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NICA COOLING PROGRAM

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Abstract

Nuclotron-based Ion Collider fAcility (NICA) is the new experimental heavy-ion complex being constructed at Joint Institute for Nuclear Research, Dubna. Main purpose of the project is to provide experiment on colliding heavy ion beams (Au) for study of manifestation of hot and dense strongly interacting baryonic matter [theor.jinr.ru]. The construction of the accelerator complex is actively performed: production of elements of new 3.2 MeV/u heavy-ion linear accelerator (HILac) is now under completion, production of Booster synchrotron elements has been started. The New Test Facility for assembly and cold testing of superconducting magnets for NICA Booster, collider and SIS100 synchrotron (FAIR, Darmstadt) started to assemble and perform magnetic measurements of the first of series magnets [Trubnikov *et al.*, 2014].

Beam cooling systems are suggested for application at NICA. The Booster equipped with 35 keV electron cooling system is intended for the storage of $^{197}Au^{31+}$ ions to an intensity of about $4 \cdot 10^9$ particles and the formation of the necessary beam emittance using the electron cooling system. Two beam cooling systems: stochastic and electron, are supposed to be used in the collider. Parameters of cooling systems, proposed scenario of collider operation, their design intended to achieve required average luminosity of the order of $10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at high energies are presented. Recent experimental results in stochastic cooling experiments achieved at Nuclotron which are of great practical interest for NICA collider operation are presented here and discussed.

Key words

Particle beams, storage ring, collider, beam dynamics, luminosity, electron cooling, stochastic cooling

1 Introduction

The detailed scheme of the NICA complex is described in Ref. [Trubnikov *et al.*, 2014],[Kekelidze *et al.*, 2012] main parameters are presented in Table 1.

The collider design has to provide the project luminosity and its maintenance during a long time necessary for an experiment performance. That requires formation of ion beams of high intensity with sufficiently low emittance and long ion beam life time. To reach the required parameters a beam cooling is proposed both in the Booster and in the collider rings.

2 Operation of the Booster with Electron Cooling System: Goals and Objectives

The maximum design ion energy of 4.5 GeV/u can be achieved at 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 use [Valkovich *et al.*, 2012]. The Booster will have maximum magnetic rigidity of 25 T·m that corresponds to about 660 MeV/u of the ion energy, and the stripping efficiency is not less than 80%. The operation diagram of the Booster is shown in Fig. 1.

The Booster is planned to be equiped with electron cooling system that allows to provide efficient cooling of the ions in the energy range from injection energy up to 65 MeV/u. Electron cooling at injection energy 3.2 MeV/u is required to accumulate intense beam especially if multiple injection is used. Such mode will be required also for storing highly charged ion states (e. g. Au65+ ions) or polarized ions (e. g. ↑H– atoms) with high intensity. Beam cooling at energy 60-70 MeV/u could be useful to achieve special beam parameters required by fixed target experiments on the extracted beam from the Booster.

	Booster (project)	Nuclotron		Collider (project)
		Project	Status 2014	
Circumference, m	211.2	251.5		503.0
Maximum magnetic field, T	1.8	2.0	2.0	1.8
Magnetic rigidity, T.m	25.0	45	45	45
Cycle duration, s	4.02	4.02	7 - 1000.0	$\geq$ 2000
B field ramp rate, T/s	1.2	2.0	0.8	$<$ 0.5
Accelerated/stored particles	p-$^{197}Au^{79+}$, p↑, d↑		p-Xe, d↑	p-$^{197}Au^{79+}$, p↑,d↑
Maximum energy, GeV/u				
Protons	–	12.6	–	12.6
Deuterons	–	5.87	5.2/5.8(C6+)	5.87
Ions, GeV/u	$^{197}Au^{31+}$, 0.6	$^{197}Au^{79+}$,, 4.5	$^{124}Xe^{42+}$, 1.5	$^{197}Au^{79+}$, 4.5
Intensity, ion number per cycle (bunch)				
protons	1.1011	2.1011	1.1010	2.1011
deuterons	1.1011	1.1011	4.1010	1.1011
$^{197}Au^{79+}$	1.5.109	1.109	1.104 $^{124}Xe^{42+}$	1.109

Table 1. Parameters of NICA accelerator complex

Another goal of the cooling of heavy ion beam at 60-70 MeV/u energy could be decreasing its longitudinal emittance to the value required for effective injection and acceleration 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. 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 [Kostromin *et al.*, 2011].

The magnetic system of the Booster is superconducting. Its design is based on the experience of construction of the Nuclotron SC magnetic system. The electron cooling system for the Booster is supposed to be made using conventional solenoid. For this reason, special warm-to-cold transition sections are built into the magnet–cryostat system of a straight section in the Booster ring. Considering these geometrical limitations and other requirements main parameters of the electron cooler are formulated in the Table 2. The system is quite typical: an electron beam current of 1A corresponds to the maximum electron energy, when cooling is required at the injection energy the current is limited by space charge effects and does not exceed 50–100 mA. The conceptual design of the system has been made in collaboration of JINR and Budker INP (Fig. 2), its construction is performed now at Budker INP [Bubley *et al.*, 2012].

One of the most serious problems in the electron cooling of heavy ion beams is the recombination of ions on electrons of the cooling electron beam which leads to a change in the charge state and the loss of an ion due to the change in the position of its orbit. Evaluations [Kuznetsov, Meshkov, and Philippov, 2011] of the recombination rate of Au31+ and Au51+ ions upon cooling at the energy of 100 MeV/u which were based on the experimental data from the electron cooled storage rings at CERN (Switzerland), GSI (Darmstadt, Germany), and MPI (Heidelberg, Germany), show that the ion loss within one second of cooling will be no larger than 2%. The correct choice of the ion charge state should be made to avoid the "resonant" recombination. Nevertheless, it is possible to increase the temperature of the transverse degree of freedom of electrons using modulation by the transverse electric field in the electron gun.

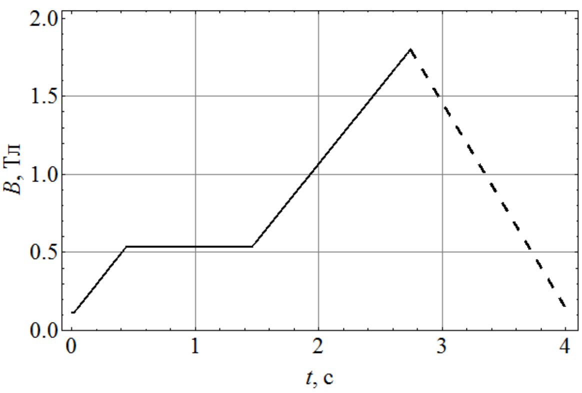

Figure 1. Booster cycle diagram (plateau at B = 0.55 T corresponds to ion energy E = 65 MeV/u)

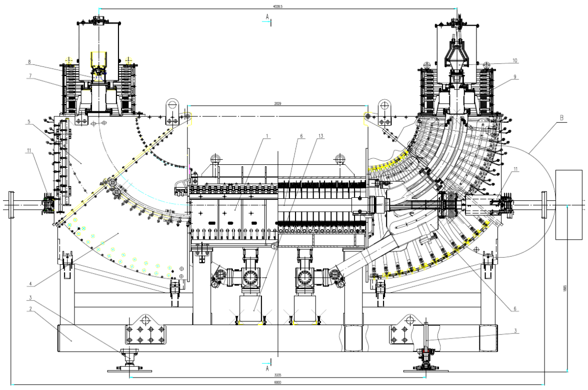

Figure 2. Electron cooling system for Booster. 1 – electron gun, 2 – magnetic coils and electrostatic plates, 3 – toroidal solenoids, 4 – straight solenoid, 5 – magnetic shield, 6 – collector of electrons, 7 – correcting coils for ion beam, 8 – ion beam chamber

Energy of electrons, keV	1,5 $\div$ 35
Energy controlling, ΔE/E	$\leq 1\cdot10^{-5}$
Electron beam current,	0,2 $\div$ 1,0
e-beam current stability, ΔI/I	$\leq 1\cdot10^{-4}$
Stright solenoid length, mm	2522
Total length, mm	5715
Long. magnetic field, T	0,1$\div$0,2
B field homogenity, ΔB/B	$<10^{-4}$
Vacuum conditions, Torr	$<10^{-10}$

Table 2. Parameters of electron cooling system

3 Low Energy Heavy Ion Collider: Requirements and Challenges for High Luminosity. Regimes of Operation

Two superconducting rings of collider will have maximum magnetic rigidity of 45 T·m each. The rings are vertically separated by 320 mm locating in the same cryo-vacuum volume: so-called "double-aperture" magnet, operating at 4.5K. The maximum field in the bending magnets is chosen to be 1.8 T. The rings are symmetrical and each consists of two arcs and two long straight sections with circumference of 503 m [Kozlov *et al.*, 2012]. The arc optics based on FODO elementary cell at 12 cells per each arc is chosen for the ring lattice. The collider operation at luminosity of between 10^{26} and 10^{27} cm^{-2}s^{-1} allows to perform experiments which should measure all hadrons comprising multi-strange hyperons, their phase-space distributions and collective flows, including also event-by-event observables. The scheme of the collider, ring composition and choice of the beam parameters to achieve design luminosity are discussed in [Kekelidze *et al.*, 2012], [Kostromin *et al.*, 2011]. Chosen beam parameters and estimated luminosity are shown in Table 3.

When the bunch phase volume is determined, the particles number per bunch is restricted by the total acceptable betatron tune shift $\Delta Q = Q_{Las} + 2\xi$ (Lasslet tune shift plus doubled beam-beam parameters corresponding to 2 IP's). For chosen working point $(Q_{x/z} = 9.43/9.44)$ of the collider the limiting value is about $\Delta Q \leq 0.05$. This strategy of the parameter optimization allows to have the luminosity above10^{27} cm^{-2}s^{-1} in the energy range from about 3 up to 4.5 GeV/u. In this energy range the tune shift can be even less than the limiting value of 0.05. Below 3 GeV/u maximum luminosity is reached at maximum tune shift due to dominated effect of the Lasslet tune shift. Expressing the luminosity via the tune shift we have the following estimation:

$$L = \beta^5\gamma^2\Delta Q^2_{total}\frac{A^2}{Z^4}\cdot\frac{4\pi\varepsilon_{unnorm}c}{r_p^2\beta^*}\cdot\left(\frac{k_{bunch}}{\gamma^2}+\right.$$
$$\left.+\,n_{IP}(1+\beta^2)\right)^{-2}\cdot\frac{n_{bunch}}{C_{Ring}}\cdot f_{HG},$$
$$k_{bunch} = \frac{C_{Ring}}{\sqrt{2\pi}\sigma_s},\quad nIP = 2. \qquad (1)$$

That shows that in the IBS dominated regime the luminosity scales with the beam energy approximately as $\beta^5\gamma^6$ if $\xi << \Delta Q_{Las}$. The Keil-Schnell criteria for longitudinal microwave instability is satisfied for the bunch intensity in whole energy range.

The beam cooling application in the collider rings has two goals:

— beam accumulation using cooling-stacking procedure;

— luminosity preservation during experiment.

The first goal can be achieved with electron and stochastic cooling system of reasonable technical parameters, because in this case the beam has rather low linear particle density. It is discussed in chapter below and in [Katayama *et al.*, 2013]. The second goal is more important. Dedicated scenario of using stochastic and electron cooling systems to cover whole energy range with maximal achievable luminosity at low energies and to have luminosity of the order of 10^{27} cm^{-2}s^{-1} at maximal energies is discussed below.

In equilibrium between IBS and the cooling the luminosity life-time is limited mainly by the ion interaction with the residual gas atoms. The vacuum conditions in the collider rings are chosen to provide the beam life time of a few hours. The beam preparation time is designed to be between 2 and 3 minutes. Therefore, the mean luminosity value is closed to the peak one. To realize this regime the cooling times have to be equal to the expected IBS heating times for all degrees of freedom. The way to increase the luminosity at low energy is to provide powerful cooling with cooling times sufficiently shorter than the IBS times. In such a regime (so called "*Space charge dominated*" regime) the bunch emittance is limited by achievable tune shift value but the momentum spread and the bunch length are determined by synchrotron tune suppression. Stochastic and electron cooling technique at the collider are proposed to have required luminosity with possibility of energy scan. 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. However it cannot provide short cooling time at low energies.

Simulation showed that for the energy from 3 GeV/u and higher a cooling system has to provide the cooling times of about 500 seconds and more – that will be achieved by stochastic cooling system at bandwidth of 3 GHz. At low energies starting from E = 1 GeV/u cooling has to be of the order of ten seconds (that will be provided by electron cooling system) [Kekelidze *et al.*, 2012], [Kostromin *et al.*, 2011].

Proposed cooling scenario for NICA collider is the following (Fig. 3): in the ion energy range from 1 to 3 GeV/u the electron cooling can provide rather short cooling times to keep *Space charge dominated regime* and increase luminosity in comparison with IBS dominated one. HV electron cooling system with energy up to 1.5 MeV looks realistic. In the energy range from 3 to 4.5 GeV/u the usage of the stochastic cooling system is more preferable. Here the luminosity is equal to 10^{27} $cm^{-2}s^{-1}$ and the collider can operate in *IBS dominated regime*.

Numerical simulations of the beam dynamics in the collider under stochastic and electron cooling are in progress.

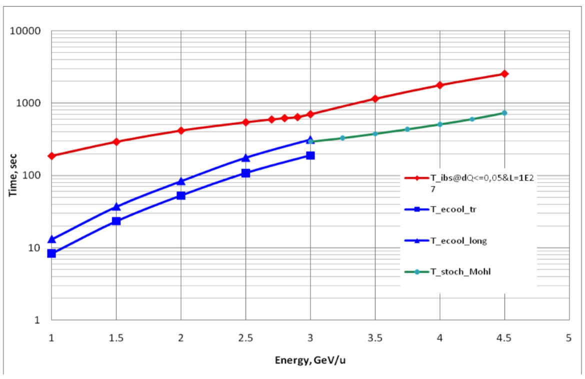

Figure 3. Fig. 3. IBS growth times in the IBS dominated regime (red curve), electron cooling times – blue curves (below 3 GeV/u) and stochastic cooling time – green curve (above 3 GeV/u)

4 Beam Stacking in Longitudinal Phase Space

The beam accumulation in the collider in longitudinal phase space is planned with application of RF barrier bucket (BB) technique. This provides independent optimization of the bunch intensity, bunch number as well as controlling of the beam emittance and momentum spread during the bunch formation. The comparison of the beam stacking in the longitudinal phase space with stationary and moving under action of electron cooling or without cooling are presented in [Smirnov *et al.*, 2013].

Simulation of the particle accumulation for NICA collider with the stationary barrier buckets and the electron cooling system [Smirnov *et al.*, 2013],[Katayama *et al.*, 2012] showed that efficiency of accumulation is good at low ion energies and is not sufficient at higher energies. We found the serious disadvantage of using stationary barriers. Particles are injected into unstable region (potential "top"), period of their phase motion is longer in comparison to that one in stack. The cooling rate when particles are in injected region is slower because of large initial dp/p [Meshkov, 2014]. In addition (if particle energy is below transition one) while travelling through barriers from injection zone into stack, particles experience positive energy kick if their energy is above synchronous one and negative - if below. As result cooling time increases.

The simple scheme of stacking [Mohl *et al.*, 1980] with moving barriers can be proposed using special conditions at injection [Smirnov *et al.*, 2013]. The pulse of the injection kicker is designed to be no less than 800 ns i.e. it occupies 1/2 of the collider's circumference in phase space. So the injection zone can not exceed 1/2 of the ring. But this difficulty can be circumvented when moving barriers are used, because phase space occupied by barrier pulses can be used for the leading and trailing edges of the kicker pulse.

The presented stacking scheme is not 100% adiabatic that leads to the additional emittance growth in comparison to the ideal stacking process. The key element for the adiabaticity of the accumulation process is the "correct merging technique" of newly injected and stacked beam:

1. Momentum spread of the injected particles should be as close as possible to momentum spread of stack ones before the merging.
2. The barrier width and height between the injected and stacking beam should be adiabatically decreased precisely in proper way.

The using of the electron cooling with moving barriers can significantly decrease the particle losses as well as final momentum spread (Fig. 4, 5). As it was mentioned above the electron cooling time exceeds the time interval between injections for the energy of ions above 2.5 GeV/u if the scheme with 2 stationary barriers is implemented. The proposed stacking scheme with four moving barriers permits to apply the cooling method to all particles during whole accumulation procedure without particle losses in the injection region.

Ring circumference, m	503,04		
Number of bunches	23		
Rms bunch length, m	0.6		
β-function in the IP, m	0.35		
FF lenses acceptance	40· mm· mrad		
Long. acceptance, p/p	±0.010		
Gamma-transition, tr	7.091		
Ion energy, GeV/u	1.0	3.0	4.5
Ion number per bunch	$2.75{\cdot}10^8$	$2.4{\cdot}10^9$	$2.2{\cdot}10^9$
Rms momentum spread, 10^{-3}	0.62	1.25	1.65
Rms beam emittance, h/v, (unnorm), π·mm·mrad	1.1 / 1.01	1.1 / 0.89	1.1 / 0.76
Luminosity, 1027 $cm^{-2}{\cdot}s^{-1}$	1.1e25	1e27	1e27
IBS growth time, sec	186	702	2540

Table 3. Collider beam parameters and luminosity

Ion energy, GeV/u	1.5	2.5	4.5
Barrier height,(Δp/p)×10-3	0.87	1.08	2
Electron cooling rates, s^{-1}	1.0	0.25	0.03
Without cooling, %	68	70	74
With electron cooling, %	93	91	93

Table 4. Stacking efficiency (%) with moving barriers

The ring optics of the NICA collider was optimized for the stochastic cooling at high energies (from 3 to 4.5 GeV/u). The barrier height (in units of momentum spread) has the maximum value for the maximum ion energy 4.5 GeV/u and smaller values for low energies. On the other hand the electron cooling is faster for lower energies. Simulations of the stacking efficiency for the different energies for the same parameters of barrier bucket system without and with electron cooling are presented in Table 4.

The presented simulation with moving barrier buckets shows that the beam stacking in the longitudinal phase space has a good efficiency for the expected parameters of injected beam even without cooling. However implementation of cooling methods is mandatory for the colliding.

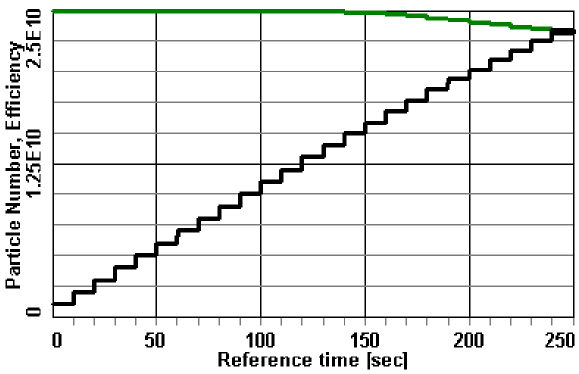

Figure 4. Accumulation with electron cooling and IBS: particle number (black) and accumulation efficiency (green). Ion energy E = 4.5 GeV/u.

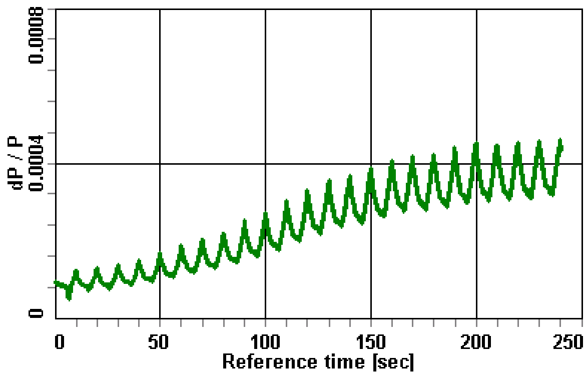

Figure 5. Accumulation with electron cooling and IBS: momentum spread. Ion energy E = 4.5 GeV/u.

5 Stochastic Cooling

The stochastic cooling (SC) is proposed for the collider to preserve the required luminosity at higher energies. For this goal the SC has to provide equilibrium with the expected IBS heating. In our case for cooling of the longitudinal degree of freedom more preferable is to use Palmer method because of wider dynamical range of momentum deviation in comparison with other methods. At the optimum gain and neglecting the amplifier noise the stochastic cooling rate can be estimated for all degrees of freedom by the following formula [Mohl *et al.*, 1980]:

$$\frac{1}{\tau} = \frac{W}{N_{eq}} \frac{(1 - 1/M_{pk}^2)^2}{M_{kp}} \qquad (2)$$

The "wanted" mixing from kicker to pick up is given by M_{kp} and in ideal case it has to be close to unity if ring slip-factor is fixed. Here $\eta_{pk}, \eta_{kp}, T_{pk}, T_{kp}$ – are the partial slip-factor and time-of-flight from pickup to kicker and from kicker to pickup correspondingly.

The chosen lattice of the collider permits to optimize the pickup and kicker positions to provide small partial slip factor from the pickup to kicker (to avoid unwanted mixing) in the total required energy range [Kostromin *et al.*, 2011]. For the Palmer method (longitudinal cooling) the pickup is located at the entrance into arc section near maximum of the dispersion function. The kicker is located in the long straight section at 132 m downstream from the pickup. The kicker position is chosen to have negative η_{pk} at maximum energy and positive at minimum energy. In this case we exclude practically the unwanted mixing in the all energy range and sufficiently increase the wanted one. At such position of the kicker one could have for the acceptable upper frequency of the band the value of about 20 GHz (at the momentum spread equal to the ring dynamic aperture $\Delta p/p = \pm 0.01$). It means that the system bandwidth is limited mainly by technical reasons. The luminosity of 10^{27} cm^{-2}s^{-1} corresponds to about $2.3 \cdot 10^9$ ions per bunch, the effective ion number is about $8 \cdot 10^{11}$. Simulations using D.Mohl's formulae [Mohl *et al.*, 1980] showed that to provide the cooling time two-three times shorter than the IBS ones (to have a technical reserve) the cooling bandwidth can be chosen from 3 to 6 GHz.

The same pick-up can be used for cooling of both longitudinal and vertical degrees of freedom. The kicker for vertical degree of freedom is located in the long straight section in the position providing required phase advance. Pickup for horizontal degree of freedom is located in the straight section upstream the arc in the zero dispersion point, the horizontal kicker – in the straight section downstream the arc in the position providing required phase advance.

6 Electron Cooling

The electron cooling is aimed to suppress completely IBS heating at low energy and provide the collider operation in the *Space charge dominated regime*. In this case at small momentum spread the transverse emittance can be sufficiently larger, than determined by equi-partitioning condition. Therefore the luminosity at small energy can be sufficiently increased in comparison with *IBS dominated regime*.

For the cooling section at reasonable technical parameters (Table 5) the cooling times were estimated for the total ion energy range [Kostromin *et al.*, 2011]. At small energies (below 3 GeV/u) the cooling times are about 20 times shorter than IBS heating times and the electron cooling is strong enough to provide space charge dominated regime of the collider operation.

Maximum electron energy, MeV	0.5-2.5
Cooling section length, m	6.0
Electron beam current, A	0.1-1.0
Electron beam radius, cm	0.5
Magnetic field in cooling section, T	0.1-0.2
Magnetic field imperfection	2×10^{-5}
Beta functions in cooling section, m	20
Collector PS, kW	2x2
HV PS stability, dU/U	1e-4

Table 5. Main parameters of the collider electron cooler

General problem which has to be solved for effective application of the electron cooling is the ion recombination with the cooling electrons. At typical temperature of electron transverse degree of freedom below 1eV the beam life-time due to recombination is about a few hundreds of seconds. There are two ways to increase the life-time: either to increase artificially the electron transverse temperature or to introduce energy shift between electrons and ions.

The main peculiarity of the electron cooler for the NICA collider is use of two cooling electron beams (one electron beam per each ring of the collider) that never has been done. Two versions of design of the cooling system are under consideration presently Fig. 6, 7 [Yakovenko *et al.*, 2013]. Design of the collider electron cooling system is performed in cooperation with All-Russian Electrotechnical Institute (AEI, Moscow) and Budker INP on the basis of cascade-type high voltage generator [Yakovenko *et al.*, 2013]. In JINR-AEI scheme the acceleration and deceleration of the electron beams is produced by common high voltage (HV) generator. The cooler consists of three tanks. Two of them contain acceleration/deceleration tubes and are immersed in common superconducting solenoids. The third one contains HV generator. The second scheme (BINP) has two coolers (one per each ring of the collider). The coolers have own high voltage systems. The electron cooler consists of two tanks. One tank contains acceleration/deceleration tubes which immersed in own magnetic field created by separated coils accommodated inside the tank [Yakovenko *et al.*, 2013].

In both cooler versions magnetized electron beams are planned to be used. The longitudinal magnetic field is formed with superconducting solenoids – straight and toroidal ones. In the "a" version (JINR-AEI) the superconducting solenoids form the magnetic field along all electron trajectories – from the gun up to collector. These solenoids in acceleration/deceleration area are placed inside the tanks. In the "b" version (BINP) the solenoids in high-voltage part are located inside the tanks and are "warm" (normal conducting). Other part of the system is superconducting. Both solenoid systems have straight and toroidal sections of different diameter. Magnetic field formation at solenoids' connection is done with magnetic shields.

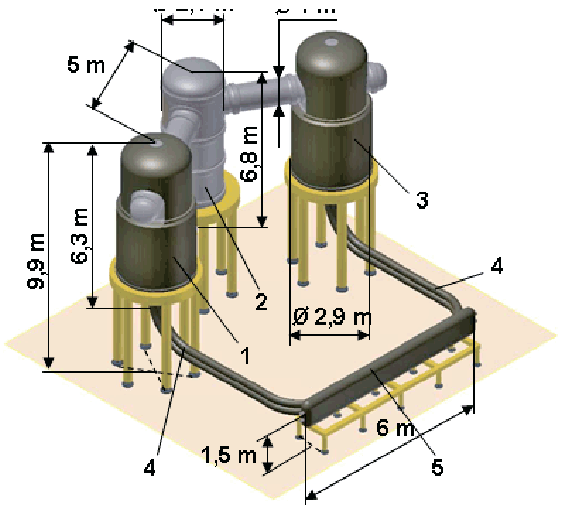

Figure 6. JINR-AEI version of HV electron cooler for NICA Collider. 1, 3 – the tanks with electron gun and acceleration tube and deceleration tube + collector for electron beams of opposite direction , 2 – tank with HV generator, 4 – beam transportation solenoids, 5 – electron cooling section;

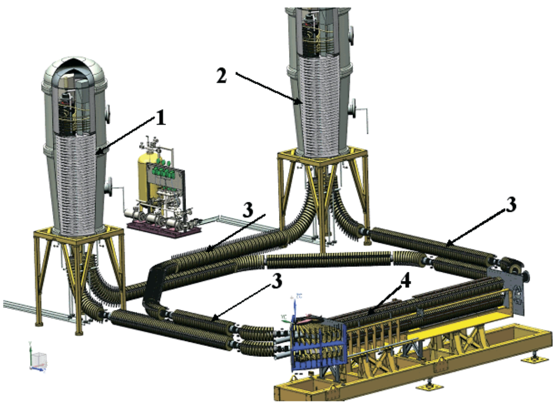

Figure 7. BINP version of HV electron cooler for NICA Collider. 1, 2 – tanks with electron gun and acceleration tube and deceleration tube + collector, 3 – beam transportation solenoids, 4 – electron cooling section

7 R&D for Collider Stochastic Cooling System. Recent Results at Nuclotron Complex

The Nuclotron having the same magnetic rigidity as the future NICA collider and based on the same type of the magnetic system is the best facility for testing of the collider equipment and operational regimes [Trubnikov *et al.*, 2014]. Application of the beam cooling in the collider rings has the goal of beam accumulation using cooling-stacking procedure and luminosity preservation during experiments.

It was proposed to install the prototype of the stochastic cooling system for collider at operating Nuclotron synchrotron. The pick-up and kicker stations of the stochastic cooling system prototype elaborated in cooperation with FZJ are similar to that one designed for the HESR of the FAIR project [Stassen, *et al.*, 2007]. Simulations of the stochastic cooling process at Nuclotron have been performed for different types of particles: protons and carbon ions C(6+): for proton beam the required power for beam cooling expected to be of order of 30-40W with gain at 140dB. For the carbon beam C^{6+} the power requirements correspondingly decreases to 10W and 130dB gain. During 2011-2013 the elements of the stochastic cooling system for Nuclotron were designed, constructed and installed in the ring. Main parameters of the system are the following: bandwidth 2-4 GHz, optimal beam kinetic energy 3.5 GeV/u, system (and notch filter) delay accuracy 1 ps, $N_{ion} \sim 1e9$. This work performed in close collaboration with the Forschungszentrum Jlich (FZJ) is also important for testing elements of the stochastic cooling system designed for the High-Energy Storage Ring (HESR, FAIR) [Stassen, *et al.*, 2007].

Simulation of the collider magnetic system operational conditions had been performed at Nuclotron in 2012-2013 with long plateau (up to 1000 seconds) of the magnetic field at 1.5 T was demonstrated. In March 2013 the effect of the longitudinal stochastic cooling using filter method had been demonstrated at the Nuclotron for the first time. Cooling time experimentally obtained for deuteron beam is in good agreement with simulation results. The next experiment for the stochastic cooling effect had been successfully demonstrated in December 2013 both for coasting and bunched carbon beams (Fig. 8, 9) [Trubnikov *et al.*, 2014], [Shurkhno *et al.*, 2013]. Transverse Schottky signals of the beam were also measured. Due to small charge of ions (D+) and short pick-up structure the betatron side-bands are almost at noise level, but signals were discernible.

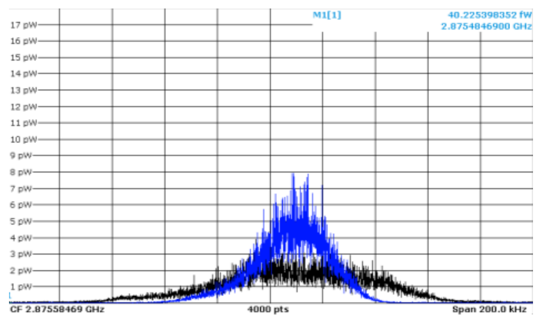

Figure 8. Experimental results of beam stochastic cooling of coasting $^{12}C^6+$. Schottky beam spectra: black – initial beam, blue – cooled beam. Coasting beam, $I \sim 2e9$ ions, $E \sim 2.5Gev/u$, $\Delta p/p_{initial} \sim 0.15e-3$, $\Delta p/p_{final} \sim 0.07e-3$, $\tau_{cool} \sim 27$ sec

W, GHz	Init.rms dp/p, 10ˆ-3	Energy GeV/u	Number of ions	Palmer or filter	h full turn	h, PU-kicker	h	Cooling time lower than:
2-4	0.62	1	6×10ˆ9	Both	0.215	0.199	22	200s
2-4	1.	2	1×10ˆ10	Both	0.082	0.067	22	350s
2-4	1.25	3	5.3×10ˆ10	Both	0.037	0.021	22	700s
2-4	1.65	4	4.8×10ˆ10	Both	0.016	0.00061	22	1500s
2-4	1.65	4.5	4.8×10ˆ10	Both	0.0099	-0.0057	22	2000s

Table 6. Parameters and requirements for the collider stochastic cooling system

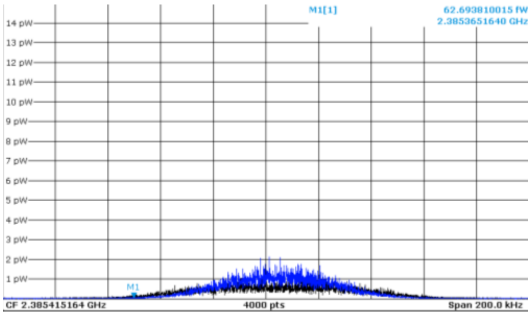

Figure 9. Experimental results of beam stochastic cooling of bunched $^{12}C^{6}+$. Schottky beam spectra: black – initial beam, blue – cooled beam. Right: bunched beam, I∼2e9 ions, E∼2.5 Gev/u, dp/p_{initial} ∼ 0.2e-3, dp/p_{final} ∼0.13e-3, τ_{cool} ∼ 64 sec

New scheme of beam cooling system, which includes FZJ ring-slot couplers as pick-up and kicker, unique optical notch-filter and a full remote-controlled automation of measurements and adjustments, has been successfully commissioned in 2013. New optical comb filter was developed and commissioned. The device has a compact size, low insertion loss and dispersion. Comb filter adjustment was automated with developed special software, which sufficiently reduces adjustment time and increases accuracy up to a few Hz. This filter has new optimized parameters in comparison to standard coaxial and optical filters: in average the attenuation of minimal signal amplitudes increased by 5 dB, dispersion is decreased from 25 Hz to 5-7 Hz. The progress in development of such automated comb filter has great importance for stochastic cooling in NICA collider, where it is planned to use for damping of synchrotron signals excited in bunched beam.

We also started experimental study of the potential band-overlapping process in the energy range E = 2.5–4 GeV/u at Nuclotron, that is extremely important for collider. Here it is possible carefully study of stochastic cooling time dependence for the bunched beam when increasing RF amplitude one measures beam momentum spread (Δp/p) which gives direct estimation of the efficient mixing factor.

The concept of start-up configuration of the stochastic cooling system for the collider has become a result of simulations using dedicated program code [Shurkhno *et al.*, 2013] (benchmarked with experimental results from Nuclotron). It is considered as follows at this moment: 32 rings each is 8-electrodes slot-coupler RF structure (FZJ design), bandwidth of 2–4 GHz. For the ion energy E = 3.5 GeV/u, Iions = 2.7e10, Δp/p = 6e-4, proposed to use filter method for longitudinal cooling and standard betatron method for transverse cooling, the expected optimal gain of the system is to be at 75 dB, output power at kicker is at 765 W, "longitudinal" cooling time is around 730 seconds.

Estimations for the stochastic cooling system operated in the energy range 3–4.5 GeV/u show expected output power of the system equal to 1200 W for longitudinal and 500 W for transverse degrees of freedom correspondingly. The table with initial parameters for stochastic cooling simulations shown below (Table 5). Palmer method for longitudinal cooling looks as preferable. The collider optics is self-consistent from point of view of beam stability and tunability, unfortunately it is not perfect for the Palmer method because dispersion in the pick-up position is comparatively small (about 2.5 meters). On the other hand filter method could be successfully applied in our case only in the narrow energy range (high momenta) due to expected band overlapping. That is why we investigate now possibilities to optimize geometry of pick-up, requirements for beam misalignment, etc in order to find solution for effective stochastic cooling in all energy range from 3 to 4.5 GeV/u.

Simulations made by L.Thorndall [Thorndall, 2014], showed that beam misalignment on the PU center and high betatron amplitudes could lead to the degradation of longitudinal cooling performance. The common mode problem for a pickup dispersion of 2.7 m remains a major worry for the Palmer cooling. This should be foreseen in pickup geometry precision, beam position and microwave echo reasons. The following requirements are formulated: the r.m.s. initial betatron amplitudes should not be larger than 1mm, the same has to be to applied to the beam misalignment (with respect to the pickup center). In other case each additional mm in misalignments will lead to reduction by ∼20% in cooling efficiency.

It is shown also that for higher intensities and same gains the betatron cooling overtakes the momentum cooling. The betatron cooling has more effective bandwidth: 2 side bands per revolution frequency interval instead of only one.

As a further possible development we consider design upgrade of the slot coupler aimed reducing the aperture from 90 to 70 mm that could give advantage in achieving more powerful useful beam signal when intensity is not high (few per cent of designed value) and beam r.m.s. size is around 1–2 mm. Simulations for comparison of the optimal bandwidth in the total energy range (2–4 GHz or 3–6 GHz) are now in progress.

Another important result of our experimental measurement at Nuclotron is that we expect to be safe with using slot-coupler structures and filter method for the bunched beam with low bunching factor. At Nuclotron it is equal to 5, in collider will be 22. Basing on our experience we can preliminary expect that with decreasing of particle intensity (and "power" of Schottky signal as a consequence) at the same system gain, the cooling time will also decrease. It means those structures will efficiently cool the bunched beam in NICA collider at it's start-up configuration: bunch intensity 3–5e8, Δp/p$\sim$4e-4, energy 3–4.5 GeV/u, bunch length, s =1.2 m, 22-nd harmonics. We need further experimental investigations.

8 NICA Start-Up Configuration

Start-up configuration of the NICA collider has been proposed. Energy range for first experiments chosen from 3.5 to 4.5 GeV/u, factor 1/4 of the design intensity (5e8 instead of 2e9 ions per bunch). Advantage is that at low beam intensity one can neglect with parasitic collisions in the straight sections. Expected luminosity in the start-up configuration is $1\div 7\text{e}25\text{cm}^{-2}\text{s}^{-1}$.

As soon as collider will start to operate at fixed energy (comparatively high) – we do not need electron cooling system at the first stage of operation. One can restrict ourselves with reduced (initial) version of stochastic cooling system: filter method for longitudinal degree of freedom and betatron cooling method for the transverse one. Both methods are tested at Nuclotron. We plan also to start with "reduced version" of collider RF system consisting of Barrier Bucket (BB) RF system and RF-2 – for beam bunching at harmonics h = 22. Operation scenario will be the following: stacking with BB RF system + longitudinal stochastic cooling, then bunching forming 22 bunches with length about 1.2 m instead of 0.6m, momentum spread of 4.2e-4 instead of 1e-3. It allows us to reach the "start-up luminosity".

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