APPLICATION OF COOLING METHODS TO NICA PROJECT

S.Kostromin, I.Meshkov, A.Sidorin, A.Smirnov, G.Trubnikov*, JINR, Russia

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 experiments with colliding heavy ions up to Au for experimental study of hot and dense strongly interacting baryonic matter and search for possible signs of the mixed phase and critical endpoint in the centre-of-mass energy range $\sqrt{S_{NN}}$ = 4-11 GeV. Beam cooling systems are proposed for elements of the NICA project. The Booster synchrotron will be equipped with an electron cooling system. Two beam cooling systems – stochastic and electron will be used in the collider rings. Parameters of cooling systems, proposed scenario of operation and peculiarities of their design intended to achieve required average luminosity of the order of $10^{27}cm^{-2}s^{-1}$at high energies are presented in this report.

INTRODUCTION

The goal of the NICA project [1] is construction at JINR of the new accelerator facility that consists of:

- cryogenic ESIS ion source "KRION" with 6T solenoid;
- source of polarized protons and deuterons;
- the existing linac LU-20 (energy up to 5 MeV/u);
- a new heavy ion linear accelerator (3 MeV/u);
- a new 600 MeV/u Booster-synchrotron;
- modernized heavy ion synchrotron Nuclotron (4,5 GeV/u maximal kinetic energy for ions with Z/A = 1/3);
- two new superconducting rings of the collider;

The facility will have to provide ion-ion (1÷ 4.5 GeV/u), ion-proton collisions and collisions of polarized pp (5 ÷ 12.6 GeV) and dd (2 ÷ 5.8 GeV/u) beams. The Booster will be equipped with a slow extraction system to provide medicine, biological and other applied researches.

The collider will have two interaction points. The Multi Purpose Detector (MPD) in the first IP, and the second IP is used for the Spin Physics Detector (SPD).

Collider will be operated at fixed energy without acceleration of 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 is to provide collider experiment with heavy ions like Au, Pb, or U at average luminosity above $1\cdot10^{27}$ $cm^{-2}\cdot s^{-1}$ in the maximal wide energy range up to 4,5 GeV/u. Therefore in this report it is discussed heavy ion mode of the facility operation only, and $^{197}Au^{79+}$ 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.

*E-mail: trubnikov@jinr.ru

ELECTRON COOLING SYSTEM FOR BOOSTER. OPERATION MODES.

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 be used (Table 1). 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 not less than 80%.

The Booster is equipped with room-temperature electron cooling system that allows to provide efficient cooling of the ions in the energy range from injection energy up to 100 MeV/u (Fig.1). Electron cooling at injection energy 3 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 (for example Au^{65+} ions) or polarized ions (for example $\uparrow H^-$ atoms) with high intensity. Beam cooling at higher energies (up to 100 MeV/u) could be useful to achieve special beam parameters required by fixed target experiments on the extracted beam from Booster.

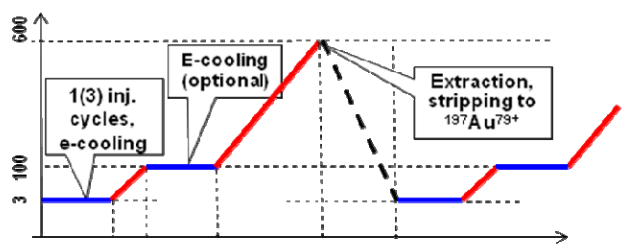

Figure 1: Booster cycle diagram (Y-axis: energy, MeV/u)

The magnetic system of the Booster is superconducting. Its design is based on the experience of construction of the Nuclotron SC magnetic system [3]. Parameters of the Booster cooler are typical for conventional electron cooling systems. Design of the cooler had been performed by JINR and its construction is planned to be done in collaboration with Budker INP.

Main goal of the cooling of heavy ion beam at 100 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.

At the electron cooling of heavy ions one of the serious problems is the recombination. The rate of Au^{31+} ions losses in the Booster cooler was extrapolated from the experimental data obtained at GSI and CERN. The estimation has shown that during 1s of cooling the ion losses will be less than 10%. The use of high field 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.

LUMINOSITY OF THE COLLIDER

Two collider rings have a maximum magnetic rigidity of 45 Tm that is equal to Nuclotron one. The rings are vertically separeted by the scheme "twin bore magnets".

The maximum field in the bending magnets was chosen to be 1.8 T. The ring consists of two arcs and two long straight sections with total length of be about 503 m (Fig. 2). Here we discuss the arc optics based on FODO elementary cell at 12 cells per each arc (FODO-12). Comparable parameters of the ring can be achieved when arc is built from 8 triplet cells (Triplet8), however FODO structure is more convenient for beam injection.

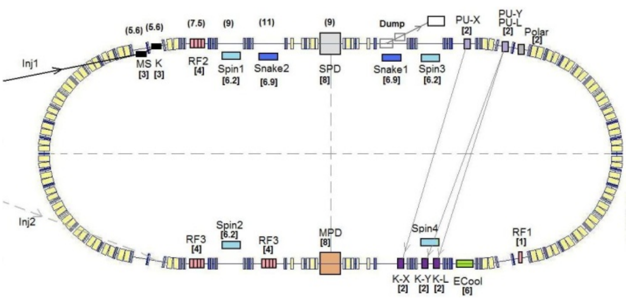

Figure 2: Collider ring composition (1st ring).

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. This includes also event-by-event observables.

At identical colliding bunches of a round shape cross-section the peak luminosity can be estimated by the following formula:

$$L = \frac{N_b^2}{4\pi\varepsilon\beta^*} F_{coll} f_{HG}\left(\frac{\sigma_s}{\beta^*}\right), \quad (1)$$

where $\boldsymbol{N_b}$ is the ion number in the bunch, ε is the transverse unnormalized r.m.s. emittance, β^* is the beta function value in the collision point, σ_s the ion bunch length (σ-value for Gaussian distribution of the ion density in the bunch). The collision repetition rate $\boldsymbol{F_{coll}}$ can be determined by the well known formula formula

The so called "hour-glass effect" is close to unit when the longitudinal r.m.s bunch size σ_s is much less than the β^*:

$$f_{HG}\left(\frac{\sigma_s}{\beta^*}\right) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \frac{\exp(-u^2)du}{\left[1+\left(\frac{u\sigma_s}{\beta^*}\right)^2\right]} \quad (2)$$

The inter-bunch distance (and 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 acceptable bunch number is 23.

The bunch length has to be as small as possible to avoid the "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 leads to increase of tune shift and can provoke a coherent instability. The r.m.s. bunch length of about 60 cm was chosen as a compromise value.

Maximum achievable luminosity is reached at the bunch emittance and intensity corresponding to the space charge limit. In such a regime an increase of the bunch intensity allows increasing the luminosity at the same value of the tune shift. To keep the constant tune shift the beam emittance has to be increased proportionally to the bunch intensity and the luminosity is scaled linearly with the ion number. So, the maximum luminosity is reached when the bunch phase volume corresponds to the ring acceptance.

The proposed chromaticity correction scheme provides the transverse dynamic aperture of about 120 π·mm·mrad and dynamic aperture on the relative momentum deviation of about ±1%. From the side of bunch coherent stability the momentum spread has to be as much as possible and we assume that the value of $(1\div1.5)\cdot10^{-3}$ is acceptable. The transverse bunch emittance was chosen from the condition of equal heating rates of all three degrees of freedom due to Intra Beam Scattering (IBS). This condition corresponds to the operational regime when the bunch parameters are determined by equilibrium between IBS and beam cooling (so called IBS dominated regime). The IBS heating rates were calculated in accordance with [4] and the transverse r.m.s emittance value corresponding to chosen momentum spread is about 1 π·mm·mrad. To geometry acceptance at aperture equal to 6 r.m.s. beam radius corresponds to about 40 π·mm·mrad.

Such a small required acceptance permits the collider operation at small beta-function in the collision point. The maximum beta functions in the final focus triplets of about 200 m corresponds to the beta function of 0.35 m in the collision point. At such conditions the beam radius in the lenses of the low beta insertion section is about 40 mm that requires reasonable aperture.

When the bunch phase volume is determined, the particles number per bunch is restricted by the total acceptable betatron tune shift $\Delta Q_{Las}+2\xi$ (Lasslet tune shift plus 2 beam-beam parameters corresponding to 2 collision points). For chosen working point of the collider the limiting value is about 0.05.

This strategy of the parameter optimization allows to have the luminosity above $1\cdot10^{27}$ $cm^{-2}\cdot s^{-1}$ 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. The dominated effect is the Lasslet tune shift which can be estimated as

$$\Delta Q = -\frac{Z^2 r_p}{A}\frac{N_b}{4\pi\beta^2\gamma^3\varepsilon}F_{sc}F_b,\ F_b = \frac{C_{Ring}}{\sqrt{2\pi}\sigma_s} \tag{3}$$

where Z, A and r_p are the charge, mass numbers and classical radius of the ion correspondingly, F_{sc} – image force correction factor (usually $F_{sc} \sim 1$), F_b is the bunching factor. Expressing the luminosity via the tune shift we have the following estimation:

$$L = 8\pi^2\beta^5\gamma^6\Delta Q^2\frac{A^2}{Z^4}\cdot\frac{\varepsilon c}{r_p^2\beta^* l_{bb}}\cdot\left(\frac{\sigma_s}{C_{Ring}}\right)^2\cdot f_{HG} \tag{4}$$

That shows that in the IBS dominated regime the luminosity scales with the beam energy approximately as $\beta^5\gamma^6$ (Table 1).

Table 1. Collider beam parameters and luminosity

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	40π mm mrad		
Long. acceptance, Δp/p	±0.010		
Gamma-transition, γ_{tr}	7.091		
Ion energy, GeV/u	1.0	3.0	4.5
Ion number per bunch	$2.75\cdot10^8$	$2.4\cdot10^9$	$2.2\cdot10^9$
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, 10^{27} cm^{-2}s^{-1}	1.1e25	1e27	1e27
IBS growth time,sec	186	702	2540

The beam accumulation in the collider is planned to be realized in longitudinal phase space 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 Keil-Schnell criteria for longitudinal microwave instability is satisfied for the bunch intensity in whole energy range.

REQUIRED COOLING TIMES. THE COOLING STRATEGY

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 stochastic cooling system of reasonable technical parameters, because in this case the beam has rather low linear particle density. The second goal is more important. Dedicated scenario of using stochastic and electron beam cooling systems to cover whole energy range with maximal achievable luminosity at low energies and to have luminosity of the order of $1\cdot10^{27}$ 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 (Fig. 3) for all degrees of freedom.

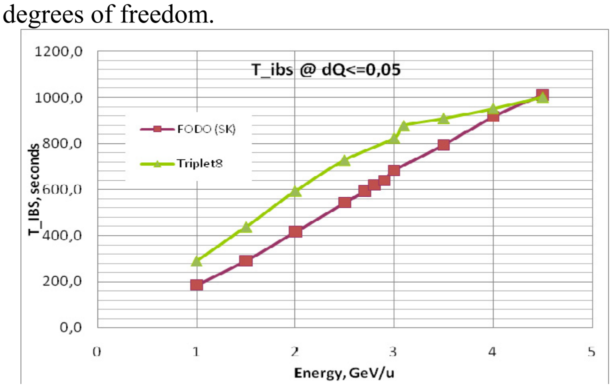

Fig. 3: Expected IBS heating times at maximum luminosity for different arc optics.

The way to increase the luminosity at low energy is to provide powerful cooling at cooling times sufficiently shorter than the IBS ones. 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. In this case the bunch parameters and beta-function in the collision point can be re-optimized depending on the experiment energy.

For instance, at the energy of 1 GeV/u the beam emittance can be increased up to dynamic aperture limitation (about 3 π·mm·mrad) with the corresponding increase of the particle number. If the bunch length and tune shift are kept constant, the luminosity scales linearly with the emittance. However, to avoid the aperture limitation we need to increase the beta-function in the collision point. The geometry acceptance is equal to

$$A \approx \frac{a^2}{\beta_{\max}}, \tag{5}$$

where a – the lens aperture β_{max} is the beta function in the final focus triplet, that depends on the β^* approximately as

$$\beta_{\max} \approx \beta^* + \frac{l_{tr}^2}{\beta^*}, \tag{6}$$

l_{tr} is the distance from the triplet to the collision point. To have the geometry acceptance equal to the dynamic one the β^* has to be increased up to about 1 m. The luminosity in this case is proportional to

$$L \sim \frac{\varepsilon}{\beta^*} \cdot f_{HG}\left(\frac{\sigma_s}{\beta^*}\right) \sim \frac{a^2}{\left(\beta^* + \frac{l_{tr}^2}{\beta^*}\right)\beta^*} f_{HG} \ . \qquad (7)$$

This dependence plotted in the Fig. 4 shows that increase of the beam emittance and β^* can give about 60% increase of the luminosity. Further increase of the luminosity is related to design of final focus lenses with large aperture.

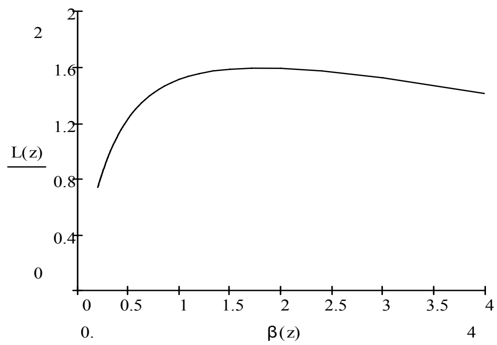

Fig. 4. Luminosity (normalized by its value at β^* = 35 cm) versus β^* in meters.

Thus, at the energy range from 3 to 4.5 GeV/u a cooling system has to provide the cooling times of about 500 s (that will be achieved by stochastic cooling system at bandwidth of 3 GHz) and at 1 GeV/u of the order of ten seconds (that will be provided by electron cooling system).

STOCHASTIC COOLING

The stochastic cooling (SC) is assumed to be used in the collider to preserve the required luminosity at higher energies. For this goal the SC has to provide equilibrium with the expected IBS heating.

For cooling of the longitudinal degree of freedom more preferable is to use Palmer method because of wider dynamical range on 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 [5]:

$$\frac{1}{\tau} = \frac{W}{N_{eq}} \frac{(1 - 1/M_{pk}^2)^2}{M_{kp}} \ . \qquad (8)$$

$W = f_{max} - f_{min}$ is the system bandwidth. For the bunched beam the equivalent particle number N_{eq} is calculated in accordance with the bunching factor (formula 5) as:

$$N_{eq} = N \frac{C}{\sqrt{2\pi}\sigma_s} \ . \qquad (9)$$

The "unwanted" mixing factor from pickup to kicker:

$$M_{pk} = \frac{1}{2(f_{max} + f_{min})\eta_{pk} T_{pk} \frac{\Delta p}{p}} , \qquad (10)$$

imposes a limit on the upper frequency f_{max} of the system band, that can be estimated as

$$f_{max} \le \frac{1}{2\eta_{pk} T_{pk} \frac{\Delta p}{p}} \qquad (11)$$

The "wanted" mixing from kicker to pick up is given by

$$M_{kp} = \frac{1}{2(f_{max} - f_{min})\eta_{kp} T_{kp} \frac{\Delta p}{p}} , \qquad (12)$$

and in ideal case it has to be close to unity. Here η_{pk}, η_{kp}, T_{pk}, T_{kp} –are the partial slip-factor and time of flight from pickup to kicker and from kicker to pickup correspondingly. Usually for the cooling rate estimation the momentum spread is substituted as $\Delta p / p \sim 2\sigma_p$, where σ_p is its r.m.s. value.

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. 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 (Fig. 5).

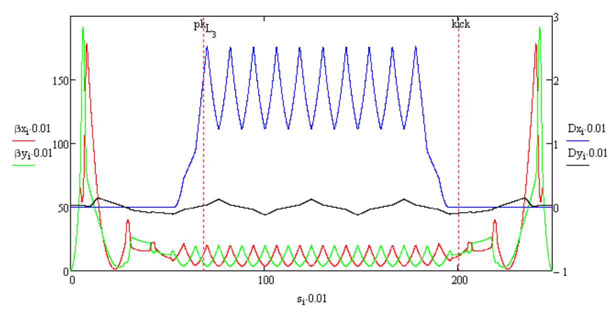

Fig. 5. Lattice functions at the half of the collider circumference with positions of pick up and kicker for longitudinal cooling.

The kicker position is chosen to have negative η_{pk} at maximum energy and positive at minimum energy (Fig. 6). 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 the condition (11) gives for the acceptable upper frequency of the band the value of about 20 GHz (at the momentum spread equal to the ring dynamic aperture ±0.01).

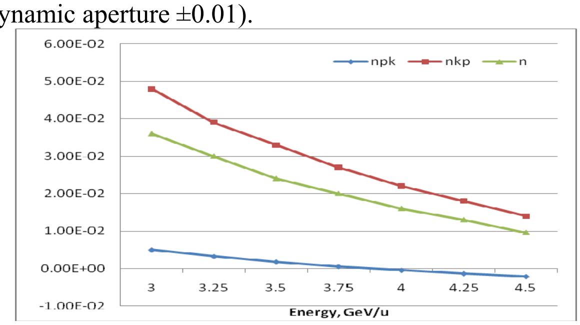

Fig. 6. Total and partial slip-factors of the ring as the function of ion energy.

It means that the system bandwidth is limited mainly by technical reasons. The luminosity of $1\cdot10^{27}$ $cm^{-2}s^{-1}$ corresponds to about $2.3\cdot10^{9}$ ions per bunch, the effective ion number is about $8\cdot10^{11}$.

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 (Fig. 7).

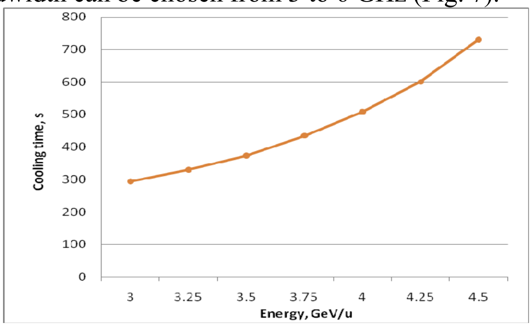

Fig. 7. Stochastic cooling time as the function of the ion energy at system bandwidth from 3 to 6 GHz.

The same pickup can be used for cooling of 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 kicker in the straight section downstream the arc in the position providing required phase advance.

ELECTRON COOLING

The electron cooling is aimed to completely suppress 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 emettance 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 2) the cooling times were estimated in accordance to Parkhomchuk formula [6] for the total ion energy range (Fig. 8). In the energy range from 3 to 4.5 GeV/u the cooling times are slightly shorter than expected IBS heating times and are comparable to stochastic cooling times. However at small energies 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.

Table 2. Main parameters of the collider electron cooler

Maximum electron energy, MeV	1.5
Cooling section length, m	6.0
Electron beam current, A	0.5
Electron beam radius, cm	0.8
Magnetic field in cooling section, T	1.0
Magnetic field imperfection	2×10^{-5}
Beta functions in cooling section, m	20
Longitudinal electron temperature meV	5.0

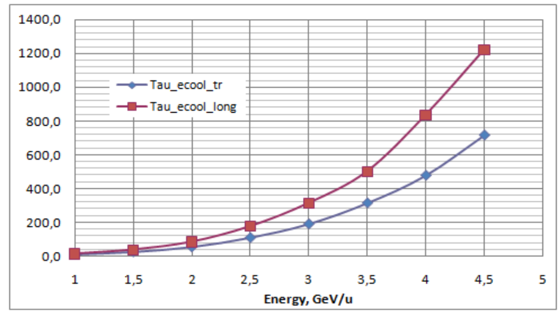

Fig. 8. Dependence of the electron cooling (transverse and longitudinal) times on the ion beam energy.

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 magnetic field in the cooler of 1T is required mainly to provide adiabatic transport of the electron beam from HV source to the cooling section. Additionally such a large value resulted in strong magnetization of electrons and permits to provide effective cooling at large transverse electron temperature. The cooling rate is determined mainly by longitudinal electron temperature (that is dominated by HV generator stability) and logarithmically depends on the transverse one. In the Fig.9 transverse electron temperature required for obtaining of the beam life-time of 10 hours is plotted versus ion energy.

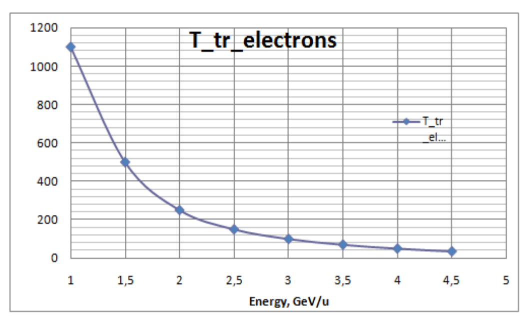

Fig. 9. Electron transverse temperature in eV required to have the ion life-time of 10 hours.

More effective way of the recombination suppression – shift of the electron energy – is discussed in [7].

R&D FOR COLLIDER COOLING SYSTEMS

Design of the collider electron cooling system is performed in co-operation with All-Russian Electrotechnical Institute (VEI, Moscow) on the basis of dynamitron-type high voltage generator.

For the stochastic cooling development we plan to perform the cooling experiment with ion beam circulating in the Nuclotron. 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 or carbon beam, which has intensity by two orders of magnitude larger than expected one for the heavy ions. The first step in realization of stochastic cooling experiment is longitudinal cooling of the coasting beam. Scheme with a notch filter and octave bandwidth 2-4 GHz was chosen for the system. 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 [8].

Simulations of the stochastic cooling process have been performed for different types of particles: protons and carbon ions C(6+). The results are presented in [9]. The results of the simulation give the following requirements for the system: in case of proton coasting beam, the power required for performing this experiment lays in 30-40W margins and gain is approximately 140dB. If the C(+6) beam will be used, the power requirements significantly decreases to 10W and 130dB gain correspondingly.

It is also proposed to study experimentally at Nuclotron the band overlapping process (if such occurs) in the energy range E = 2.5 - 4 GeV/u which 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 has to measure beam momentum spread (dP/P) which gives direct estimation of the efficient mixing factor.

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.

Booster synchrotron will be equipped with standard electron cooling system operating at electron beam energy from 1.5 to 50 keV

Stochastic and electron cooling technique at the collider are proposed to be used 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 energy.

Proposed cooling scenario for NICA collider is the following (Fig.10): in the ion energy range from 1 to 3 GeV/u the electron cooling can provide rather short cooling times to realize 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 and realizable. 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 $1 \cdot 10^{27}$ cm^{-2}s^{-1} and the collider can operate in IBS dominated regime. If one optimizes the ring lattice and Pick-up (PU) and Kicker (KK) positioning to have partial slippage factor (from PU to KK) close to zero the upper frequency of the system band is limited only by a technical reasons. The system at reasonable bandwidth of 3-6 GHz provides sufficient technical reserve (the cooling times by about three times less than IBS growth times). Final choice of the system bandwidth will be done after experimental test at the Nuclotron.

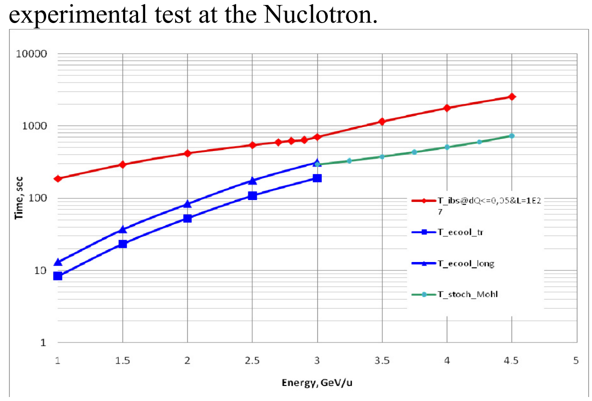

Fig. 10. IBS growth times in the IBS dominated regime, electron cooling times (below 3 GeV/u) and stochastic cooling time (above 3 GeV/u).

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 is performed in collaboration with FZJ, FNAL, CERN and BNL. The prototype of the stochastic cooling will be tested at the Nuclotron in the end of 2011.

REFERENCES

[1] G. Trubnikov, et.al., Proceedings of EPAC08, Genoa, Italy, p.2581

[2] Khodzhibagiyan, H.G., and Smirnov, A.A., Proc. of the 12th Int. Cryogen. Eng. Conf., 1988, pp. 841–844.

[3] NICA Conceptual Design Report, http://nucloserv.jinr.ru/nica_webpage/Nica_files/reports/CDR_07/, editors I.Meshkov and A.Sidorin, JINR, Dubna, 2008

[4] S. Nagaitsev, Intrabeam scattering formulas for fast numerical evaluation, Physical Review Special Topics – Accelerators and Beams, 8, 064403 (2005)..

[5]. D.Moehl, Stochastic cooling.

[6] V.V.Parkhomchuk, New insights in the electron cooling, NIM A 441 (2000) 9-17, p.9

[7] A.Philippov, these proceedings

[8] R. Stassen, et al, Recent developments of the HESR stochastic cooling system, Proceedings of COOL07, Bad Kreuznach, Germany, 2007.

[9] N.Shurkhno, G.Trubnikov et all, Stochastic cooling system prototype for Nuclotron, Proceedings of RuPAC10, Protvino, p.74