APPLICATION OF COOLING METHODS TO NICA PROJECT

E. Ahmanova, V. Bykovsky, A. Kobets, D. Krestnikov, I. Meshkov, R. Pivin, A. Rudakov, A. Sidorin, A. Smirnov, S. Yakovenko, JINR, Russia
Jürgen Dietrich, FZJ, Germany
Takeshi Katayama, GSI, Germany

Abstract

The **N**uclotron-based **I**on **C**ollider f**A**cility (NICA) is a new accelerator complex being constructed at JINR aimed to provide collider experiments with heavy ions up to Uranium at maximum energy (center of mass) equal to 11 GeV/u. It includes new 6.2 MeV/u linac, 600 MeV/u booster synchrotron (Booster), upgraded superconducting (SC) synchrotron Nuclotron and collider consisting of two SC rings, which provide average luminosity of the order of 10^{27}cm^{-2}s^{-1}. A few cooling systems are proposed for the NICA project. The Booster will be equipped with an electron cooling system. Two cooling methods – stochastic and electron ones - will be used at the collider rings. Main parameters of the cooling systems and peculiarities of their design are presented here.

INTRODUCTION

The goal of the NICA project [1] is construction at JINR of the new accelerator facility that consists of (Fig.1)

- cryogenic heavy ion source KRION of Electron String Ion Source (ESIS) type,
- source of polarized protons and deuterons,
- the existing linac LU-20,
- a new heavy ion linear accelerator,
- a new Booster-synchrotron (that will be placed inside of the yoke of the decommissioned Synchrophasotron),
- the existing heavy ion synchrotron Nuclotron (being developed presently to match the project specifications),
- two new superconducting storage rings of the collider,
- new set of transfer channels.

The facility will have to provide ion-ion (1 ÷ 4.5 GeV/u), ion-proton collisions and collisions of polarized proton-proton (5 ÷ 12.6 GeV) and deuteron-deuteron (2 ÷ 5.8 GeV/u) beams. As a result of the project realization, the potential of the Nuclotron accelerator complex will be sufficiently increased in all the fields of its current physics program: both fixed target experiments with slowly extracted beams and experiments with internal target. The Booster will be equipped with a slow extraction system to provide medicine, biological and applied researches.

The collider will have two interaction points. The Multi Purpose Detector (MPD) aimed for experimental studies of hot and dense strongly interacting QCD matter and search for possible manifestation of signs of the mixed phase and critical endpoint in heavy ion collisions, is located in one of them. The second one is used for the Spin Physics Detector (SPD).

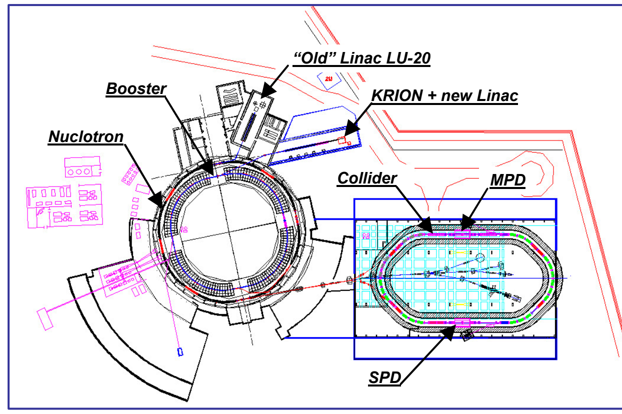

Figure 1: Schematics of the NICA accelerator complex.

Collider will be operated at a fixed energy without acceleration of an injected beam. Correspondingly the maximum energy of the experiment is determined by the Nuclotron magnetic rigidity that is equal to about 45 T·m. Main goal of the NICA facility construction is to provide collider experiment with heavy ions like Au, Pb and U at average luminosity above $1\cdot10^{27}$ cm$^{-2}\cdot$s^{-1} (at the energy of 3.5 GeV/u). Therefore in this report we discussed the heavy ion mode of the facility operation only, and the Gold nuclei $^{197}Au^{79+}$ are chosen as the reference particles.

To reach the required parameters a beam cooling is proposed both in the Booster and in the collider rings. During R&D stage we plan to test a prototype of the stochastic cooling system at the Nuclotron on a magnetic field plateau.

BOOSTER ELECTRON COOLER

The maximum design ion energy of 4.5 GeV/u can be achieved in the Nuclotron with fully stripped ions only. To provide high efficiency of the ion stripping one has to accelerate them up to the energy of a few hundreds of MeV/u. For this purpose a new synchrotron ring – the Booster is planned to be used (Table 1). Heavy ion injector-linac is designed for acceleration of Au^{32+} ions. The Booster has maximum magnetic rigidity of 25 T·m that corresponds to about 600 MeV/u of the ion energy, and the stripping efficiency is no less than 80%.

The Booster is equipped with an electron cooling system that allows providing an efficient cooling of the ions in the energy range from the injection energy up to 100 MeV/u.

The magnetic system of the Booster is superconducting. Its design is based on the experience of construction of the Nuclotron SC magnetic system [2] and SC magnetic system of SIS-100 developed later at FAIR project.

Therefore to avoid connections between "warm" and "cold" sections in the ring the solenoids of the cooler located along the Booster circumference are designed in the SC version (Fig. 2). This is main difference of the Booster cooler from a conventional electron cooling systems.

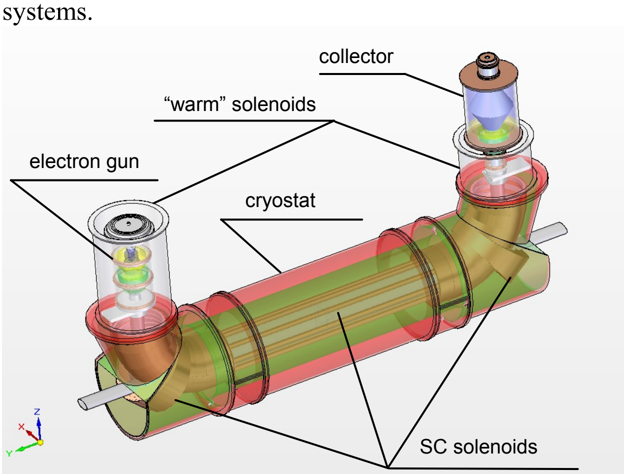

Figure 2: The Booster electron cooler.

The Booster cooling system will be used for two independent purposes:

- optimization of 6-dimentional phase space of a heavy ion beam to provide its effective acceleration in the collider injection chain and injection into the collider rings;
- formation of high quality beams when the Booster is used for medicine, biological and applied researches.

To cover total range of the ion energy in the Booster (600 MeV/u) the electron beam maximum energy has to be about 330 keV. However the cooling system at such energy is rather expensive, therefore the maximum electron energy (60 keV) is chosen as a compromise between the system price and its capability to fulfill the main project task – the ion colliding beams. A possibility to decrease the ion beam phase volume at low energy is restricted by space charge limitations.

Another criterion for the electron energy choice is related to the frequency variation range of the Booster RF system. The ion acceleration in the Booster is proposed to be performed in two steps: on the 4^{th} harmonics of the revolution frequency up to the cooler energy and on the 1^{st} one after the cooling. If the cooling is performed at the ion kinetic energy ≥ 100 MeV/u, one can use the same RF system on both steps of the acceleration.

All other parameters of the Booster cooler (Table 2) are typical for conventional electron cooling systems. Design of the cooler is performed by JINR electron cooling group and its construction is planned to be done at JINR workshop. Test of the cooler elements will be performed at existing test bench.

Main goal of the cooling of heavy ion beam is to decrease its longitudinal emittance to the value required for effective injection and acceleration in the Nuclotron and for the bunch compression in the Nuclotron before injection into the collider. Transverse beam emittance has to be stabilized at relatively large value to avoid space charge limitations in the Nuclotron and collider rings. To avoid overcooling of the transverse degree of freedom the electron beam misalignment in respect to the ion orbit can be used. Simulations of such a regime of the cooler operation performed with Betacool code showed that during 1 second of the cooling one can decrease the longitudinal beam emittance by about 3 times at practically constant transverse emittance. That is sufficient for our goal.

Table 1: Basic Parameters of the Booster and its Electron Cooling System

Ions	$^{197}Au^{32+}$
Booster circumference, m	211.2
Injection/extraction energy, MeV/u	6.2/600
Max. dipole field, T	1.8
Ion number	2×10^9
Beta functions in cooling section, m	8 / 8
Dispersion function in cooling section, m	0.6
Maximum electron energy, keV	60.0
Electron beam current, A	0 ÷ 1.0
Cooler overall length, m	4.0
Effective length of the cooling section, m	2.5
Magnetic field in the cooling section, kG	1.5
Magnetic field inhomogeneity in the cooling section, ΔB/B	$1\cdot10^{-4}$
Electron beam radius in the cooling section, cm	2.5
Transverse electron temperature, meV	200
Longitudinal electron temperature, meV	0.5
Cooling time, s	1
Residual gas pressure, Torr	10^{-11}

At the electron cooling of heavy ions one of the serious problems is the recombination - i.e. capture of cooling electrons by ions - resulting in loss of the ions due to change of their charge and deformation of the ion closed orbit. The recombination rate of Au^{32+} ions in the Booster cooler was extrapolated from the experimental data obtained at GSI and CERN. The estimation has shown that during 1 s of cooling the ion losses will be less than 10%. In any case the use of SC solenoid in the cooling section gives a possibility to provide the electron beam compression in order to suppress the recombination by increase of the temperature of transverse degree of freedom of the electron beam.

COLLIDER OPERATION

Two collider rings have a maximum magnetic rigidity of 45 Tm that is equal to the Nuclotron one. The rings are situated one upon the other by the scheme "twin bore magnets": bending and quadrupole magnets have two apertures in common yoke.

Estimations show that the required luminosity can be reached at the ion bunch intensity of 10^9 ions per bunch.

The inter bunch distance (and, correspondingly, the maximum bunch number) is limited by requirement to avoid parasitic collisions in the vicinity of interaction point. At the collider and MPD parameters [3] the maximum bunch number is below 20. At such conditions one way to increase the luminosity is to decrease the bunch length. Also, the bunch length has to be as small as possible to avoid an "hour glass" effect and to provide the luminosity concentration in the central part of the detector. On other hand a small bunch length increases the bunch peak current that can provoke a coherent instability. Finally the bunch length was chosen as a compromise between these two contradicting effects (Table 2).

In the NICA energy range the luminosity is limited by incoherent tune shift. Correspondingly, the beam emittances (Table 2) are chosen to keep the tune shift below 0.05. Beam-beam parameter at all energies is below 0.005.

Table 2: Collider beam parameters and luminosity for Au-Au collisions

Ring circumference, m	251		
Ion number per bunch	$1\cdot10^9$		
Number of bunches	17		
Beta-function in the interaction point, m	0.5		
Rms bunch length, m	0.3		
Rms momentum spread	0.001		
Ion energy, GeV/u	1.0	3.5	4.5
Rms beam emittance (unnormalized), $\pi\cdot$mm$\cdot$mrad	3.9	0.27	0.14
Luminosity, 10^{27} cm^{-2}s^{-1}	0.06	1.05	1.9

Two schemes of the collider feeding with the ions are under consideration now:

- in accordance with the first one during the feeding the collider RF system is switched on at the working harmonics of the revolution frequency and bunch prepared by the injection chain is injected into corresponding separatrix;
- the second scheme presumes storage in the collider of a coasting beam initially. After storage of a required ion number an adiabatic bunching and bunch compression are performed.

At the first scheme application the ion bunch of required int14ensity and emittance has to be prepared by the injection chain. The required bunch emittance is formed using electron cooling in the Booster. To reach the design bunch length the bunch is compressed in the Nuclotron by RF phase "jump" after acceleration. In this regime the maximum bunch number in the collider ring is limited by the injection kicker pulse duration: one needs to avoid distortion of circulating bunches by inflector pulse at injection of a new bunch.

The second scheme simplifies significantly the requirements to the injection chain. The beam storage can be realized using RF stacking procedure or with application of RF barrier bucket technique. Intensity of the injected ion portion influences on the stacking process duration only and can be arbitrary in principle. The required beam emittance is formed during the stacking by the cooling application. The maximum bunch number in the collision mode is limited by requirement to avoid parasitic collisions in the vicinity of the interaction point and can be larger than at the first scheme. However at this scheme the collider has to be equipped with two RF systems. One of them is used for the beam stacking with the Barrier Buckets and bunching of the stacked beam with sinusoidal RF at the harmonics number coinciding with the bunch number. Another one is operated at the collisions. It is conventional RF system of significantly larger harmonics number that is necessary to keep a short bunch length at reasonable RF voltage. The second scheme is preferable for the facility operation but it requires additional space of the collider circumference for RF system placing. Therefore the final choice of the storage scheme will be done at the technical design of the collider rings.

The beam cooling application in the collider rings has two goals:
- beam storage using cooling-stacking procedure;
- luminosity preservation during experiment.

The first goal can be achieved with stochastic cooling system of reasonable technical parameters, because in this case the beam has rather low linear particle density.

BEAM COOLING DURING EXPERIMENT

Without a beam cooling, during the experiment the beam emittance and the bunch length increase due to intrabeam scattering (IBS) process. The expected IBS growth time values in the collider are of the order of 10 - 50 s at the ion energy of 3.5 GeV/u. The luminosity preservation is the general goal of the beam cooling in the collider. In equilibrium between IBS and cooling, the luminosity life-time is limited mainly by the ion interaction with residual gas atoms. The vacuum conditions in the collider rings are chosen to provide the beam life time of a few hours.

In the required energy range (from 1 to 4.5 GeV/u) the both electron and stochastic cooling method can be used. However there is presently a lack of the world experience of the cooling systems of required parameters.

On one hand, the electron energy for the ion beam cooling at 4.5 GeV/u is equal to about 2.45 MeV that is much higher than in conventional electron cooling systems. Indeed, the highest energy of the electron beam reached in the Recycler cooling system (FNAL) is equal to about 4.3 MeV (that corresponds to the ion energy of about 8 GeV/u) [4]. Unfortunately this system is operated at low magnetic field value that does not allow achieving short cooling time. The existing cooling systems with magnetized cooling are operated at the electron energy below 300 keV.

Concerning stochastic cooling there is no experience of the bunched ion beam cooling. Stochastic cooling of bunched beam has been demonstrated a few years ago in pioneering work at RHIC [5] with Gold ion beam of a high energy and for longitudinal degree of freedom only. Due to some peculiarities of that cooling system design its design can not be applied directly to bunched beam cooling at low ion energy. And no experience exists yet for stochastic cooling of transverse degrees of freedom of bunched beam. Therefore design and construction of the cooling system (independently – electron or stochastic) require R&D stage of the work.

Stochastic cooling application looks very attractive because it does not lead to additional particle loss and keeps the shape of ion distribution close to Gaussian one. First simulations and feasibility study have shown the problems of both physical and technical character. Nerveless constriction of stochastic cooling system for the bunched beam of NICA parameters constitutes to be rather realistic.

Simulations of electron cooling process at cooler parameters listed in Table 3 (Fig. 3) demonstrate capability of the system to stabilize the luminosity at the required level during a long time. However, the electron cooling leads to formation of a small and dense core of the ion distribution function (Fig. 4) that determines the luminosity, and very long tails at relatively low intensity. The tails are not stabilized by the cooling and their development can lead to additional particle loss. The particle loss due to recombination in the cooling section is suppressed by increase of the electron beam temperature (to provide the beam lifetime longer then 1 hour the temperature has to be increased up to about 50 eV). Therefore, to keep sufficient value of the friction force the magnetic field in the cooling section has to be increased up to 2 T.

At the moment an optimum strategy of the beam cooling during experiment seems to be in combination of both cooling methods: electron cooling should be used to provide short cooling time for central part of the ion distribution and stochastic cooling – for stabilization of the distribution tails.

Table 3: Main Parameters of the Collider Electron Cooling System

Maximum electron energy, MeV	2.5
Cooling section length, m	6.0
Electron beam current, A	0.5
Electron beam radius, cm	0.5
Magnetic field in cooling section, T	2.0
Magnetic field inhomogeneity in cooling section	2×10^{-5}
Beta functions in cooling section, m	20
Transverse electron temperature, eV	50.0
Longitudinal electron temperature meV	5.0
Beam lifetime due to recombination, hour	1.0

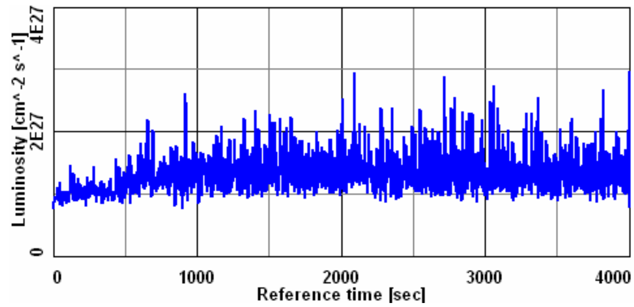

Figure 3: Luminosity variation during 1 hour of the experiment under action of the electron cooling. Ion beam energy is 3.5 GeV/u, initial ion beam parameters are taken from the Table 2. Simulations with Betacool program.

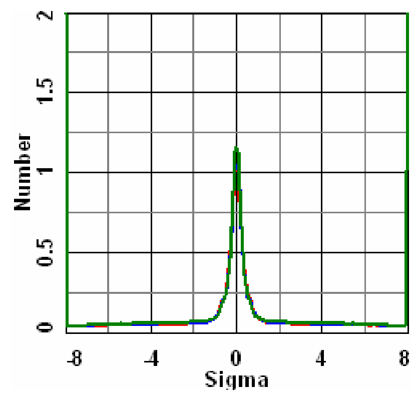

Figure 4: The ion beam profile under the electron cooling. Vertical axis is the relative particle number, horizontal – the beam profiles in the initial RMS value.

R&D FOR COLLIDER COOLING SYSTEMS

Preliminary design of the collider electron cooling system was performed in co-operation with All-Russian Electrotechnical Institute (VEI, Moscow) on the basis of dynamitron-type high voltage generator (Fig. 5). For the electron beam transport from the high-voltage vessels to the cooling section as well as for the cooling sections SC solenoids will be used. The electron beam transport inside the accelerating/decelerating columns is provided by normal conducting solenoids at relatively weak magnetic field. Such a scheme permits to provide electron beam compression in the cooling section and, correspondingly, increase the electron transverse temperature. That allows to suppress the ion recombination.

Design of the high voltage generator prototype has been started; it will be constructed in VEI and tested at total voltage.

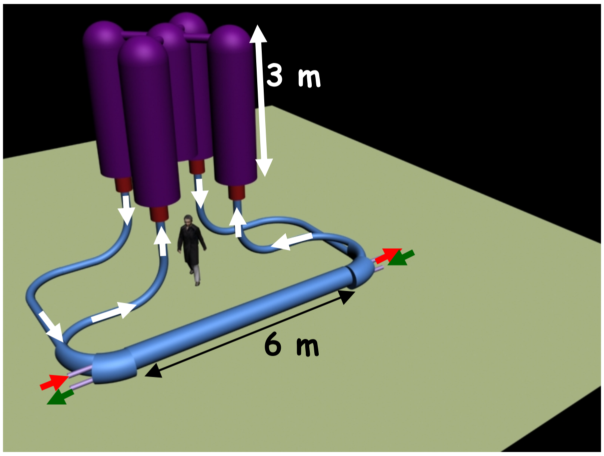

Figure 5. Artistic view of the collider electron cooling system.

For the stochastic cooling development one plans to perform the cooling experiment with ion beam circulating in the Nuclotron – cooling of longitudinal degree of freedom. Presently in the Nuclotron ring there are two free straight sections of the length of 3.5 m each one (one of them is reserved for the beam injection from the Booster, another one - for the spin control device). These sections will be used temporarily for experimental test of a prototype of the collider stochastic cooling system. The existing Nuclotron RF system can not provide the same large bunching factor for heavy ion beam as required for the collider operation. But the cooling system can be tested at the same linear particle density of a bunched deuteron beam, which has intensity by two orders of magnitude larger than expected one for the heavy ions.

The pick-up and kicker electrodes of the stochastic cooling system prototype will be elaborated in cooperation with COSY and will be similar to that one designed for the HESR of the FAIR project [6].

CONCLUSION

Application of the cooling methods is a key feature of the NICA project being developed at JINR. The project realization requires elaboration of novel cooling systems that can be done using both numerical simulations and experimental work with prototypes.

Numerical simulations of the beam dynamics in the collider under stochastic and electron cooling are in progress. The electron cooling system of the collider will be designed and constructed in collaboration with BINP, FZJ and VEI. Elaboration of the stochastic cooling system we plan to perform in collaboration with CERN, GSI, FZJ, FNAL and BNL. The prototype of the stochastic cooling will be tested at the Nuclotron.

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