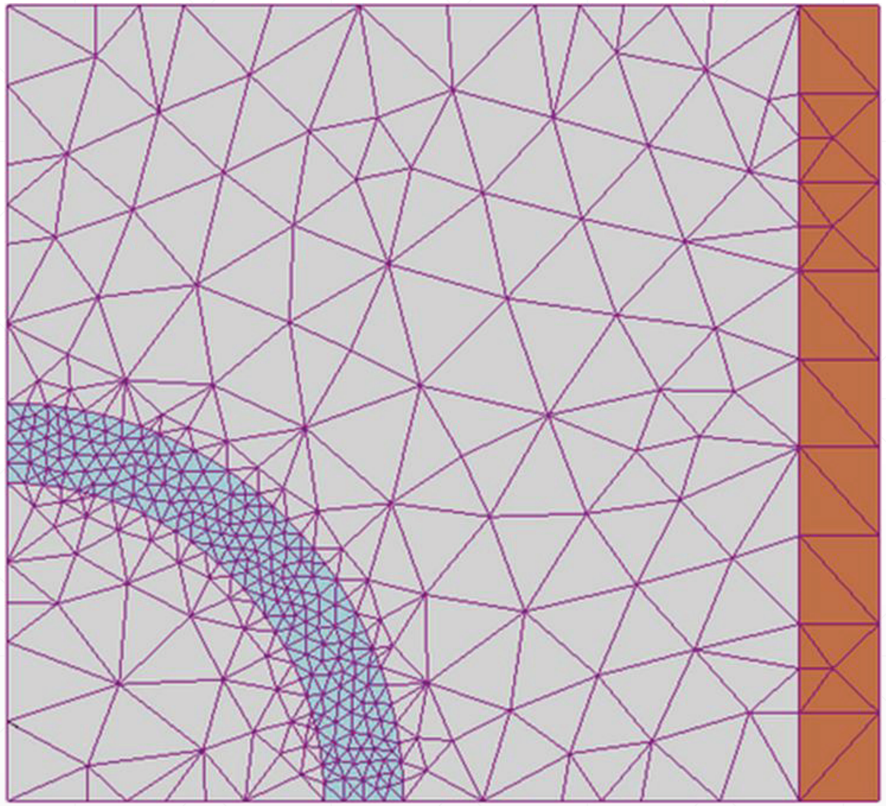
- COMSOL Multiphysics, OPERA
  - 3D electrostatic and magnetic systems
  - 3D trajectory analysis
- CST STUDIO SUITE
  - Resonators and other HF systems
  - 3D electron optical systems with space charge consideration

Programs developed in BINP

- SAM
  - Electron optical systems with flat or axial symmetry. These systems can include electrodes, dielectrics, coils, permanent magnets, linear ferromagnetics
  - Electron guns and collectors
  - Precise and fast calculations as main advantage
- MAG3D, MERMAID
  - 3D non-linear magnetostatic

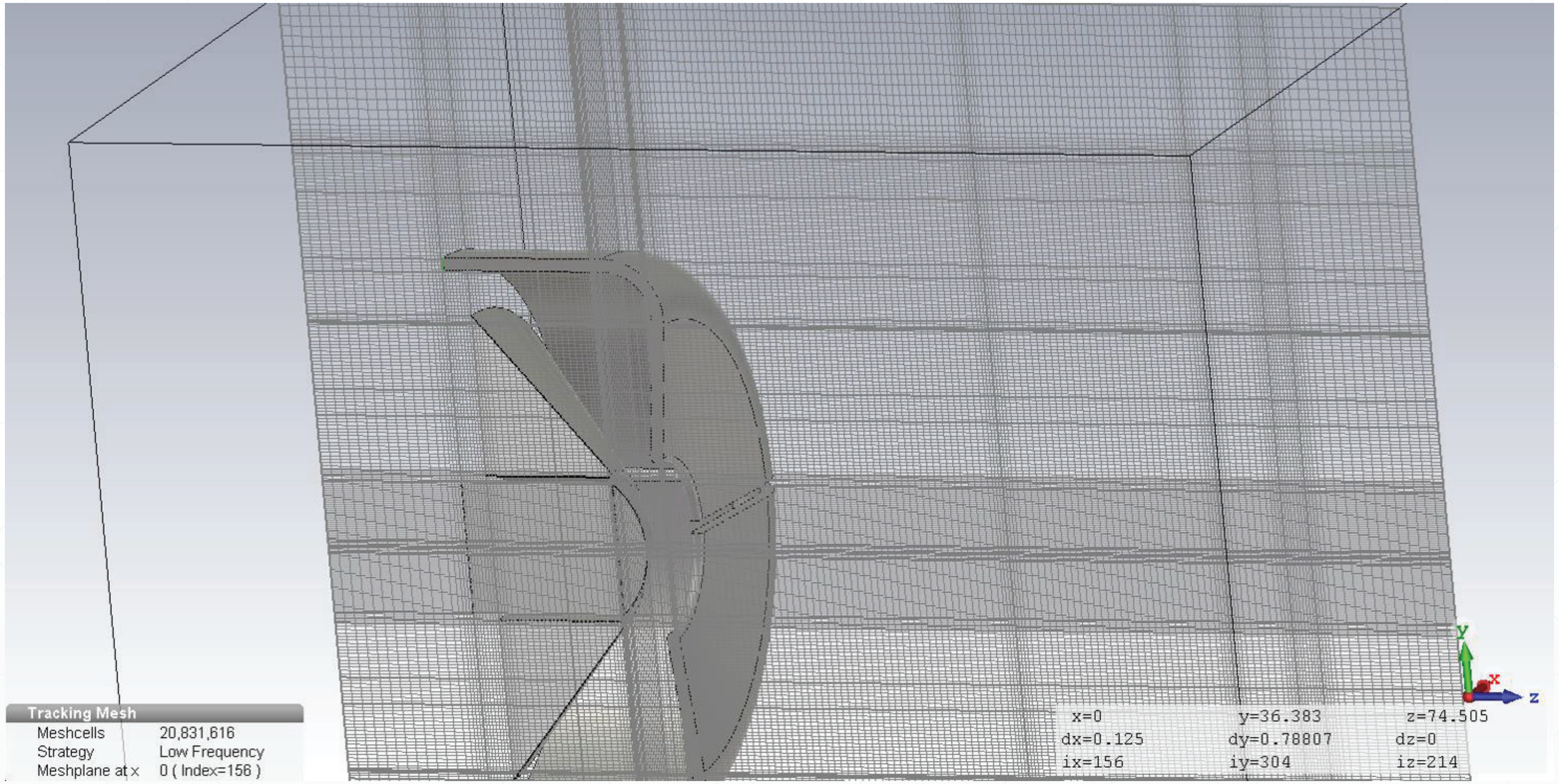

Numerical methods
Differential methods
(FDM, FEM)
Integral methods
(BEM, BIM)

Finite element method



- Universal and reliable numerical method for finding approximate solutions of boundary value problems for partial differential equations
- Representation of complex geometry by partitioning the entire domain in question into simpler parts (finite elements)
- The unknown function is interpolated in each element using base functions to best match the equation and boundary conditions
- The method is used to solve problems of electrodynamics, solid mechanics, thermodynamics, hydrodynamics, etc.

Finite element method



- It is necessary to cover by mesh the entire area under consideration, nothing can be known about the off-mesh space
- Boundary conditions must be set, often they are approximate
- In electrostatic problems, FEM provides an electrostatic potential as a solution. Numerical differentiation should be used to find the electric field

Boundary element method (SAM)

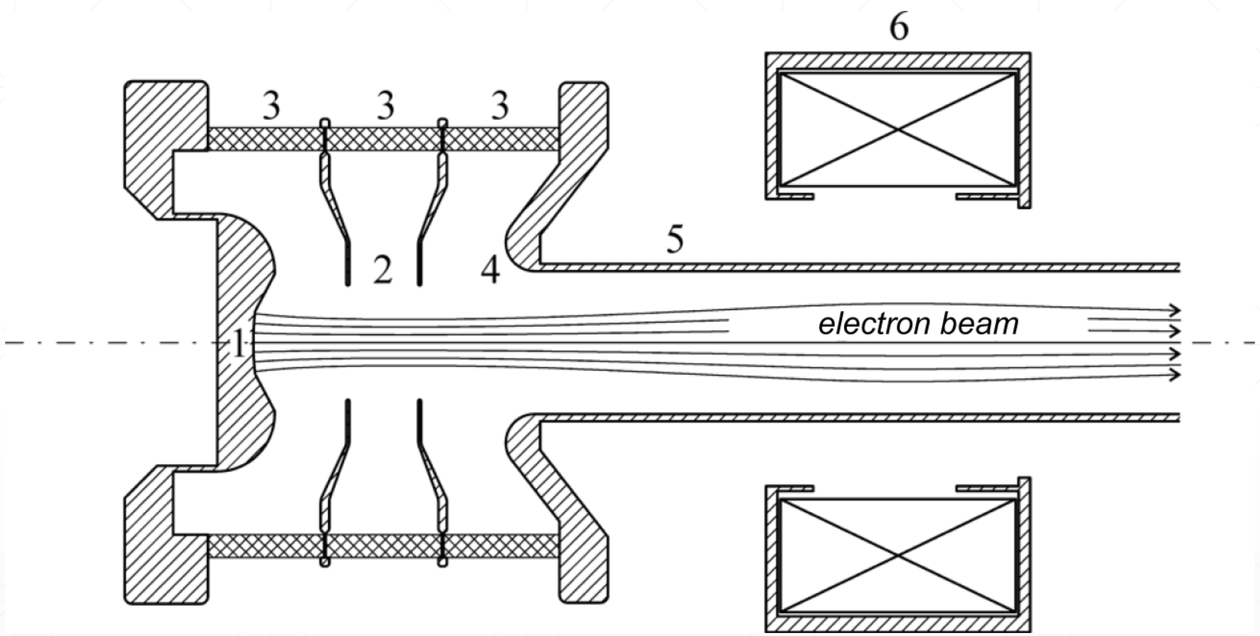
- Integral equation follows directly from the solution of the Poisson equation, written at points on surfaces of electrodes

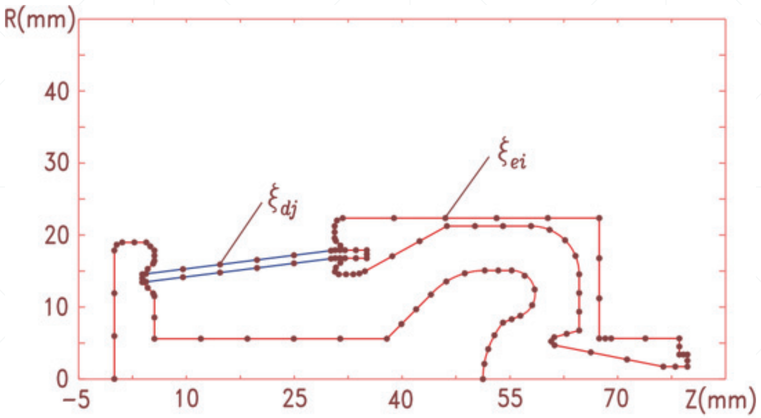
$$\phi(\vec{r}_0)=\int\limits_{S_e+S_d}\frac{\sigma(\vec{r})\;dS}{|\vec{r}_0-\vec{r}|}+\int\limits_{V_b}\frac{\rho(\vec{r})\;dV}{|\vec{r}_0-\vec{r}|}\quad\Rightarrow\quad\int\limits_{S_e+S_d}\sigma(\vec{r})\frac{1}{|\vec{r}_e-\vec{r}|}dS=\varphi_e-\int\limits_{V_b}\frac{\rho(\vec{r})\;dV}{|\vec{r}_e-\vec{r}|}$$

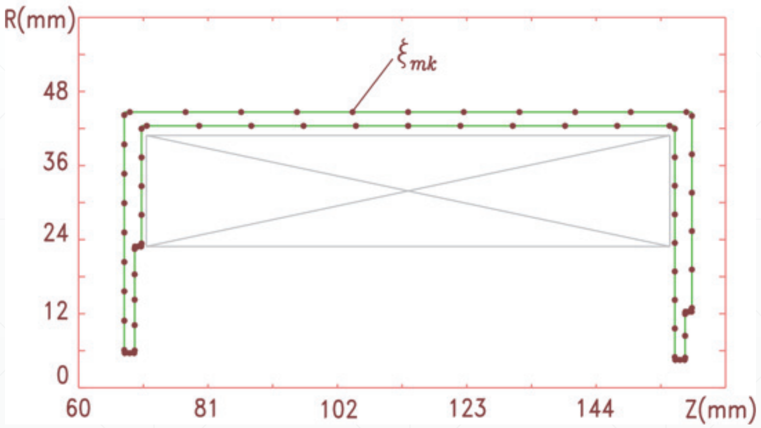
  here φ_e – electrode potential, S_e and S_d – surfaces of electrodes and dielectrics, V_b – the volume occupied by the beam.

- To solve this equation, the surface charge density distribution can be described by any linear interpolation. Unknown coefficients of this interpolation can be found from the following condition: the integral equation must be accurate at a number of points on the electrode surface – collocation points.
- The problem of linear magnetostatics can be considered in the same way.
- Reduction of the dimension of the problem!

Boundary element method (SAM)



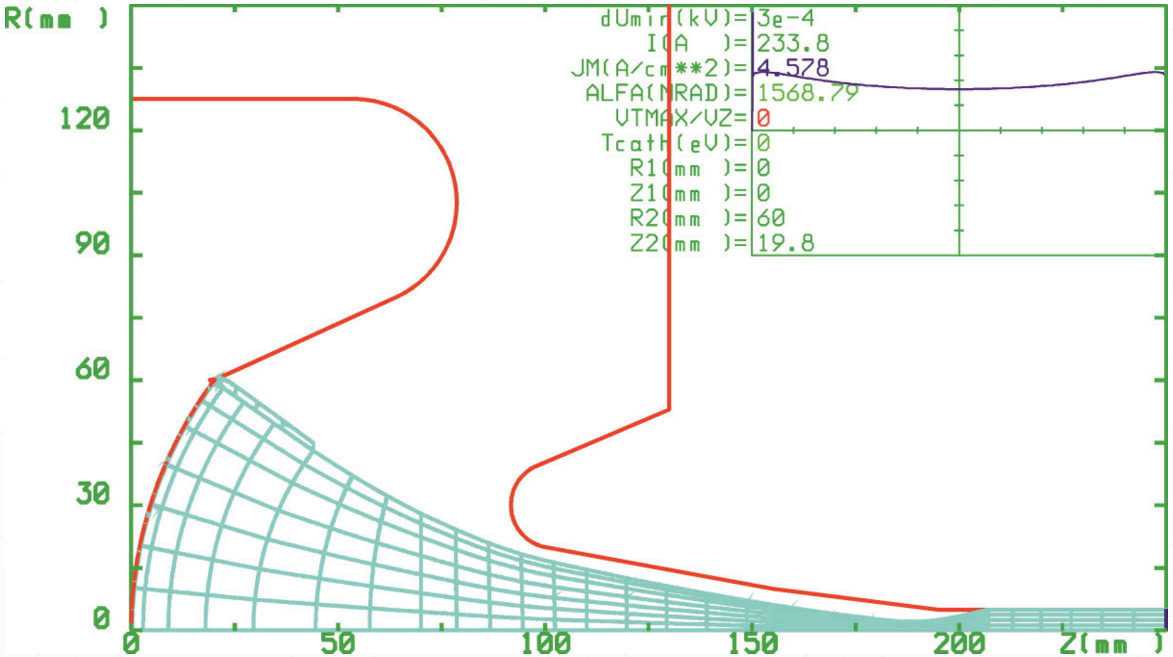




Boundary element method (SAM)

- Unlike FEM, the problem is set with open boundaries - the problem area is unlimited, there are no problems with boundary conditions.
- In BEM we have the field sources as the solution, we need to compute numerically the corresponding integrals to find the potential and the fields.
- Potential and fields are calculated with equal accuracy.
- If there is no space charge in the problem under consideration, then the spatial mesh is not needed – one should only place the collocation points on the surface of the elements.

Boundary element method



- The space charge must be taken into account when modeling the electron gun / collector. It is necessary to calculate both the corresponding integrals in the right parts of the integral equations and the integrals for calculating the potential and filed induced of the beam.
- The mesh must cover the entire space occupied by the space charge. There is a flexible mechanism for thickening the mesh cells where required.

SAM package – main advantages

- High accuracy of calculations, achievable even with a small number of nodes = > speed of calculations
- The relative ease of entering the geometry of the problem, the ease of mesh adjustment
- Output of all required results, possibility of interfacing with other calculation programs
- Commercial software is far from free and often requires annual license renewal. SAM – lifetime license

Boundary integral method (MAG3D)

- The magnetic field can be represented as the sum of the magnetic field of currents and the field induced by magnetized magnetic materials

$$\mathbf{H} = \mathbf{H}_c + \mathbf{H}_m$$

- Each of the terms satisfies the following equations

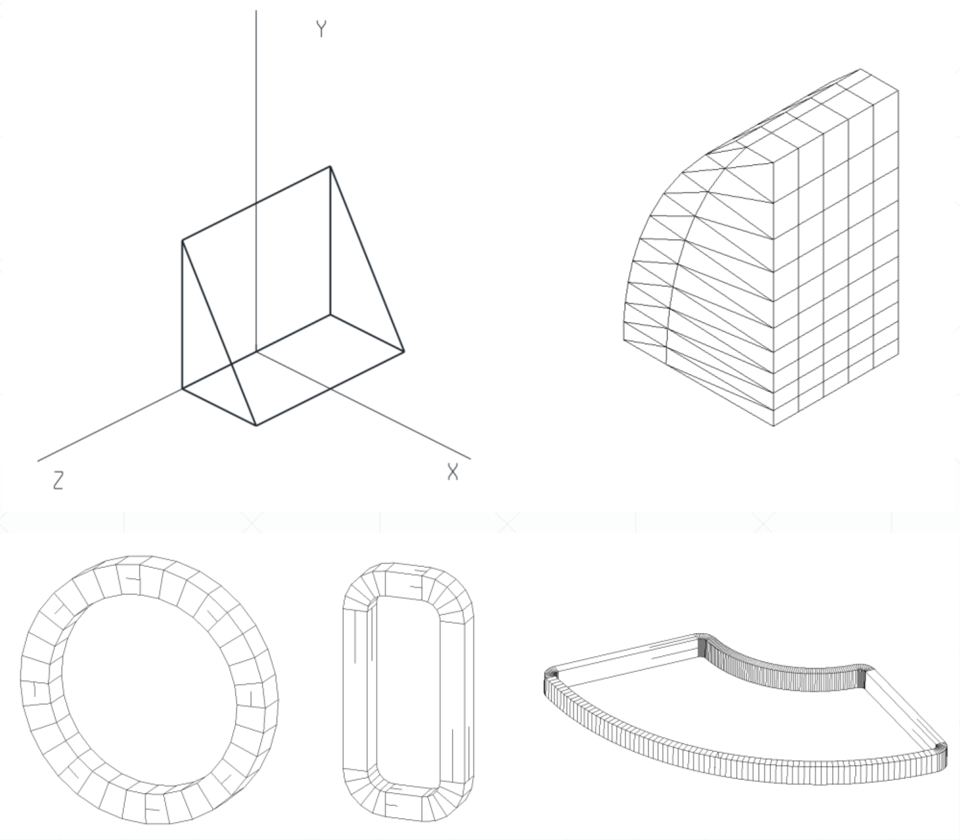
$$\mathbf{H}_c(\mathbf{r}) = \frac{1}{c}\sum_{n=1}^{N_c}\int_{V_{cn}} \frac{\left[\mathbf{j}(\mathbf{r}')\times(\mathbf{r}-\mathbf{r}')\right]}{\left|\mathbf{r}-\mathbf{r}'\right|^3}\, dV'$$

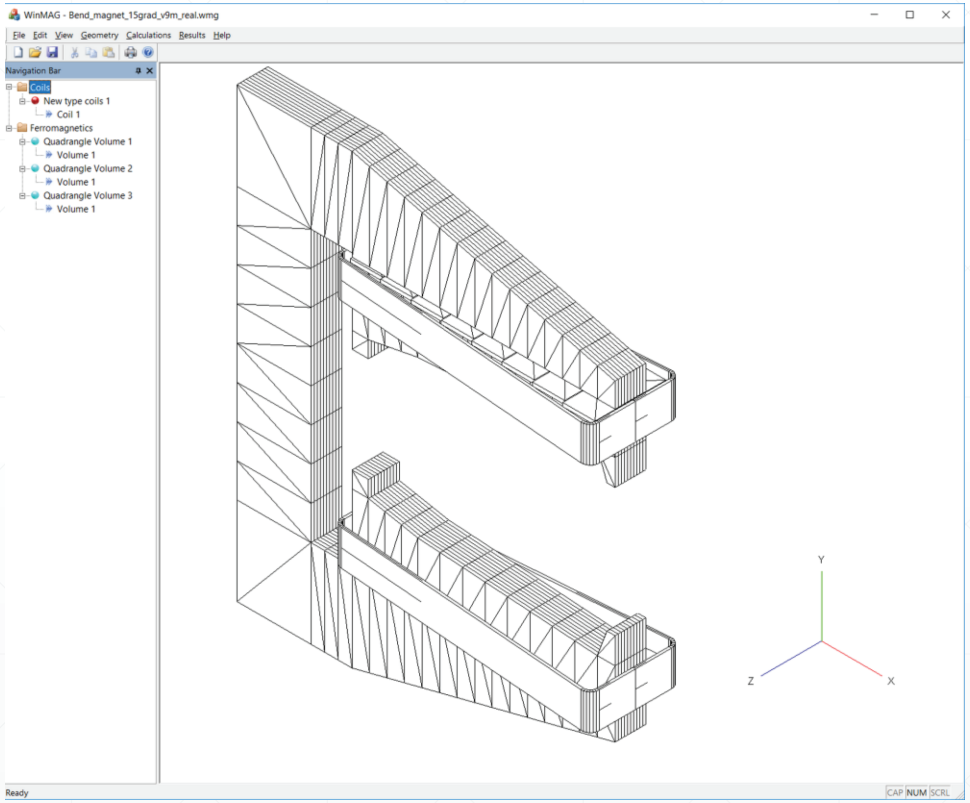
$$\mathbf{H}_m(\mathbf{r}) = -\nabla\psi(\mathbf{r}), \quad \psi(\mathbf{r}) = \frac{1}{4\pi}\int_{V_m} \frac{\mathbf{M}(\mathbf{r}')\cdot(\mathbf{r}-\mathbf{r}')}{\left|\mathbf{r}-\mathbf{r}'\right|^3}\, dV', \quad \mathbf{M} = \chi(H)\cdot\mathbf{H}$$

- Finally, we found

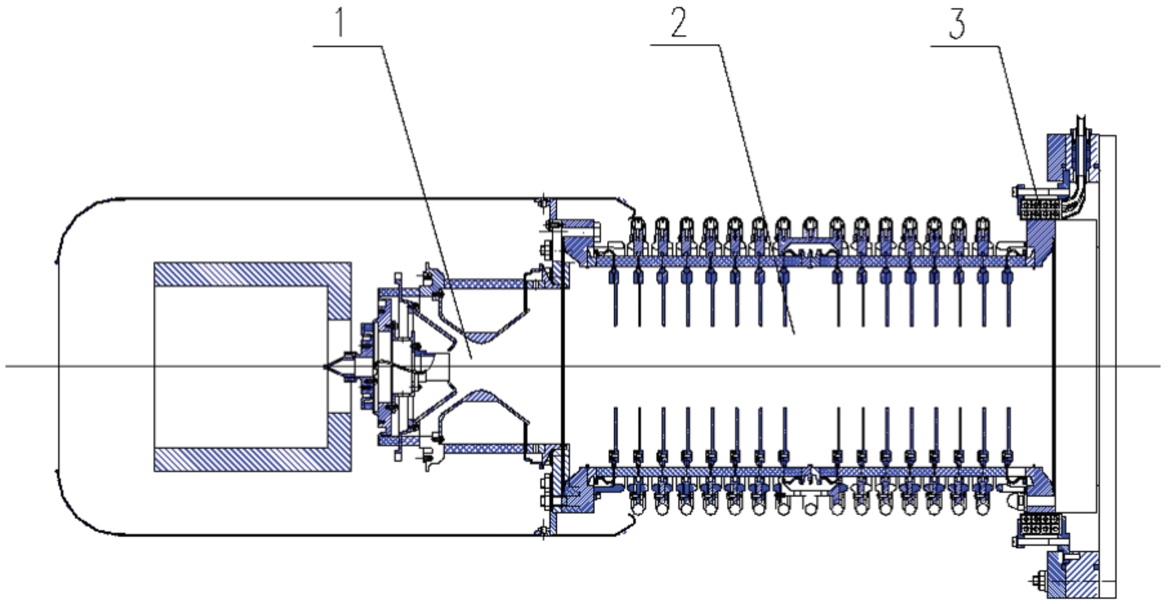
$$\mathbf{H}(\mathbf{r}) + \frac{1}{4\pi}\nabla\int_{V_m} \chi\left(H(\mathbf{r}')\right)\frac{\mathbf{H}(\mathbf{r}')\cdot(\mathbf{r}-\mathbf{r}')}{\left|\mathbf{r}-\mathbf{r}'\right|^3}\, dV' = \mathbf{H}_c(\mathbf{r})$$

Boundary integral method (MAG3D)





Development of electron guns for electron coolers

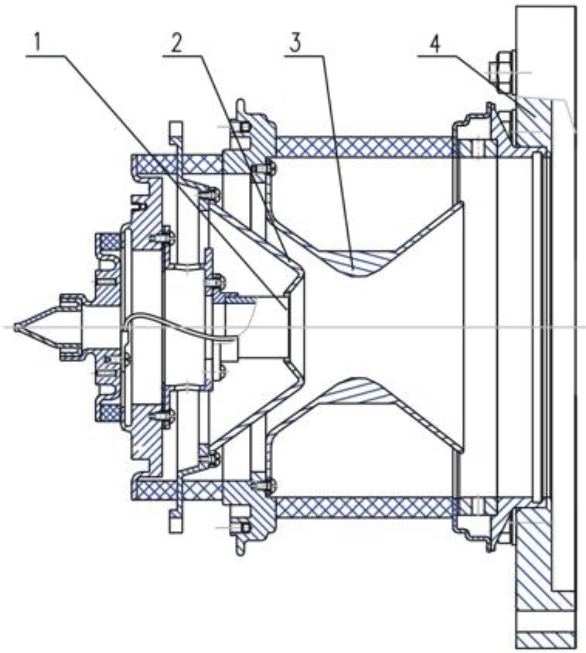


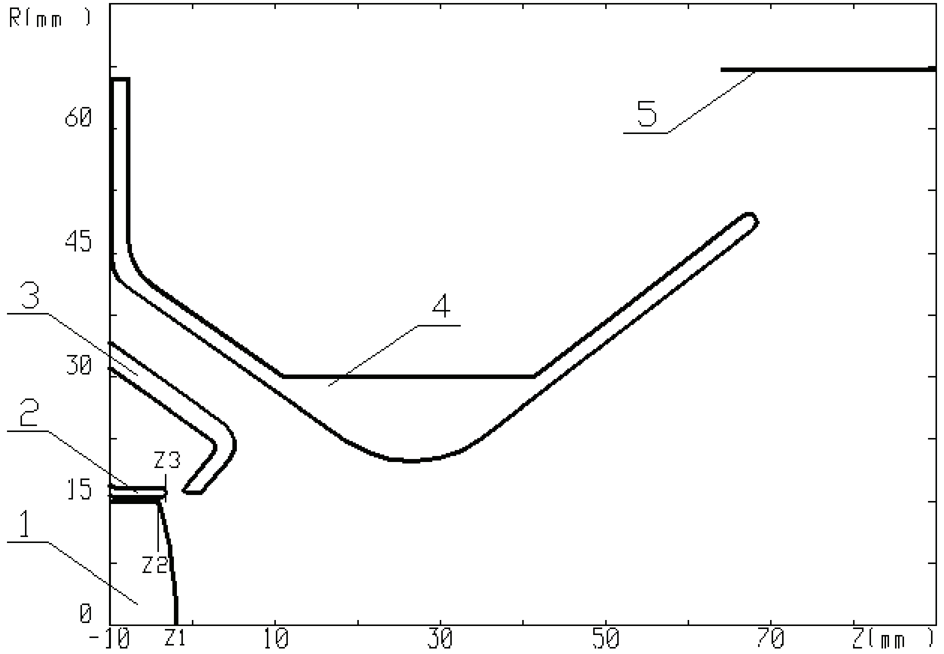
Electron gun and accelerating section of EC300 electron cooler

- 1 – electron gun, including cathode, control electrode and anode;
- 2 – accelerating tube
- 3 - corrector

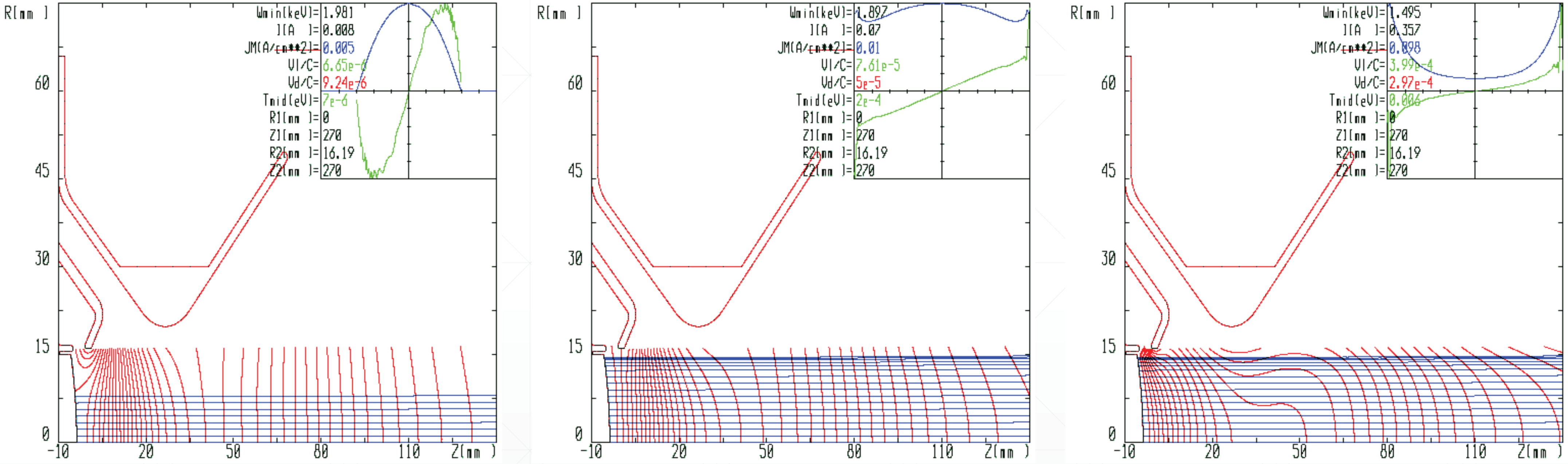
- Required perveance
- Independent current and energy control
- Low transverse temperature of the beam
- Independent adjustment of the current density distribution

Electron gun with variable beam profile

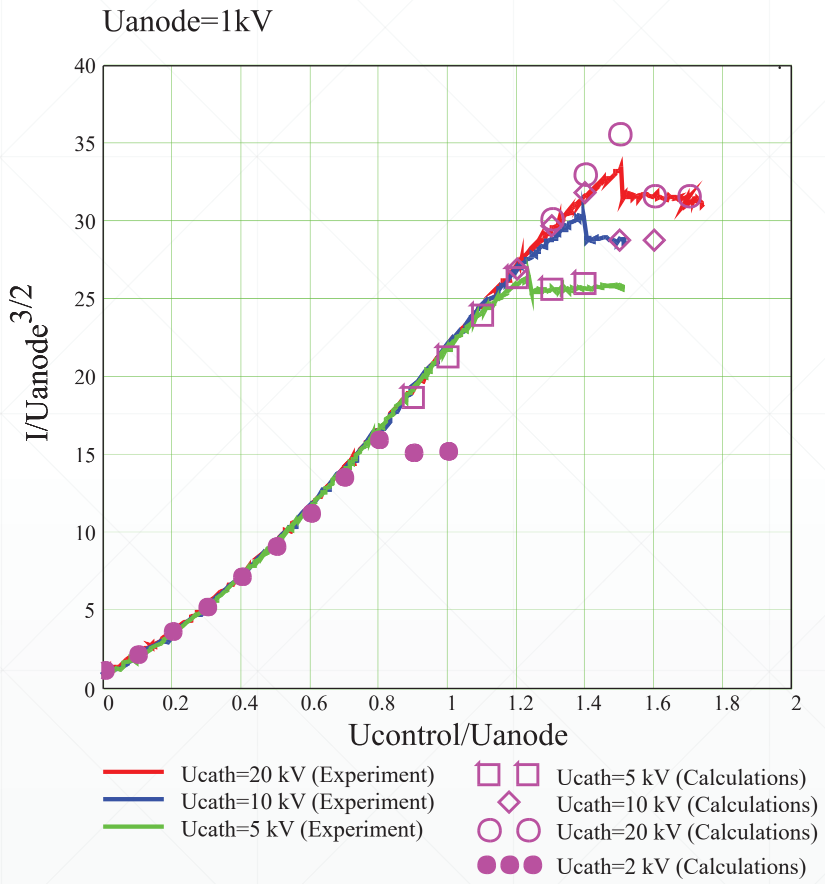


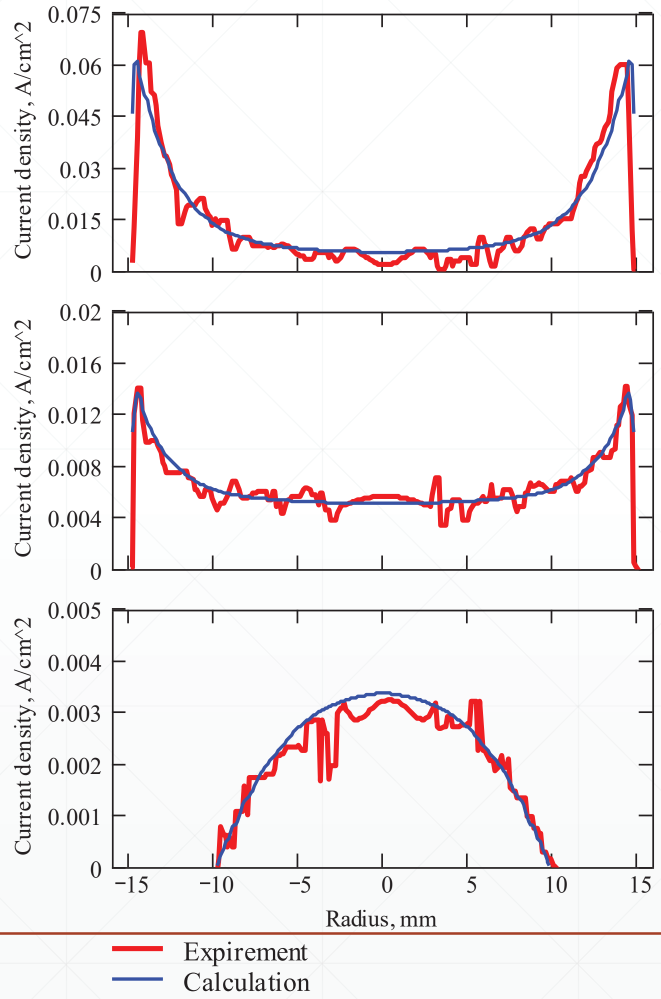


Electron gun of EC35 / EC300 (IMP, Lanzhou)

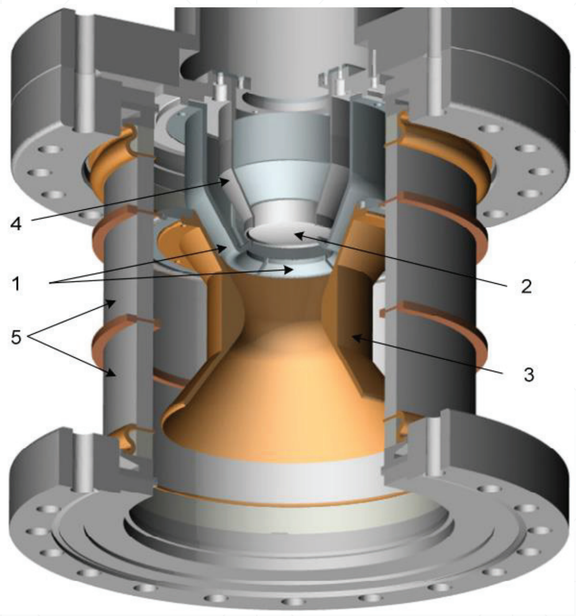


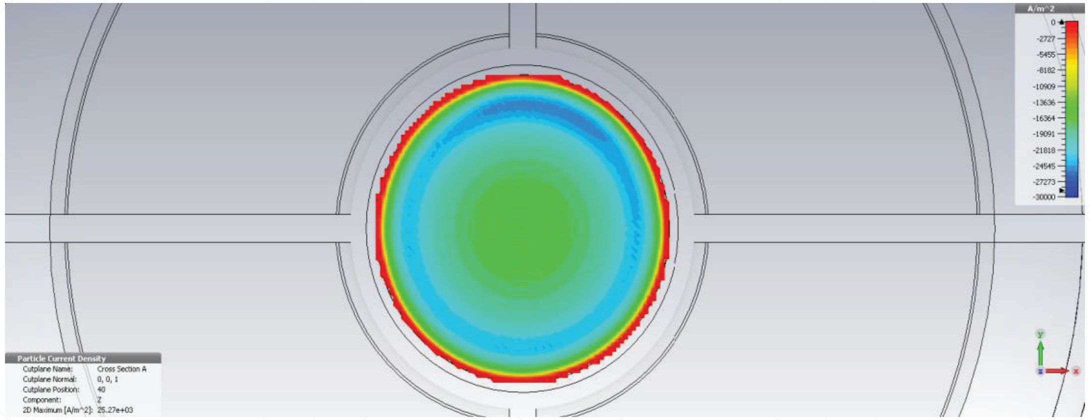
Electron gun of EC35 / EC300 (IMP, Lanzhou)

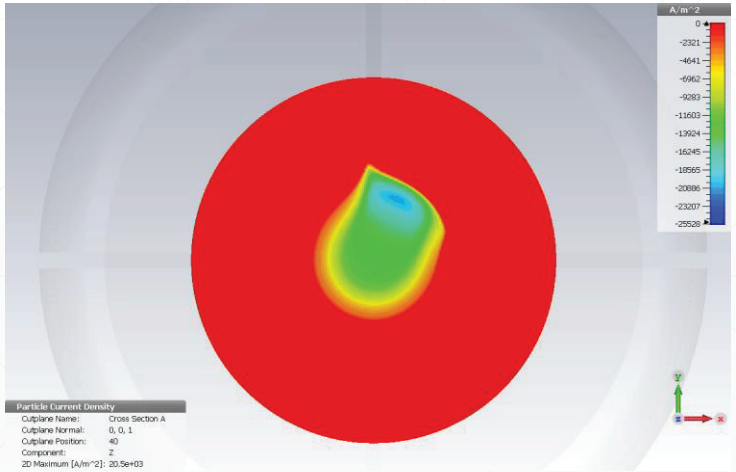


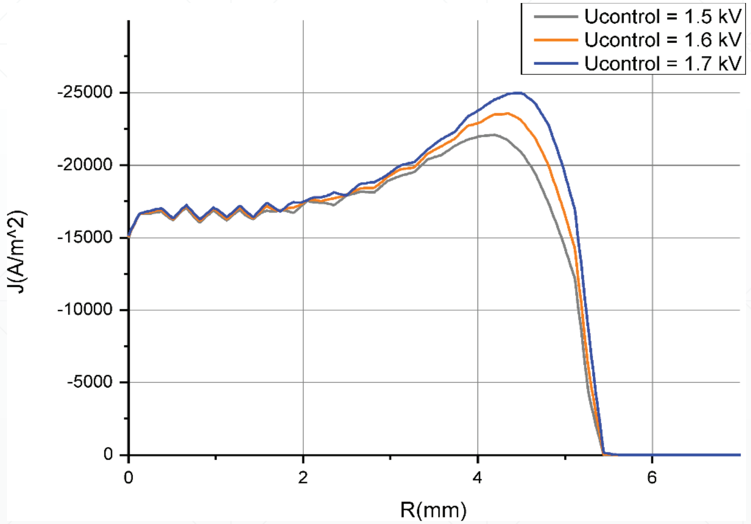


The electron gun with 4-sectors control electrode

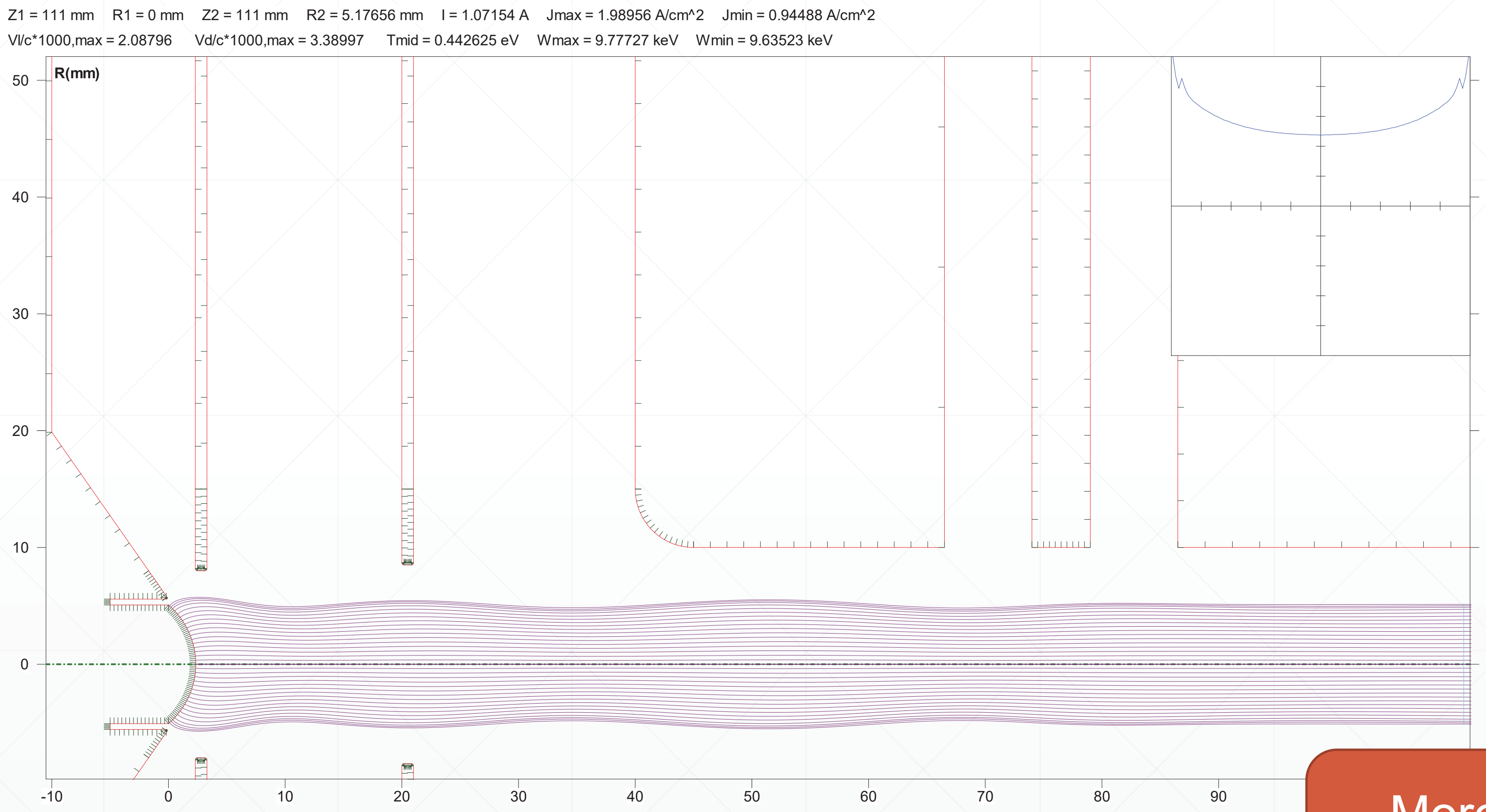






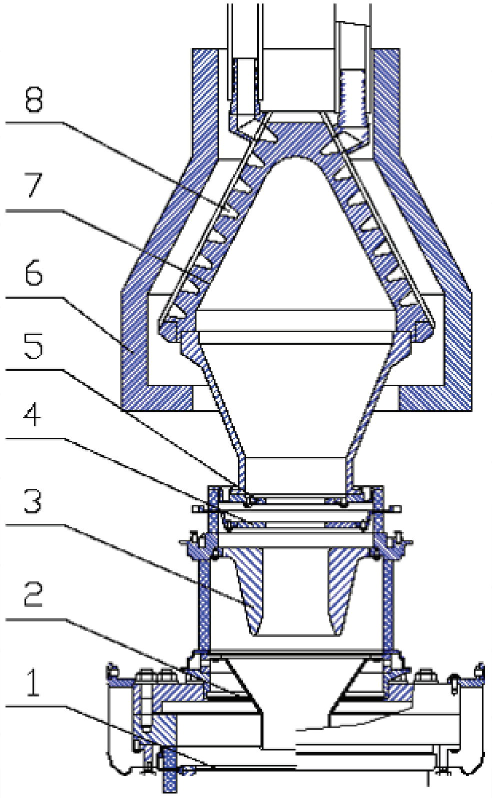


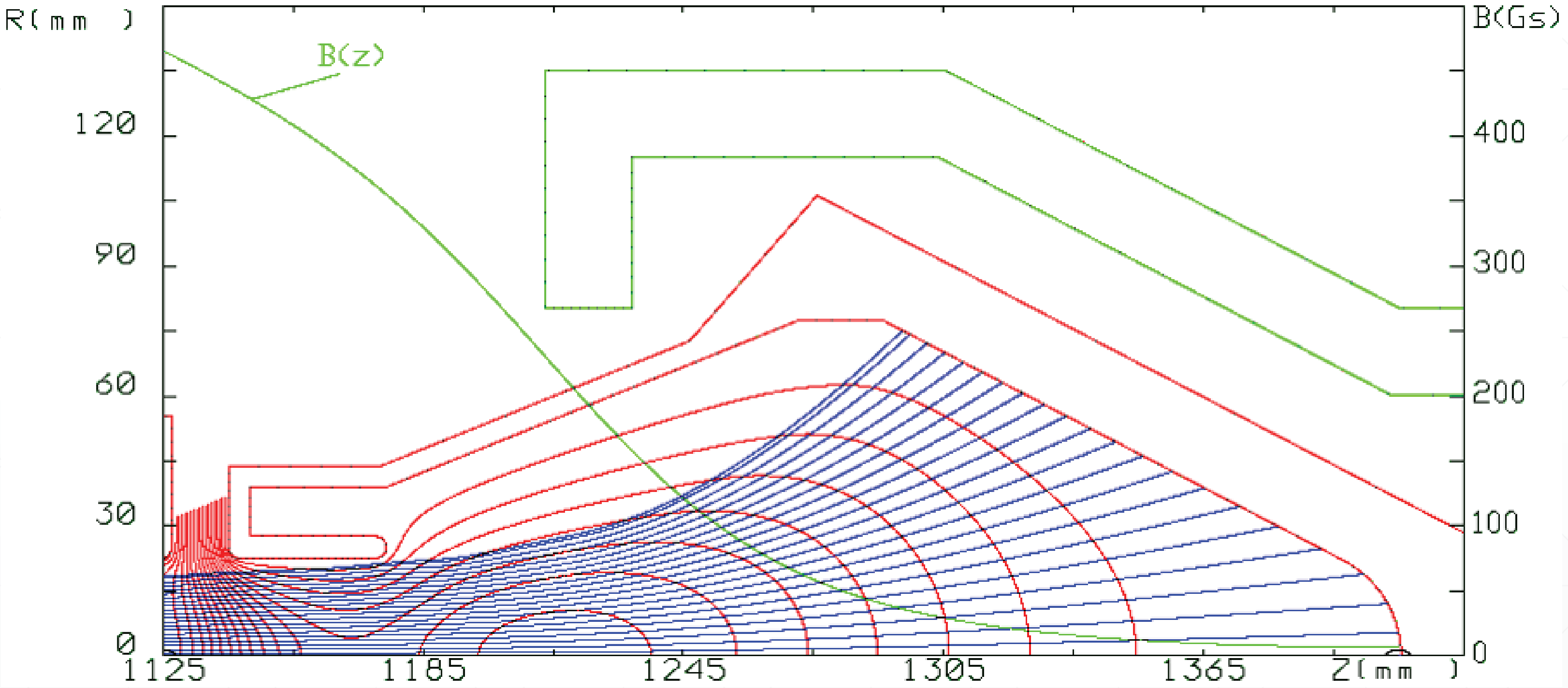
Compact electron gun for electron cooler of the NICA collider (JINR, Dubna)



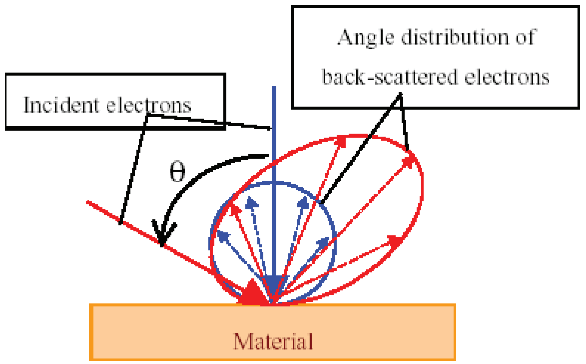
More details in MOA02

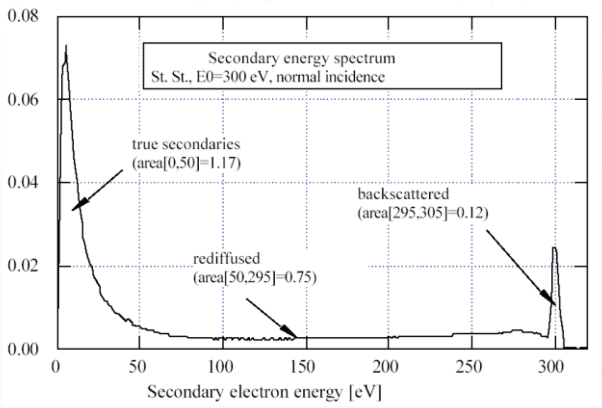
Collector EC300 (IMP, Lanzhou)



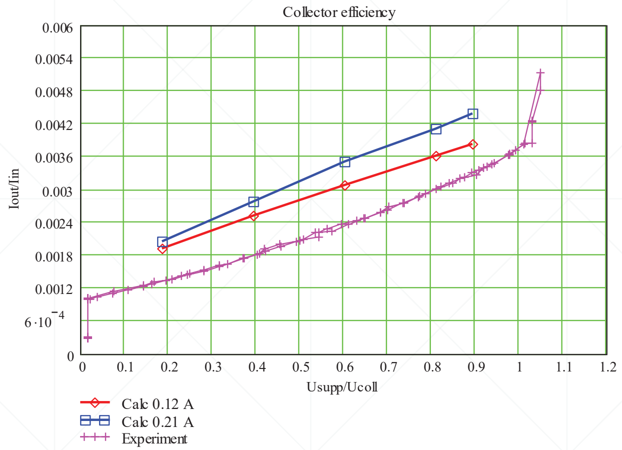


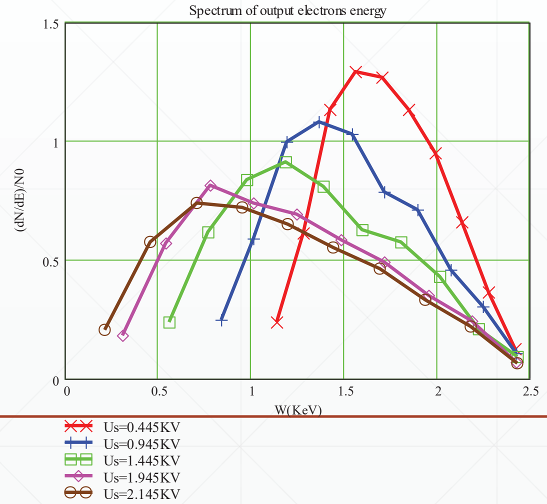
Calculation of secondary emission



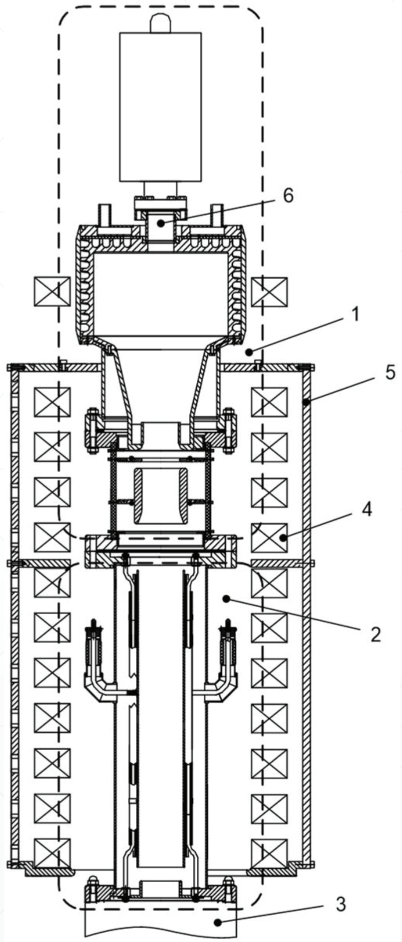


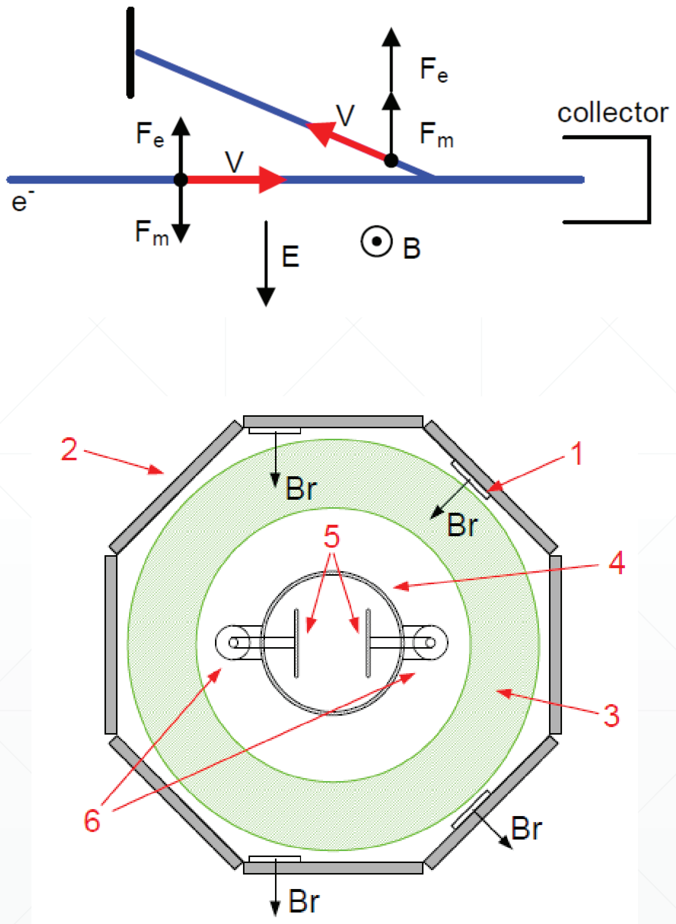
- Model of secondary emission must consider all three types of secondary electrons, namely their coefficients, angle and energy distributions.
- Several generations of particles must be taken into account.

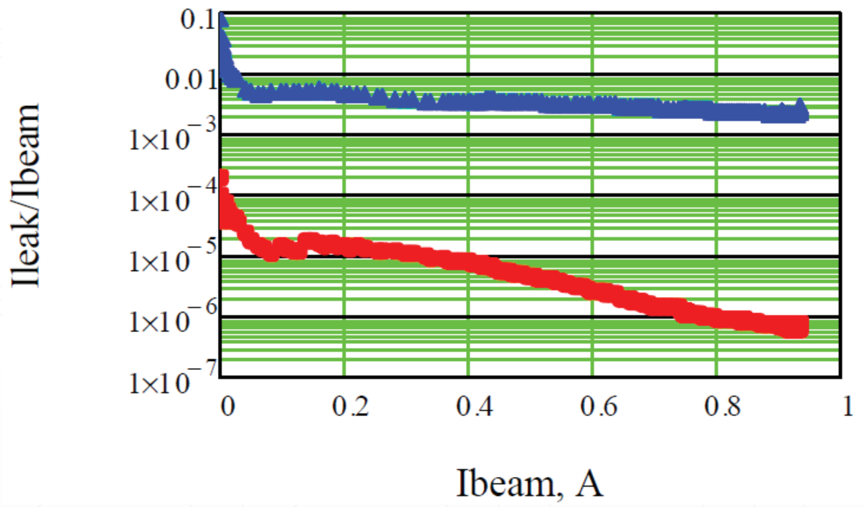




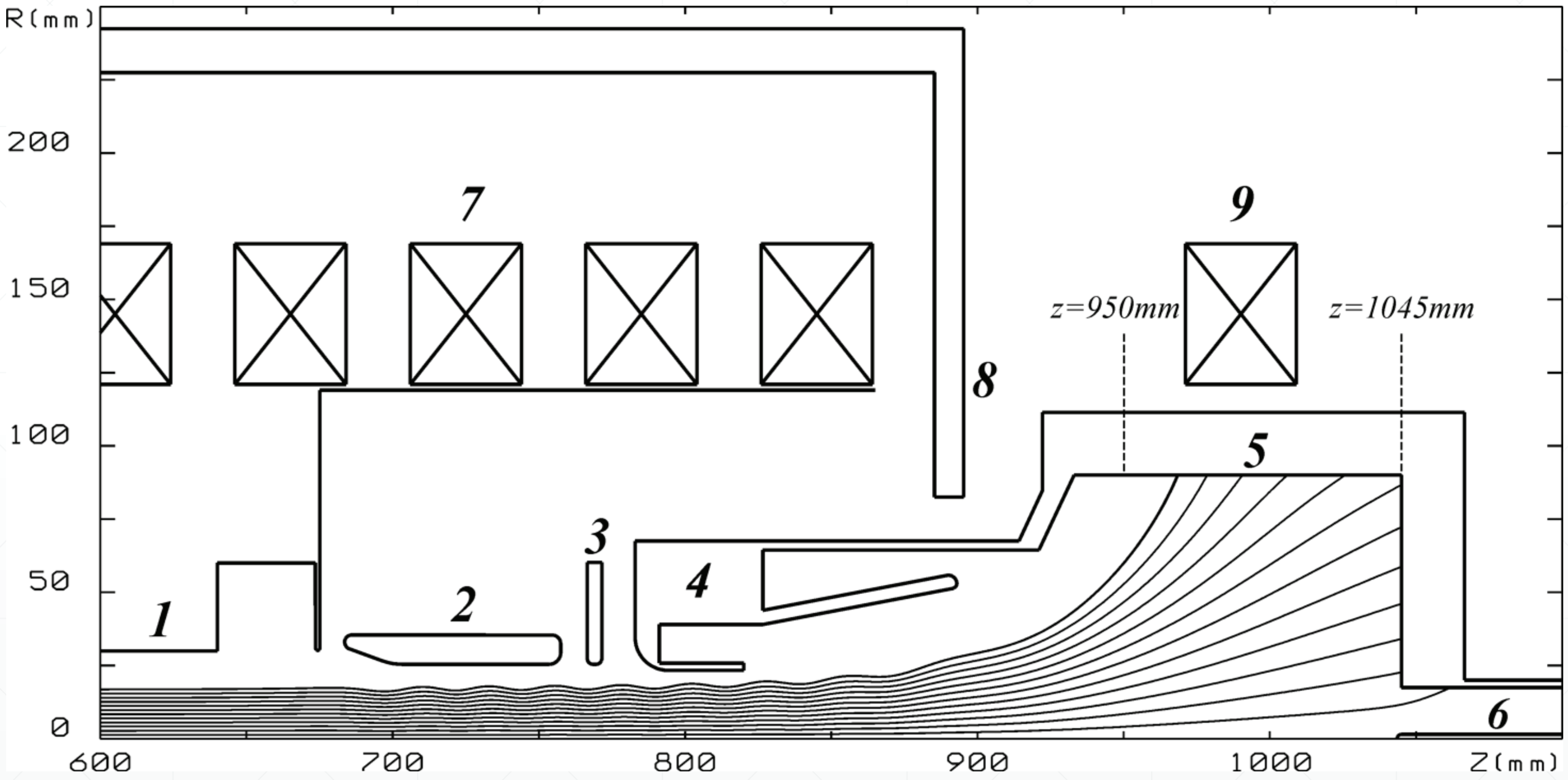
Collector with Wien filter of COSY cooler (Forschungszentrum Jülich)



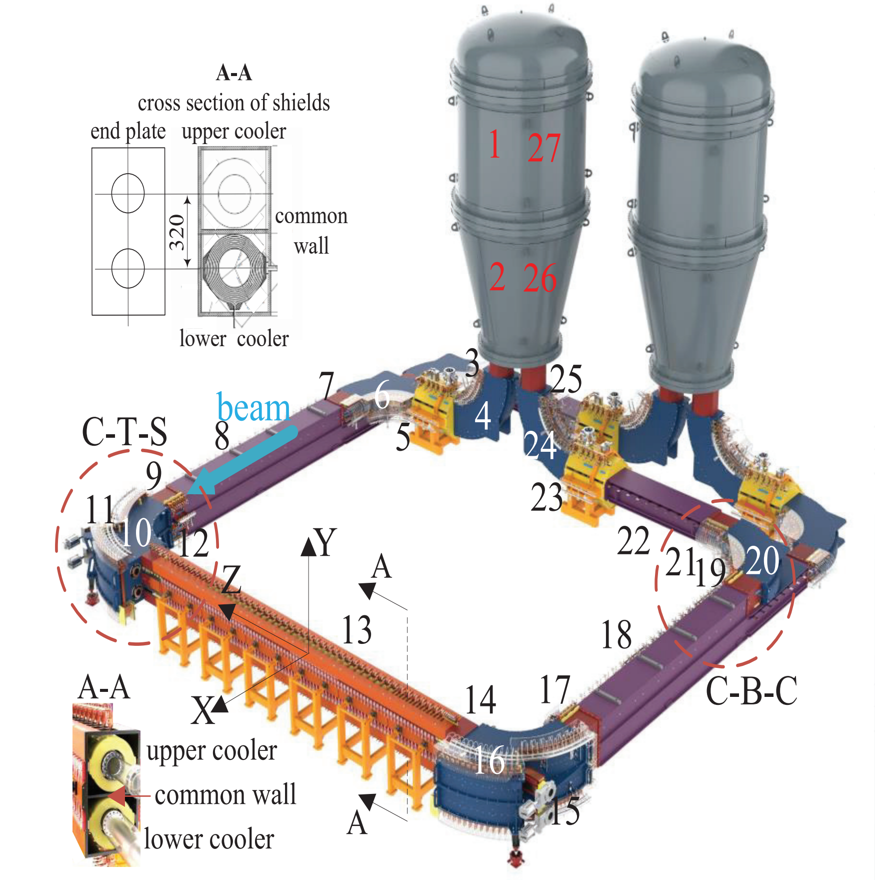


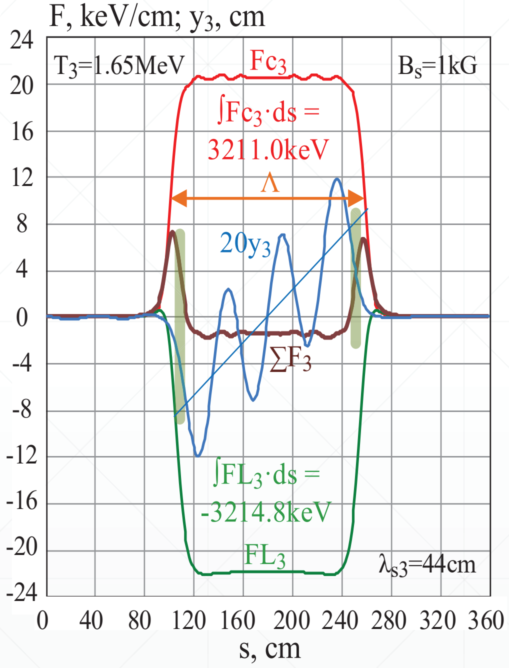


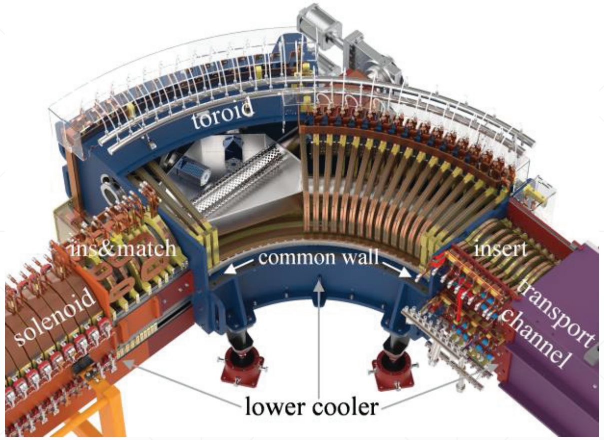
Collector of COSY cooler (Forschungszentrum Jülich)

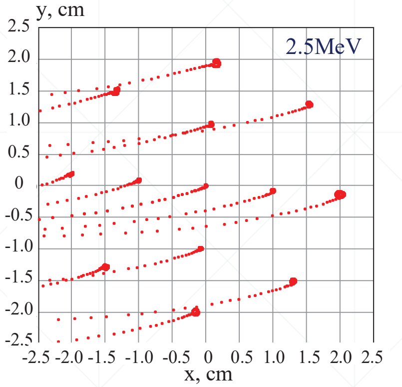


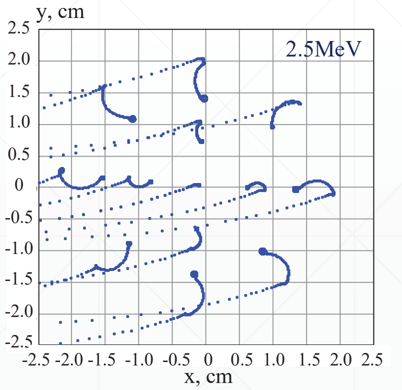
Calculation of motion in bends and toroids in electron cooler of collider NICA (JINR, Dubna)







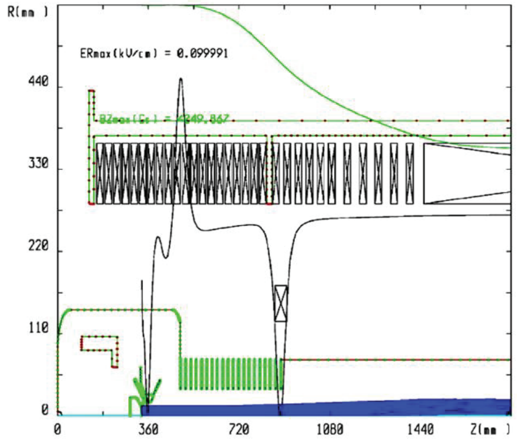


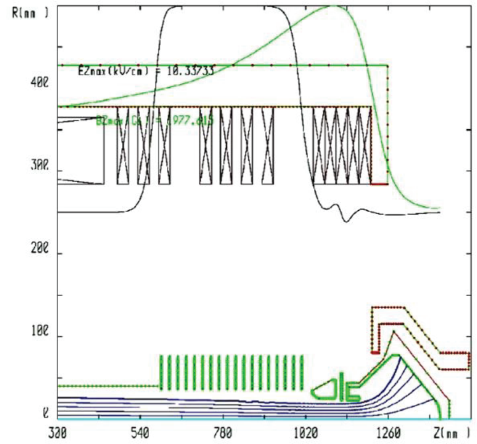


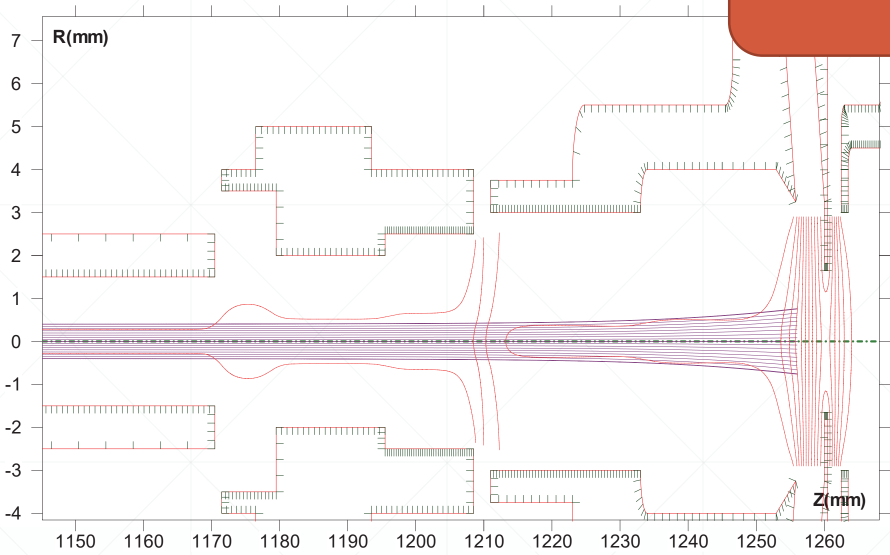
More details in TUPS15

SAM program outside BINP

KRION source,
Dubna





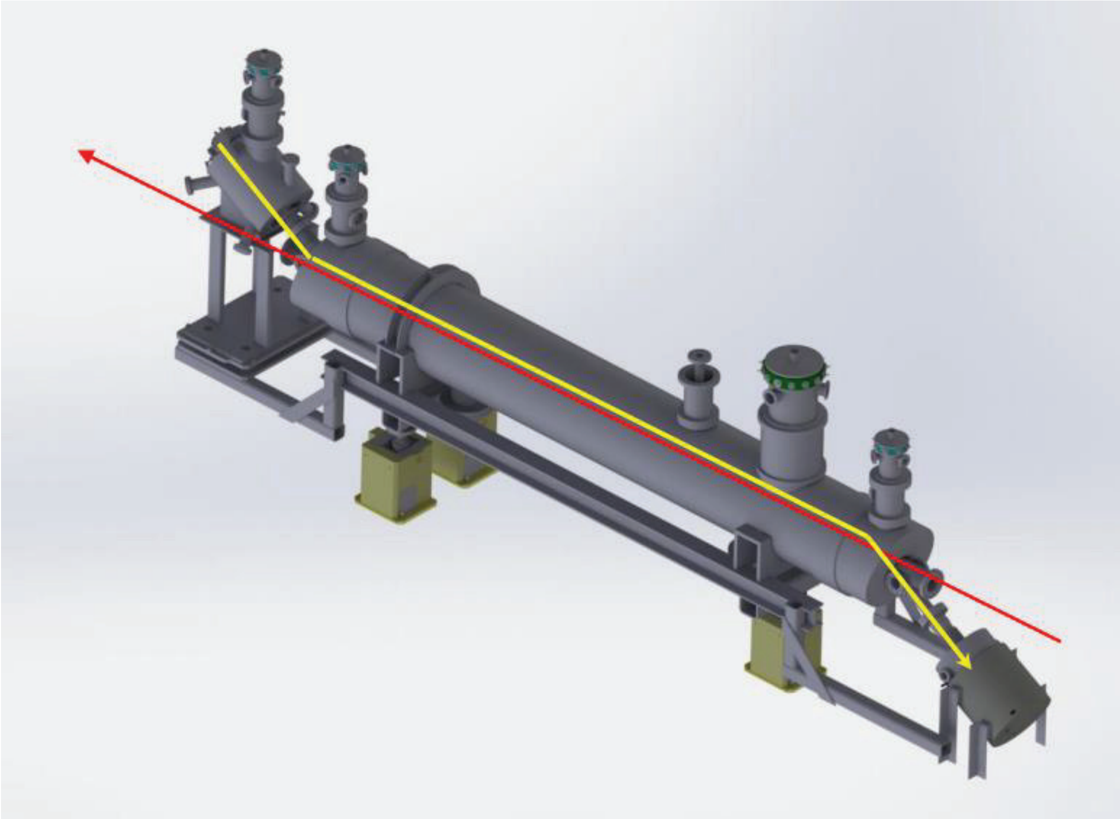


- JINR, Dubna, Russia
- Institute of Modern Physics, Lanzhou, China
- Fermi National Accelerator Laboratory, Batavia, USA
- other centers

COOL 2017,
Mei-Tang Tang et al

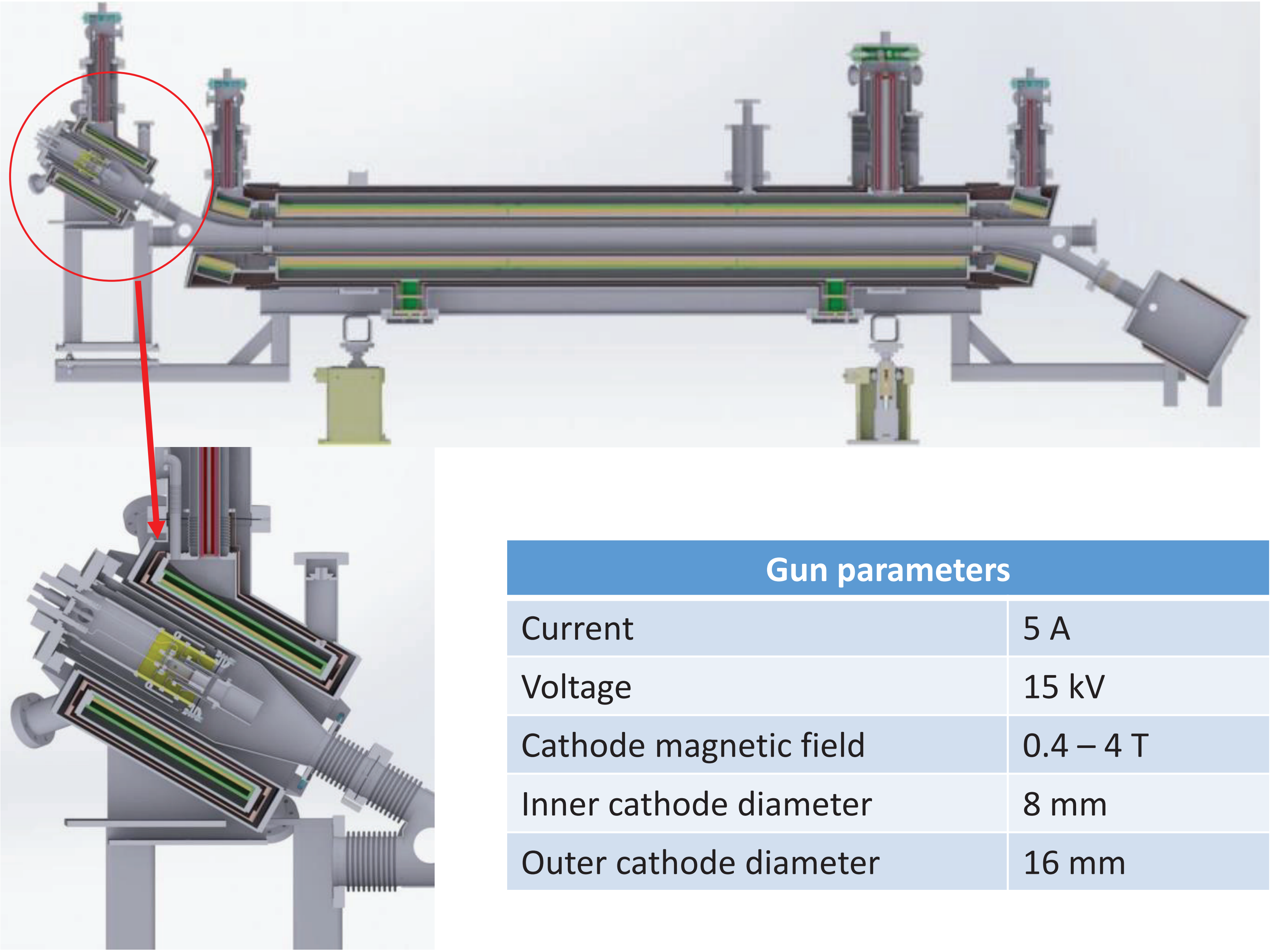
Electron lens for LHC

The demand for high luminosity in modern colliders leads to ever-increasing beam power and ever-smaller cross-sectional area of increasingly high-energy particle beams. Even small losses of the circulating beam can lead to catastrophic consequences due to damage to the accelerator and detectors if they are not carefully controlled. The record power density (power per unit beam area) makes collimation of such beams extremely difficult. An acceptable collimator for such systems may be a hollow electron beam.



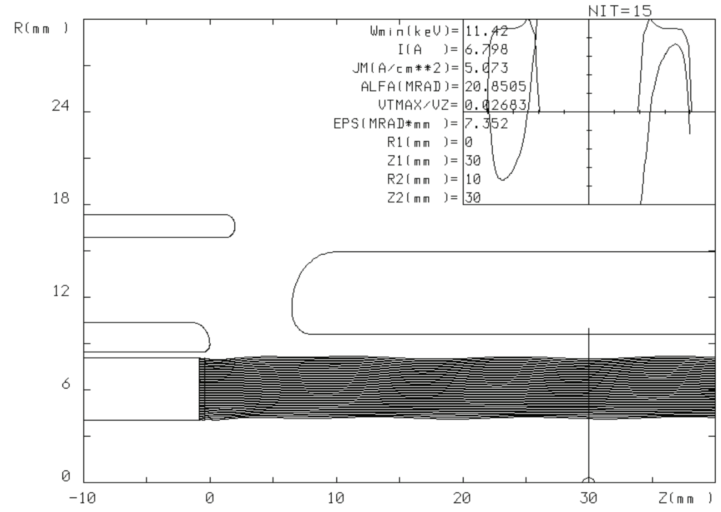
The concept was successfully demonstrated at the Tevatron Collider, its remarkable efficiency leading to the initiation of a development program to generate hollow electron beam collimation for high-power beam collimation at the LHC. The picture shows a lens model for the LHC (Red line corresponds to the propagation of the proton beam, yellow-ring electron)

Electron gun with ring cathode for electron lens

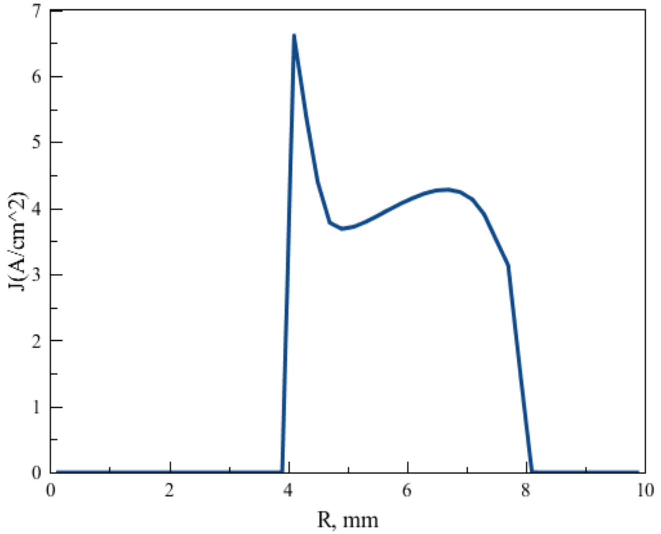


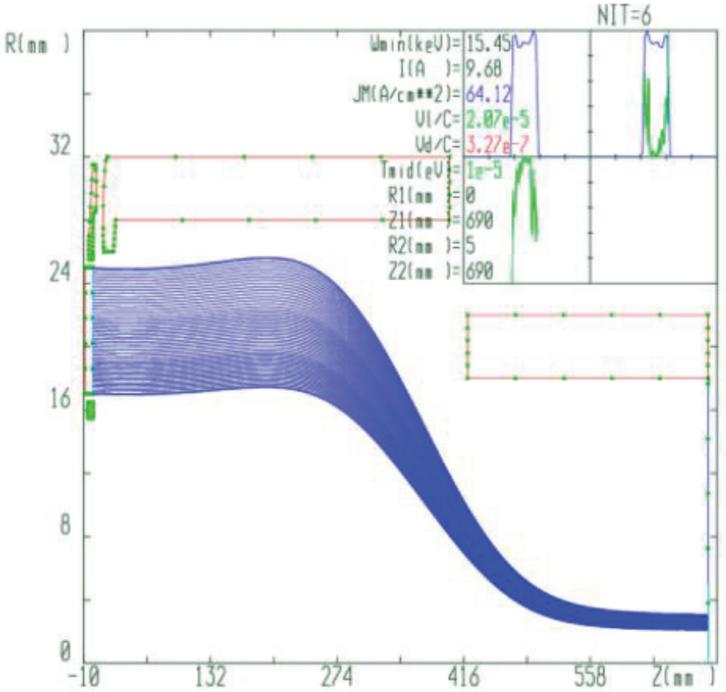
Gun parameters	
Current	5 A
Voltage	15 kV
Cathode magnetic field	0.4 – 4 T
Inner cathode diameter	8 mm
Outer cathode diameter	16 mm

Simulation of the gun with ring cathode with help of SAM code

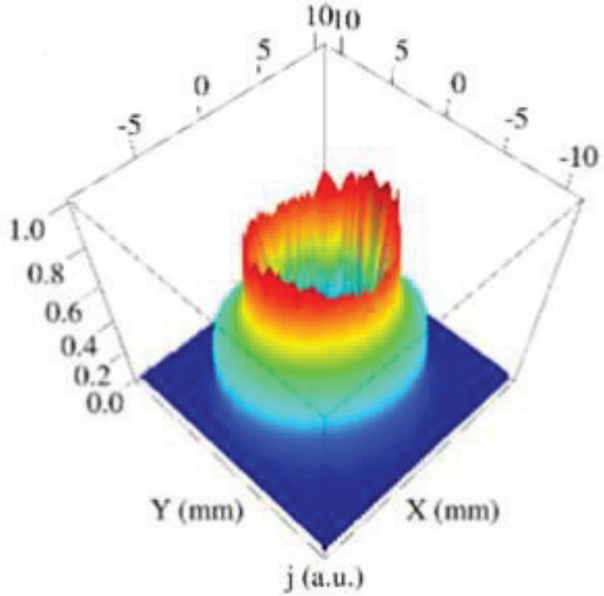


Calculated beam profile





Measured beam profile



Conclusion

- Several programs are created and widely used in BINP for simulation of electron optical systems and dynamic of charged beams (together with other available software). These programs are based on integral methods, and they provide fast and accurate calculations.
- These programs are used at the development of our coolers – for simulations of electron guns, collectors, toroids and bends, making its contribution to this complex work.