ISBN: 978-3-95450-218-9 ISSN: 2226-0374 doi:10.18429/JACoW-COOL2019-THX01

THE STATUS OF THE ELECTRON COOLING SYSTEM FOR THE NICA COLLIDER *

M.B. Bryzgunov, A.V. Bubley, A.D. Goncharov, A.P. Denisov, N.C. Kremnev, V.V. Parkhomchuk, V.M. Panasuk, A.A. Putmakov, V.B. Reva, S.V. Shiyankov, Budker INP, Novosibirsk, Russia

Abstract

The new electron cooling system is being designed to cool two heavy ion beams propagating in opposite directions at a distance of about 30 cm from each other. Engineering solutions for its basic elements are presented. The measurements of the magnetic system of the electron cooler and the influence of the adjacent solenoids in the cooling section on the resulting magnetic field are described. The potential opportunities to improve parameters of experiments with ion beams using the electron cooling system are discussed

INTRODUCTION

The history of the development of electron cooling began at the Institute of Nuclear Physics (Novosibirsk) just after the first successful experiments conducted there with electron-electron and electron-positron colliding beams. Radiation cooling plays a decisive role in achieving high luminosity in electron and electron-positron colliders. Cooling based on ionization losses in the matter was suggested earlier, but the interaction with the target nuclei hampered application of this method because it makes the beam lifetime too short.

The idea of using electron cooling, proposed by G.I. Budker in 1965 [1], consisted in switching from cooling with a stationary target to using a pure beam of electrons (without nuclei). The electron cooling progress began in 1967 with theoretical studies [2] and the development of an electron beam facility [3] (Fig. 1). That project was to verify the electron cooling concept. The electrons travel with the same average velocity as the proton beam does. Of course, the electron beam density is much smaller than the electron density in condensed matter, but in this case electrons are traveling together with the proton beam and the interaction efficiency between the two beams depends only on the spread of relative velocities of the protons and the electrons. The drift motion of the electron beam because of space charge repulsion is suppressed using a high magnetic field B along the electron trajectory. A strong longitudinal magnet field in the cooling section is used for suppression of ion-electron recombination. The main feature of cooling by magnetized electron beams is the possibility of suppression of the ion electron recombination due to high transverse temperature of electrons without losses in the cooling efficiency [4].

Since 1991 BINP have produced a lot of coolers for different laboratories: GSI SIS-18, IMP CSRm, CSRe, and CERN LEIR. The cooler with a highest voltage of 2 MV was designed for Forschungszentrum Julich (KFA) GmbH. The experience of designing the COSY cooler was used as a base for the 2.5 MV cooler for the NICA ion*ion collider at JINR (DUBNA). Figure 2 shows the origination of the NICA cooler.

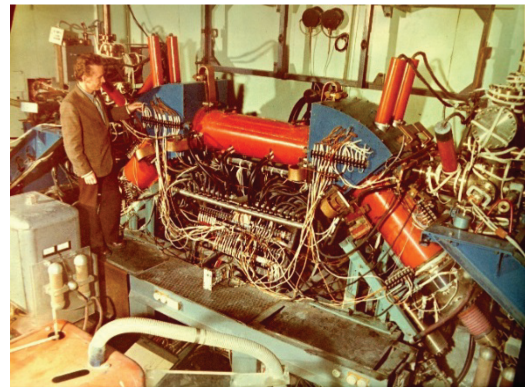

Figure 1: First electron cooling installation in NAP-M storage ring (1974).

The cooler will be placed in a special building near the beam straight section of the NICA ring. The vertical distance between the ion beams is only 32 cm, and the design of two solenoids with such a small gap is a very complicated task. For testing the design, a prototype 1 m long of the cooling section was created (Fig. 3).

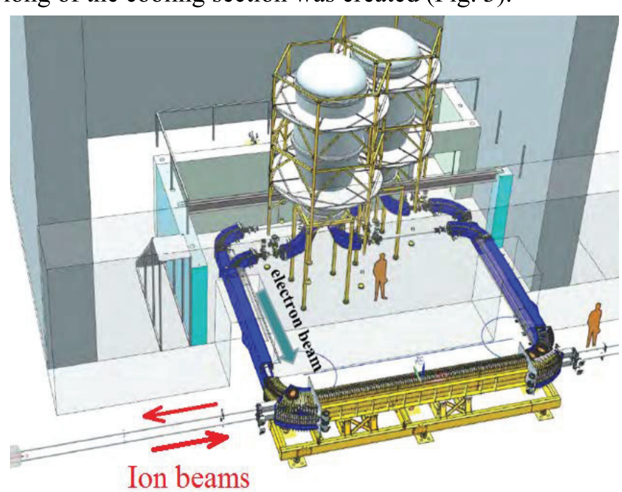

Figure 2: 3D design view of 2.5 MV NICA cooler.

The maximum magnetic field in the cooling section is 0.2 T. The solenoids consist of adjustable coils for straightening the lines of magnet field by rotating coils. This procedure will involve a specially designed compass with a laser beam reflecting from the compass mirror for precise angle measurement.

The penetration of the transverse magnetic field from the upper solenoid to the lower solenoid does not exceed 0.01, and thus the procedure of magnetic field measure-

ISBN: 978-3-95450-218-9 ISSN: 2226-0374 doi:10.18429/JACoW-COOL2019-THX01

ment should ensure suppress ion of the mutual influence of the two solenoids.

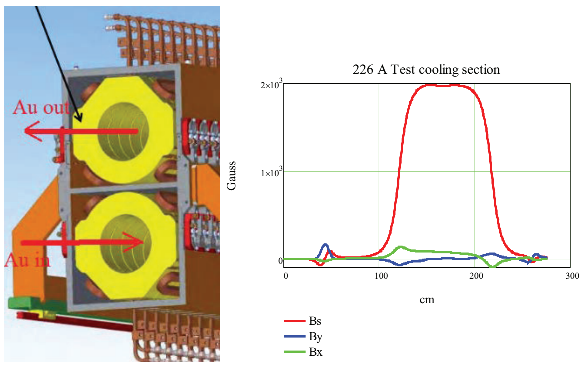

Figure 3: Design of solenoids for cooling section and results of magnetic field measurement along center line of solenoid.

The maximum magnetic field in the cooling section is 0.2 T. The direction of the lines of the magnetic field of solenoid will be corrected by gentle inclination or rotation of coils in the vertical axis. Figure 4 shows the change in the magnetic fields when one coil is tilted by 4 mm.

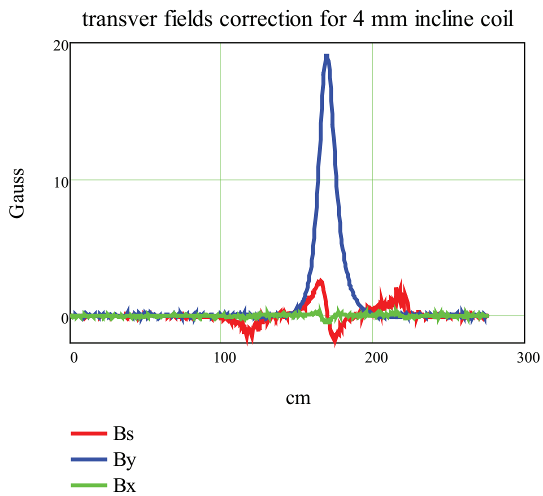

Figure 4: Change in vertical component of solenoid after tilting single coils of solenoid by 4 mm.

From Fig. 4 it is clear that inclination of individual coils by 4 mm corrects the angle of line by $\Delta B\perp/B$ 10^{-3}. For the accuracy of the magnetic line angle to be better than 10^{-5}, the shifting accuracy should better than 0.04 mm.

DESIGN OF NICA COOLER

The main task for the NICA cooler will be to obtain high luminosity in the ion*ion collision mode. Table 1 shows the main parameters of the NICA cooler. The most serious limitation was from the restriction to the total power consumption. It means that the maximum amount of copper is limited by distance of 32 cm between the ions of orbit.

Table 1: Main Parameters of NICA Cooler

Parameter	Value
Energy range	0.2 – 2.5 MeV
Number of the cooling sections	2 for both beams
Stability of energy (ΔU/U)	$\leq 10^{-4}$
Electron current	0.1 – 1 A
Diameter of electron beam in the cooling section	5 – 20 mm
Length of cooling section	6 m
Bending radius in the transport channel	1 m
Magnetiv fiels in the cooling section	0.5 – 2 kG
Vacuum pressure in the cooling section	10^{-11} mbar
Height of the beam lines	1500/1820 mm
Total power consumption	500 – 700 kW

Figure 5 shows the plane of the cooling section more than 6 m long.

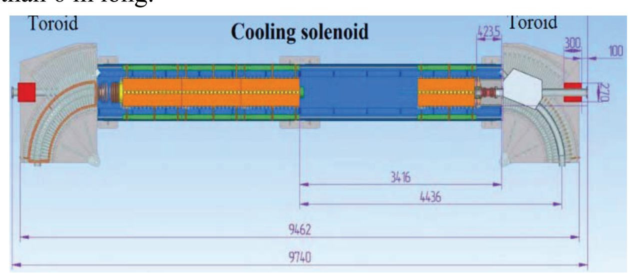

Figure 5: Cooling section sketch.

The toroid part is for separation of the ion beam orbits and turning the electron beam through 90 degrees for sending the electron beam by the transport beamline to the acceleration tube in the vertical vessel. The toroid is the most complicated place, where two beamlines (for electrons and ions) meet together. In addition, the ion corrector should be located in this place, as well as vacuum pumps. The coils for the bending field are placed on the toroid side. In addition to all other problems, the distance between the two electron beams should be 32 cm (Fig. 6).

Most of the problems can be solved via decreasing the magnetic field in the toroid. However, there is no such thing as a free lunch. The cooling section (6 m) is shorter than the straight section along the ion orbit (6.84 m). The distance of 0.84 m is used for the matching section.

ISBN: 978-3-95450-218-9 ISSN: 2226-0374 doi:10.18429/JACoW-COOL2019-THX01

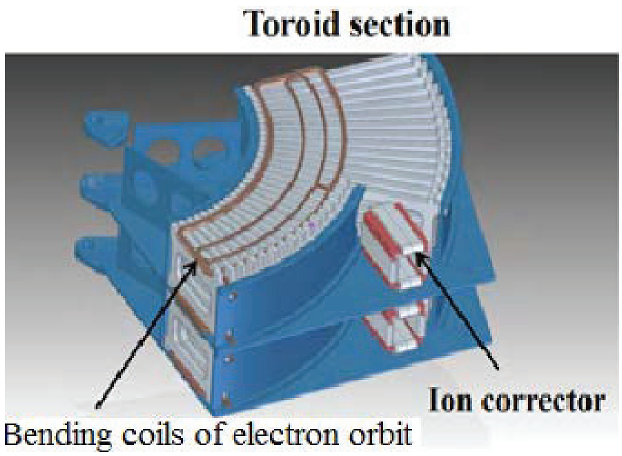

Figure 6: Toroid for bending electron beams.

ELECTRON COOLING

The experience of cooling of high-charge ions at the existing coolers shows very high brightness of ion beam after electron cooling. From the very beginning, there was a problem of ion losses from the ion beam because of recombination. The experiment at the NAP and ESR [4,5] demonstrated that at a strong magnetic field and high "Larmor" temperature, the recombination rate is less than the cooling rate. In the NICA case, the cooling time can be estimated as follows:

$$\tau_{cool} = \frac{\gamma(\frac{V_i}{c})^3}{4r_e r_i n_e \eta c \ln(\frac{\rho_{max}+\rho L}{\rho L})}, \quad (1)$$

where $\rho_{max} = \Theta_i dl_c$, $\Theta_i = \sqrt{\varepsilon/\beta\chi}$, V_i is the velocity of ion in the beam system, $\rho L = (m*c*VL)/e*Bs$ is the radius of the Larmor rotation, γ is the relativistic factor, βx is the beta function in the cooler, ne is the electron beam density in the beam system (moving), and η is the ion orbit fraction occupied by the cooler. For calculation of the recombination we used the well known equation [6]

$$\alpha_{REC} = 1.92 \times 10^{-13}\ \mathrm{cm^3\ s^{-1}} \times \frac{q^2}{\sqrt{kT_{e\perp}}} \times \left\{ \ln\left(\frac{5.66q}{\sqrt{kT_{e\perp}}}\right) + 0.196\left(\frac{kT_{e\perp}}{q^2}\right)^{1/3} \right\} \quad (2)$$

,

Where $T_{e\perp} = me*VL^2/2$ is the temperature of the Larmor rotation in eV. The recombination lifetime is

$$\tau_{rec} = \gamma/(\alpha_{rec}*ne*\eta) \quad (3)$$

For the 4 GeV/u NICA cooling, results for gold ions (+79Au197) are shown in Table 2.

Table 2: Results for Gold Ions

Te, eV	τcool, sec	τrec, sec	τrec/τcool
0.1	16	76	4.7
1	19	182	14
10	25	1000	42
100	35	4200	120
100	55	17000	320

It is easy to see from this calculation that with increasing energy of the Larmor rotation, the recombination decreases very fast as compared with the cooling rate. It is one of main advantages of "magnetized cooling".

HIGH VOLTAGE ACCELERATION

The electron beam is generated inside the vessel filled with SF6 (elgas) under a pressure of up to 10 bar, Fig. 7a.

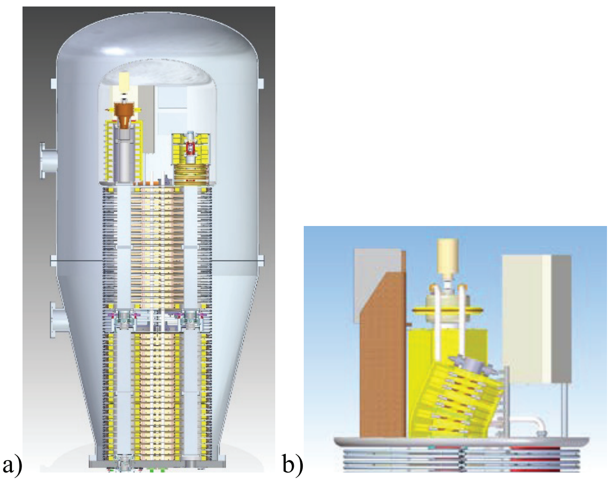
a) b)

Figure 7: a) Vessel for acceleration section and acceleration tube. B) electron gun with bending of electron beams for saving cathode.

The bending part near the electron gun protected the cathode from bombardment by the secondary ions from ionization of the residual gas in the acceleration tube (Fig. 7b). A few prototype acceleration sections were tested with air at a voltage of up to 20 kV. The corona current was measured from 10 kV, but training with air increased the voltage for sparking. The sections along the columns are powered by a cascade transformer consisting of 42 rings coupled by insulated coils, Fig. 8. The operation frequency is 20 kHz and the power exceeds 30 kW.


Figure 8: Cascade transformer on test bench for solenoid component after tilting individual coils of solenoid by 4 mm.

ISBN: 978-3-95450-218-9 ISSN: 2226-0374 doi:10.18429/JACoW-COOL2019-THX01

Figure 9: Vessel for high voltage equipment produced in Novosibirsk

Figure 9 show vessel after production at Novosibirsk factory.

THE ELECTRON COOLING AT NICA

The interaction between the cooler and NICA is subject of many articles and discussion. This article gives no space for discussion, but it will be interesting to see any results on these questions. The dynamics of emittance at NICA were calculated in a simple model including IBS and electron cooling. For calculation of the influence of the space charge, the IBS was intensified when the Laslet tune got closer to a value of 0.1. It is clear that this model is too simple, but a more skilful model has not yielded calculation results so far. Any way, it would be interesting to look at the results of the very simple model, shown in Fig. 10.

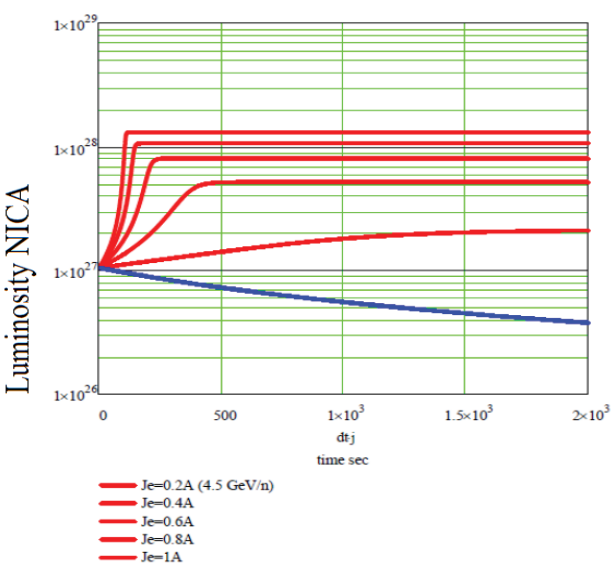

Figure 10: Time variation of luminosity for electron current varying from 0 to 1 A.

As shown in Fig. 10, an electron current of just over 0.2 A will increase the luminosity. The development of the simulation code will continue at BINP and JINR, but we will be able to verify the results after commissioning of NICA with the cooler.

CONCLUSION

The high-voltage cooler with the magnetized electron beam will help to obtain high luminosity of the NICA collider. This collider is one of a few Mega-science projects in Russia, and its commissioning is very important for future acceleration science.

ACKNOWLEDGMENT

The authors are only a small part of the large collective of BINP working on problems of the design and construction of coolers. The authors are thankful to A. Batrakov, O. Belikov, E. Bekhtenev, I. Gusev, V. Chekavinsky, S. Fadeev, M. Fedotov D. Senkov and many other colleges who help to create the high voltage cooler for NICA.

REFERENCES

[1] G.I Budker, “Efficient method for damping of particle oscillations in proton and antiproton storage ring”, *Atomnaya Energiya* 22 p.346-348, 1967.

[2] V.V. Parkhomchuk, A. N. Skrinskii, “Electron cooling: 35 years of development”, *Phys. Usp.*, vol. 43, no. 5, p. 433–452, 2000. doi: 10.1070/PU2000v043n05ABEH000741

[3] V. V. Parkhomchuk, “New insights in the theory of electron cooling”, *Nucl. Instr. and Meth. A*, vol. 441, Iss. 1-2, p. 9-17, Febr. 2000. doi: 10.1016/S0168-9002(99)01100-6

[4] N. S. Dikanskii *et al.*, “Development of techniques for the cooling of ions”, *Phys. Usp.*, vol. 61, p. 424–434, 2018. doi: 10.3367/UFNe.2018.01.038297

[5] P. Beller, K. Becket, *et al.,* “Observation of a reduction of recombination between ions and electrons”, *Nuclear Instruments and Methods in Physics Research* Section A, Volume 532, 2004, p. 427-432.

[6] H. Beyer, *et al. Part. Accel.* 24 (1989)1989.