ISBN: 978-3-95450-218-9 ISSN: 2226-0374 doi:10.18429/JACoW-COOL2019-MOA02

DESIGN OF A COMPACT ELECTRON GUN FOR THE HIGH-VOLTAGE ELECTRON COOLING SYSTEM OF THE NICA COLLIDER

A. P. Denisov, M. I. Bryzgunov, A. V. Bubley, A. V. Ivanov, V. V. Parkhomchuk, A. A. Putmakov, V. B. Reva, Budker Institute of Nuclear Physics, Novosibirsk, Russia

Abstract

The low temperature of the electron beam is the key for the high efficiency of the electron cooling, and the strong guiding magnetic field is the means for it. However, high-voltage electron cooling systems come with the challenge of providing the low-temperature beams, as the guiding magnetic field is limited. The electron gun design for the NICA collider cooling systems combines the utilizing the magnetic field and the electrical field constructing, by using the electrodes of special shapes.

INTRODUCTION

The NICA collider is designed to operate ion beams with energies up to 4.5 GeV/u [1]. In order to increase the ions accumulation efficiency and ions lifetime in the collider the electron cooling system must provide 2.5 MeV electron beams [2]. During the electron cooling process, the ions lose excess energy due to electrical interactions with electrons. The more electrons, the more energy it can take from ions. Therefore, the efficiency of the cooling depends on the electron beam current density and the momentum spread in the electron beam [3].

Budker Institute of Nuclear physics has a lot of experience in creating electron cooling systems for different beam energies, starting from the first electron cooling system where the very principle of the electron cooling were demonstrated [4], ending with the high-voltage cooler for COSY [5] and low-energy cooling system for NICA [6] Booster. All those systems exploit the similar design of an electron gun, sometimes with small modifications. The main part of the used gun designs is a control electrode, which allows controlling the emission from different parts of a cathode. Later, for electron coolers for COSY and NICA Booster the design of the control electrode was improved by splitting it into four sectors with independent high-voltage power supplies.

The previous design of electron guns used in electron cooling systems produced in BINP exploit a 3 cm diameter cathode. The radius of ion beams in NICA collider is just 0.3 cm (rms). The high-voltage electron cooling system for the NICA collider will use a new electron gun able to produce a 1 cm diameter continuous electron beam with current up to 1 A.

REQUIREMENTS FOR THE ELECTRON GUN

Electron Beam Current Density

The electron beam current density and momentum spread are two major factors that affect the cooling efficiency. According to Parkhomchuk's empirical formula (1), the cooling time is inversely proportional to the electrons density, and for the NICA collider we want it to be at least one order of magnitude lower than the IBS growth time.

$$\frac{d\vec{p_i'}}{dt'}=\frac{4Z^2e^4n_e'\Lambda}{m_e}\cdot\frac{-\vec{v_i'}}{\left[v_i'^2+v_{eff}^2\right]^{3/2}} \qquad (1)$$

Here n_e', v_i', p_i' are the electron density, ions velocity and momentum in the beams frame of reference. v_{eff} is the parameter describing the magnitude of electrons motion, and Λ is a Coulomb logarithm.

Taking into account the NICA collider design parameters, shown in Table 1, and using the cooling time estimation (2) resulting from Parkhomchuk's formula, the necessary electron current density amounts to 0.8 A/cm^2. The final design electron current is 1 A, corresponding to 1.5 A/cm^2.

Table 1: NICA Collider Parameters for Cooling Time Estimations

Parameter	Value		
Z/A	79 / 197		
Ion energy, GeV/u	1.0	3.0	4.5
Hor/ver rms emittance, π·mm·mrad	1.1 / 0.95	1.1 / 0.85	1.1 / 0.75
IBS growth time, s,	160	460	1800
Beta function at the cooling section, m	10		
Collider circumference (L_P), m	503		
Cooling section length (L_C), m	6		
Cooling time (t_{Cool}), s	16	46	180
j_e, A/cm^2	0.05	0.6	0.8

$$\tau_{Cool}\sim\frac{x'^3}{j_e}\cdot\frac{A}{Z^2}\cdot\frac{\gamma^5 m_e m_p v_0^4}{4e^3\Lambda}\cdot\frac{L_P}{L_C} \qquad (2)$$

Here v_0 is the mean ion beam velocity, x' is the r.m.s. angle in the ion beam in the cooling section, L_P/L_C is used to take into account that the cooling takes place only in a small part of the ion collider. Λ is approximately equal to 5.

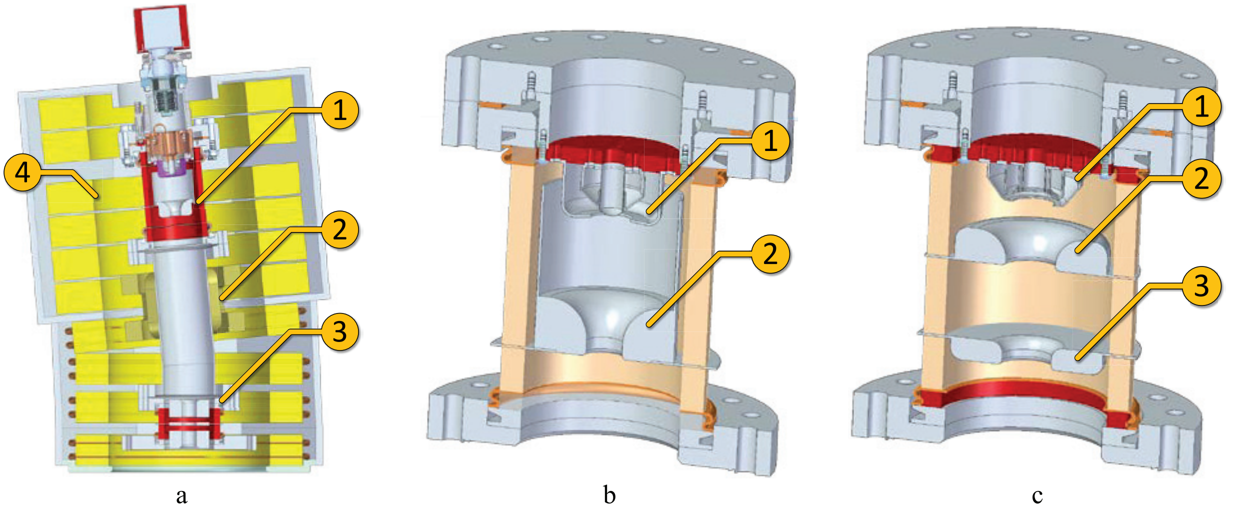


Figure 1: The design of the electron gun for the NICA collider electron cooling system. (a) is the electron gun with magnetic bending site: (a-1) a cathode assembly, (a-2) magnetic correctors, (a-3) the electrostatic lens, (a-4) solenoid coils for creating guiding magnetic field. (b) is the design of the convex cathode assembly: (b-1) the four-sector control electrode, (b-2) the anode. (c) is the design of the flat cathode assembly: (c-1) the four-sector control electrode, (c-2) the anode, (c-3) the auxiliary electrode for setting the electron beam output energy.

Electron Beam Momentum Spread

The acceptable momentum spread that electron beam can have is defined by the accuracy of available methods to measure it. The new high-voltage electron cooling system [2] is based on the magnetized motion of electrons along the entire electron beam transport channel, and magnetic coils and correctors for creating the guiding magnetic field take most of the space. The only available tools for electron beam diagnostics are beam position monitors (BPM).

In the high-voltage column where the electrical and magnetic fields have axial symmetry, the motion of electrons has axial symmetry as well. Thus, the non-zero electron beam momentum spread results in beam size oscillation in the longitudinal magnetic field. The amplitude of such oscillations can be measured using BPMs [7]. The typical sensitivity of a BPM is about 10-30 µm that corresponds to 1 eV oscillations of electrons in 1.5 kG magnetic field.

THE ELECTRON GUN DESIGN

The new electron gun designed for the high-voltage cooling system of the NICA collider consists of five main parts (Fig. 1a): a cathode assembly, a solenoid for creating the guiding magnetic field, a magnetic bending site, magnetic correctors for compensating drift of electrons in the bending site and the electrostatic lens.

The magnetic bending of the electron beam is necessary to shift the cathode from the acceleration tube axis to protect it from the incident ions of the residual gas occasionally travelled into the acceleration tube.

The cathode assembly for the electron gun has two variants. The first one is based on the convex cathode to achieve larger beam current while preserving the controllability of the beam current density (Fig. 1b). The second one (Fig. 1c) uses a flat cathode and a shielding electrode placed at the Pierce angle to the cathode surface that helps reducing the radial electrical fields near the cathode and the resulting amplitude of electrons Larmor oscillations.

The electrostatic lens (Fig. 2) consists of shielding electrodes at the gun's output potential for localizing the electrical field from the lens, and an electrode, electrical potential of which varies from -7.5 kV to +7.5 kV with respect to the potential of the shielding electrodes. The gap between the lens electrode and shielding electrodes is 7.5 mm, which defines the maximum voltage safe for the lens operation (10 kV/cm). The lens electrode thickness is 5 mm and its aperture is 22 mm. As the radius of the electron beam is 5 mm, the dependency of the radial electrical field of the lens on the radial coordinate is close to linear in the beam area (Fig. 3)

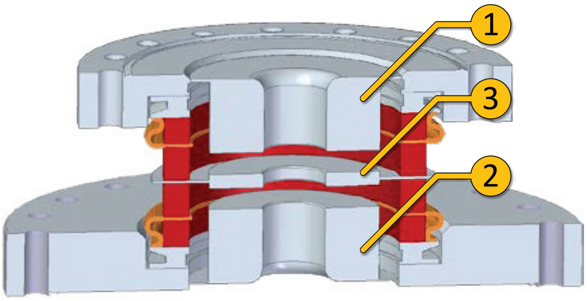


Figure 2: The electrostatic lens design: (1, 2) electrodes at the beam potential, (3) the electrode for creating a focusing electrical field.

CALCULATIONS OF THE CATHODE ASSEMBLY

Both variants of the cathode assembly were optimized to achieve lower electron beam momentum spread values and sufficient controllability. The calculations of electrical fields and electron beam parameters were made using SAM software developed in BINP [8].

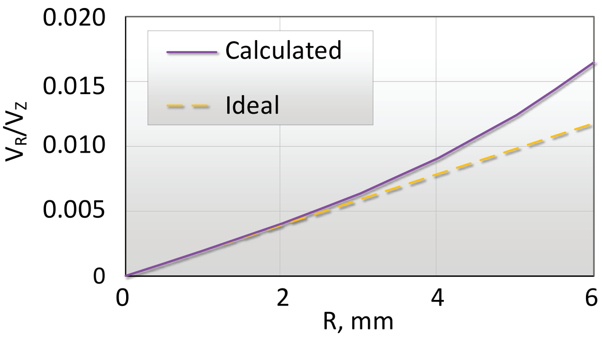


Figure 3: The focusing strength of the electrostatic lens. The lens voltage is 1 kV and energy of electrons is 10 keV.

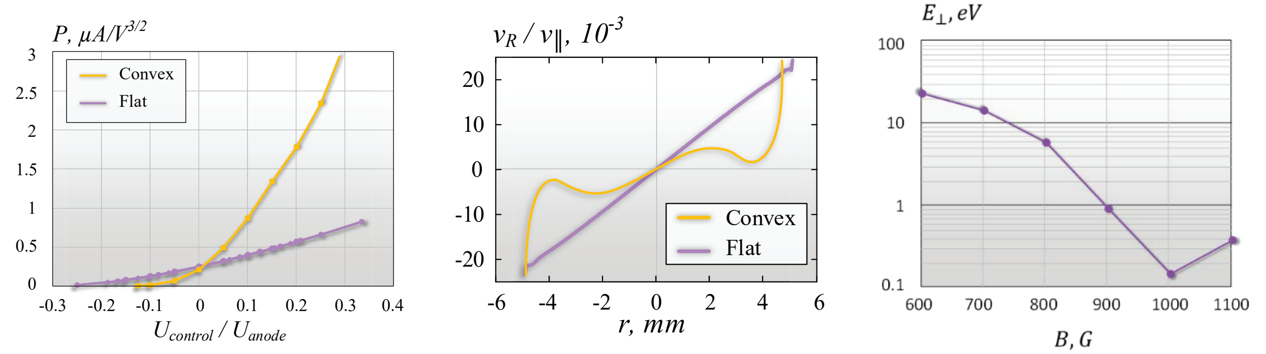
Naturally, the perveance of the convex cathode is higher as the emissive surface is larger and electrical field is concentrated due to the cathode curvature (Fig. 4a). However, the velocities profile of the electron beam produced by the convex cathode is non-linear (Fig. 4b). By the velocities profile we mean the dependency of the electrons radial velocity on the radial coordinate in the beam cross-section. As electrons oscillate in the magnetic field, the profile changes with the longitudinal coordinate. The profiles shown in Fig. 4b correspond to the moment when the electrons on the beam edge have the radial velocity only. In case of the flat cathode, the electrostatic lens kick can decrease the amplitude of Larmor oscillations. As for the convex cathode, reducing the oscillations amplitude of the electrons near the beam edge using a simple electrostatic lens will lead the electrons near the beam center to gain momentum and vice versa.

The momentum spread of the electron beam at the output of the gun depends on the configuration of the electrical and magnetic fields. The beam energy in the cathode assembly is about 10-20 keV. Given the magnetic field 1000 G, the step of Larmor helix is about 3 cm that is close to the distance between the electrodes. Because of that, there is resonant behaviour in the electrons motion, which can be easily seen in calculations made for the flat cathode assembly, where the additional electrode is introduced. The additional electrode defines the output beam energy 10 kV, while anode has higher voltage to extract more current from the flat cathode (15 kV). The electrons passing through these electrodes gain transverse momenta due to the radial electrical field. However, at a certain value of the guiding magnetic field (1000 G), the direction of the electrical force and the electrons transverse velocity can be out of phase most of the time due to Larmor oscillations, causing the amplitude of oscillations to decrease (Fig. 4c).

According to [9], the controllability of a current density profile is essential to prevent instability development in ion beams caused by overcooling. By increasing electron emission from the cathode edges using the control electrode, the emission from the center of the cathode can be suppressed by the space charge electrical field. In this case, the electron beam becomes “hollow”. The cooling rate for ions with small amplitudes of betatron oscillations is lower than for those with large amplitudes; therefore, the ion beam cools more evenly. The designed gun with a convex cathode allows increasing the emission from the edges about two times, while keeping the current density at the cathode center at 2 A/cm^2 (Fig. 5). The electron gun with a flat cathode is less flexible (Fig. 6). Changing the voltage on the control electrode brings the cathode assembly out of the Pierce optics and causes the radial electrical fields near the cathode to grow. As a result, the increase of the emission from the cathode edge is accompanied by the growth of the electron beam momentum spread. Another disadvantage, caused by the Pierce optics approach used in the gun with the flat cathode, is that changing the voltage on control electrode affects the electrical field near the cathode surface almost evenly, and it is difficult to get current density near the beam edges much larger than near the beam center (Fig. 6).

CONCLUSION

The electron gun for the high-voltage electron cooling system for the NICA collider has the design different from other electron guns produced in BINP for electron coolers.



a b c

Figure 4: (a) Computed perveance for two variants of the cathode assembly. (b) Comparison of transverse velocities profiles of electron beams produced by two variants of the cathode assembly. (c) The dependency of the energy of electrons Larmor oscillations at the output of the flat cathode assembly on the magnitude of the guiding magnetic field.

ISBN: 978-3-95450-218-9 ISSN: 2226-0374 doi:10.18429/JACoW-COOL2019-MOA02

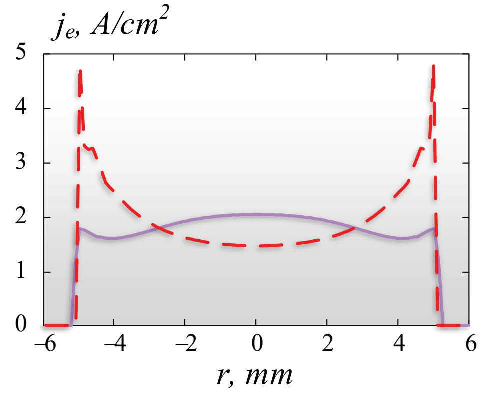


Figure 5: The electron current density distribution of the beam produced by the convex cathode assembly. Normal regime (purple line): U_{anode} = 15 kV, $U_{control}$ = 1.3 kV. Hollow beam (red dashed line): U_{anode} = 10 kV, $U_{control}$ = 2 kV. Guiding magnetic field is 1000 G.

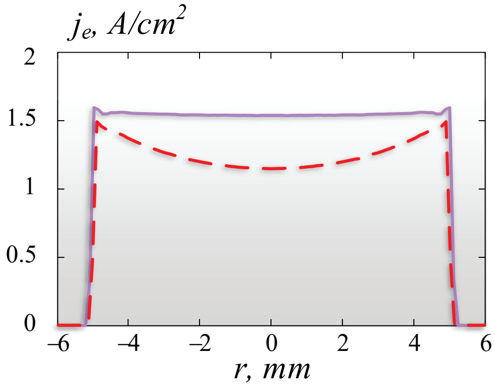


Figure 6: The electron current density distribution of the beam produced by the flat cathode assembly. Normal regime (purple line): U_{anode} = 20 kV, $U_{control}$ = 2.5 kV. Hollow beam (red dashed line): U_{anode} = 10 kV, $U_{control}$ = 4 kV. Guiding magnetic field is 900 G.

It is designed to produce a 1 cm diameter continuous electron beam with current up to 1 A and transverse momentum spread corresponding to the energy about 1 eV. The new gun design with magnetic bend of the electron beam provides protection of the cathode from the high-energy ions of the residual gas that can occasionally get into the acceleration tube. In order to reduce the amplitude of electrons Larmor oscillations with energies exceeding the defined limit of 1 eV, the supplementary electrostatic lens is placed at the end of the gun site.

The test bench for measuring the parameters of the gun prototype is under construction.

REFERENCES

[1] A. Kovalenko *et al.*, "Status of the NICA project at JINR", *EPJ Web Conf*, vol. 191, p. 01003, Oct. 2018.

[2] V. B. Reva *et al.*, "High voltage cooler NICA status and ideas", in *Proc. 11th International Workshop on Beam Cooling and Related Topics (COOL17)*, Bonn, Germany, January 2018, paper TUM21, pp. 25-27.

[3] V. V. Parkhomchuk, A. N. Skrinsky, "Electron cooling: 35 years of development", *UFN*, vol. 170, no 5, pp. 473–493, 2000, `http://mi.mathnet.ru/eng/ufn1754`

[4] V. V. Parkhomchuk *et al.*, "Investigation of fast electron cooling", `http://www.inp.nsk.su/images/preprint/1979_056.pdf`

[5] V. B. Reva *et al.*, "Recent experiments with high energy electron cooler in COSY", in *Proc. of RuPAC2016 (RuPAC2016),* St. Petersburg, Russia, October 2016, paper WECAMH04, pp. 67-69.

[6] A. V. Smirnov *et al.*, "Commissioning of electron cooling system of NICA Booster", in *Proc. of 26th Russian Particle Accelerator Conference (RUPAC2018),* Protvino, Russia, September 2018, paper TUPSA22, pp. 188-190.

[7] V. B. Reva *et al.*, "COSY 2 MeV cooler: design, diagnostics and comissioning", in *Proc. of IPAC2014,* Dresden, Germany, 2014, paper MOPR1075, pp. 777-779.

[8] A. Ivanov, M. Tiunov, "UltraSAM – 2D code for simulation of electron guns with ultra high precision", in *Proc. of EPAC 2002,* Paris, France, 2002, pp. 1634-1636.

[9] V. V. Parkhomchuk, "Development of a new generation of coolers with a hollow electron beam end electrostatic bending", in *Proc. of International Workshop on Beam Cooling and Related Topics (COOL05)*, Galena, Illinois, U.S.A., September 2005, paper CP821, pp. 249-258.