PRESENT STATUS OF NICA PROJECT

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Abstract

Nuclotron-based Ion Collider fAcility (NICA) is the new accelerator complex being constructed in Joint Institute for Nuclear Research. General goal of the project is to start experimental study 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. In this report the present status of the NICA accelerator complex are presented.

PROGRESS IN NICA CONSTRUCTION

The **N**uclotron-based **I**on **C**ollider f**A**cility (NICA) [1] is a new accelerator complex being constructed at JINR (Fig. 1). It is aimed to provide collider experiments with

- heavy ions $^{197}Au^{79+}$ at $\sqrt{s_{NN}}$ = 4÷11 GeV (1÷4.5 GeV/u ion kinetic energy) at average luminosity of $1\cdot10^{27}$ cm$^{-2}\cdot$s^{-1} (at $\sqrt{s_{NN}}$ = 9 GeV);
- light-heavy ions colliding beams of the same energy range and luminosity;
- polarized beams of protons $\sqrt{s}$ = 12÷27 GeV (5÷12.6 GeV kinetic energy) and deuterons $\sqrt{s_{NN}}$ = 4÷13.8 GeV (2÷5.9 GeV/u ion kinetic energy) at average luminosity ≥ $1\cdot10^{31}$ cm$^{-2}\cdot$s^{-1}.

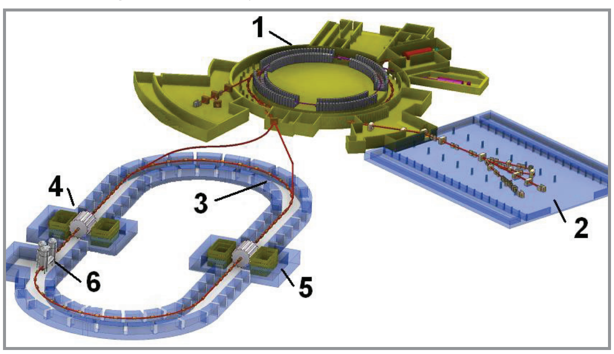

Figure 1: The NICA facility: 1 - Existing building with KRION-6T, SPP, LU-20, HILac, booster synchrotron and Nuclotron, 2 - fixed target experimental hall; 3 – Collider rings; 4 and 5 - the Multy Purpose Detector (MPD) and Spin Physics Detector (SPD); 6 – high voltage electron cooling system.

As the first step in the realization of the NICA heavy-ion program, Baryonic Matter at Nuclotron (BM@N) - a new fixed-target experiment developed in cooperation with GSI, Darmstadt - has been approved by JINR's Program Advisory Comittee and Scientific Council and is now under construction [2].

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Presently in parallel with the existing accelerator complex development the technical design of the NICA collider had been prepared for the State expertise in Governmental authorities that is planned at 2013.

The development of NICA injection complex is actively performed [3]. New ESIS-type heavy ions source KRION-6T with 6 Tesla solenoid is assembled and at the stage of commissioning with electron beam now. New source of polarized particles SPP had been assembled and tested in 2013, we plan to perform several experimental runs for polarimetry measurements on it during 2013-2014 at the test bench. Construction of new 3.2 MeV/u heavy-ion linear accelerator (HILac) is now under way in cooperation with the BEVATECH Company, its commissioning in Dubna is scheduled for the beginning of 2014.

RF stations for the Booster manufactured at BINP are scheduled for commissioning at Dubna in the end of 2013. Electron cooling system to the Booster had passed TDR phase and it's construction will start in 2013 at BINP.

The full-scale Nuclotron–type superconducting model dipole and quadrupole magnets for the NICA booster and collider were manufactured during 2010 – 2012 [4]. First magnets for the Booster have successfully passed the cryogenic test on the bench. Serial production of the booster magnets is expected start in early 2014. To construct the Booster and collider rings, it is necessary to fabricate more than two and half hundreds of the dipole magnets and lenses during a short period of time. Special Test Facility for the magnet assembly and full-scaled tests required for the magnet commissioning is currently constructed. This Facility is planned to be used also for assembly and cold testing of quadrupole magnets for SIS100 (FAIR project).

The NICA cryogenics [5] will be based on the modernized liquid helium plant that was built in the early 90's for the Nuclotron. The main goals of the modernization is increasing of the total refrigerator capacity from 4000 W to 8000 W at 4.5 K and construction a new distribution system of liquid helium. These goals are achieving now by construction of a new 1000 l/hour helium liquefier, "satellite" refrigerators located near the accelerator rings, and a liquid nitrogen system that will be used for shield refrigerating at 77 K and at the first stage of cooling down of three accelerator rings with the total length of about 1.5 km and "cold" mass of 220 tons.

Application of the cooling methods is a key feature of the NICA project. The project realization requires elaboration of novel cooling systems that can be done

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using both numerical simulations and experimental work with prototypes. Main attention in this paper is devoted to the role of the beam cooling in the project, strategy of the cooling application at different stages of the beam formation and status of R&D works for the cooling systems.

ROLE OF BEAM COOLING

Goals of the NICA facility at the first stage of its operation are to provide fixed target and collider experiments with heavy ions like Au, Pb, or U at the energy range up to 4.5 GeV/u. In this report we discuss the heavy ion mode of the facility operation only, and the Gold ions are chosen as the reference particles. The ions $^{197}Au^{31+}$ generated in Electron String Ion Source (ESIS) will be accelerated in the accelerator chain consisting of

- heavy ion linear accelerator (HILac);
- 25 T·m Booster-synchrotron equipped with an electron cooling system;
- modernized 45 T·m heavy ion synchrotron Nuclotron.

The Booster magnetic rigidity is chosen to provide the ion energy sufficient for effective stripping to the bare nuclei.

The fixed target experiment BM@N requires the beam intensity of 10^9 ions per acceleration pulse at duty factor of about 50%. The beam will be delivered to the target using existing slow extraction system at spill duration of 5 s, correspondingly the acceleration cycle duration is designed to be below 5 s.

The beam intensity in the collider is limited by space charge effects and depending on the beam energy varies from $6\cdot10^9$ to $5\cdot10^{10}$ approximately. It will be provided by stacking in the collider corresponding number of consequent injection pulses.

To provide the required beam intensity and the beam phase volume necessary for effective stacking in the collider the Booster will be equipped with an electron cooling system operating at electron beam energy from 1.5 to 35 keV.

The beam cooling in the Collider is mandatory to provide sufficient luminosity life-time, effective beam stacking and formation of short bunches. At the ion energy from 1 to about 3 GeV/u these goals will be reached by electron cooling application, at higher energy – by stochastic one.

ELECTRON COOLING IN THE BOOSTER

The new ESIS and HILac are designed to provide 8 μs pulse of $2\cdot10^9$ $^{197}Au^{31+}$ ions [3] that is sufficient to have the required intensity of the accelerated beam at single turn injection into the Booster. For storage of other heavy ions (for instance Uranium) and as a reserve option for operation with Gold ions a repeated multiturn injection into the Booster is presumed. In this case the electron cooling will be applied at injection energy to provide the ion accumulation.

Initial stage of the beam acceleration is provided at 5-th harmonics of the revolution frequency. At the magnetic field plateau at intermediate energy the beam will be debunched and the electron cooling will be used to form required parameters of its phase volume. Further acceleration in the Booster is provided at first harmonics.

The strategy of the bunch formation is presented in the Table 1, where N is the particle number, ε - the rms an-normalized transverse emittance, σ_p and σ_s are rms momentum spread and bunch length correspondingly.

Table 1: Injection Chain and Beam Parameters

Acceleration stage	Energy, MeV/u	N, 10^9	ε,π mm mrad	σ_p	σ_{s}, m
Injection from HILac	3.2	2	Depending of injection scheme		
Acceleration in the Booster at 5-th harmonics					
After cooling in the Booster	65	1.5	0.73	$6.6\cdot10^{-5}$	C*
After acceleration in the Booster at 1-st harmonics	578	1.35	0.24	$3.1\cdot10^{-4}$	8.5
At injection into the Nuclotron	572	1.1	0.72	$4.1\cdot10^{-4}$	8.5
After acceleration in the Nuclotron	1000	1	0.55	$3.6\cdot10^{-4}$	8
	3000	1	0.24	$1.7\cdot10^{-4}$	8
	4500	1	0.18	$1.2\cdot10^{-4}$	8

* coasting beam

For effective stacking in the collider the beam emittance and momentum spread have to be small enough. The momentum spread at the cooling in the Booster is limited by micro-wave instability. The emittance value at injection into the Nuclotron (in the Table it is estimated taking into account the growth due to interaction with the stripping target and mismatch at injection) corresponds to Lasslet tune shift ΔQ = 0.05. The particle losses in the Booster are related with interaction with residual gas and recombination during the electron cooling. The bunch length after acceleration in the Nuclotron is optimized for stacking scheme in the collider. For the fixed target experiment the beam will be adiabatically debunched before the extraction.

Parameters of the Booster cooler are typical for conventional electron cooling systems. The system will be constructed in BINP (Novosibirsk). Conceptual design providing required cooling times was prepared in 2012 [6].

BEAM COOLING IN THE COLLIDER

Application of the beam cooling methods (electron and stochastic) in the collider rings has the purposes of beam accumulation using cooling-stacking procedure, formation of short bunches and luminosity preservation during experiments.

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Colliding Beam Mode One can distinguish two outmost regimes of collider [7]. First of them we call *space charge dominated* (SCD) mode when maximum achievable luminosity of the Collider can be reached. In this operation mode the bunch emittance and intensity correspond to the space charge limit, i.e. betatron tune shift ΔQ does not exceed certain value. 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 coincides with the ring acceptance. At the designed acceptance of the Collider ring the maximum acceptable beam rms emittance is estimated by about 1.1 π·mm·mrad.

The second regime when equilibrium state is provided with equality of Intra Beam Scattering (IBS) and cooling rates we call *IBS dominated* (IBS-D) mode. The minimum IBS growth rates correspond to the condition of equal rates in all three degrees of freedom. In IBS-D mode luminosity is limited by "artificial" reasons (low intensity of injection chain, detector performance, etc.).

Without cooling the luminosity life-time is limited by (IBS) process. To keep it sufficiently long the beam cooling during experiment is mandatory.

The bunch parameters calculated from the conditions formulated above are listed in the Table 2 [8]. The bunch number is limited by the requirement of avoiding parasitic collisions in the region of colliding beam overlapping/separation. The bunch length is chosen to provide required luminosity distribution in the interaction point. The total betatron tune shift $\Delta Q = \Delta Q_{Las} + 2\xi$ (Lasslet tune shift plus 2 beam-beam parameters at 2 interaction points) is taken equal to 0.05 that is limiting value for the chosen working point of the collider.

Table 2: Parameters of the Collider and the Beams for Au-Au Collisions

Ring circumference, m	503,04		
Number of bunches	22		
Rms bunch length, m	0.6		
Beta-function in the IP, m	0.35		
Ion energy, GeV/u	1.0	3.0	4.5
Beam regime	SCD	IBS	IBS
Ion number per bunch, 10^9	0.28	2.4	2.2
Rms momentum spread, 10^{-3}	0.62	1.25	1.65
Rms beam emittance, h/v, (unnormalized), π·mm·mrad	1.1/ 1.01	1.1/ 0.89	1.1/ 0.76
Total tune shift	0.05	0.05	0.02
Luminosity, 10^{27} $cm^{-2}s^{-1}$	0.011	1	1
IBS growth time,sec	186	702	2540

In the energy range above 3 GeV/u the peak luminosity corresponds to the required level. Here cooling has to compensate IBS heating and stabilize the bunch parameters. In this IBS-D mode the cooling system has to provide the cooling rate equal to IBS heating one. This task can be solved with stochastic cooling system at relatively weak parameters. 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.

Below 3 GeV/u the Collider operates in the SPD mode where the peak luminosity scales with the beam energy approximately as $\beta^5\gamma^6$ (it is correct if bunch length << ring circumference). Then luminosity drops down at 1 GeV/u by about two orders of magnitude. To improve the situation one needs to provide very powerful cooling that compresses IBS completely and permits to re-optimize the bunch parameters. In SPD mode the beam will be cooled with electron cooling system that provides the cooling time by more than one order of magnitude shorter than the IBS heating time.

Thus, at the energy range from 3 to 4.5 GeV/u a cooling system has to provide the cooling time values of about 500 s. Tthat will be achieved by stochastic cooling system of bandwidth of 3 GHz. Below 3 GeV/u cooling time should be of the order of 100 - 10 seconds that will be provided by electron cooling system.

Beam Stacking and Short Bunch Formation The beam accumulation in the collider is planned to be accomplished 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 control of the beam emittance and momentum spread during the bunch formation. Different possible modes of the BB stacking are discussed in [9].

After stacking of the required ion number the obtained coasting beam is bunched preliminary using RF system operated at harmonics equal to the bunch number.

Main RF system of the collider provides matching of the short bunch during collisions. It is conventional RF system operated at harmonics number larger than the bunch number by several times that is necessary to keep a short bunch length at reasonable RF voltage. The harmonics number was chosen to be 66 that provides sufficient bucket area at the voltage amplitude below 1 MV (Fig.2).

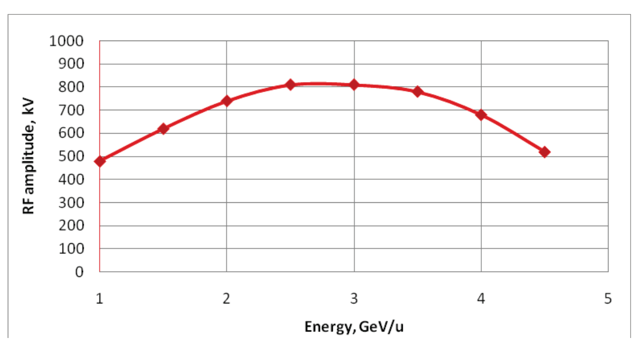

Figure 2: Dependence of the required FR amlitude on the beam energy.

A peculiarity of the beam bunching process in the NICA collider is necessity of a beam cooling during the bunching.

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It follows from the fact that at the adiabatic bunching the peak current and momentum spread increase linearly with the bunching factor while the threshold current is proportional to square of the momentum spread in accordance with Keil-Schnell criteria for longitudinal microwave instability. At the bunch parameters listed in the Table 2 the Keil-Schnell criteria is met for the bunch intensity in whole energy range because of large enough momentum spread. However the threshold momentum spread of the coasting beam at the same intensity corresponds to a longitudinal beam emittance by about three times larger than sum emittance of 22 short bunches.

STOCHASTIC COOLING

The stochastic cooling (SC) is assumed to be used in the collider to preserve the required luminosity at high ion energy (see above). For this purpose the SC has to provide equilibrium with the expected IBS heating. A serious challenge for the NICA stochastic cooling is to cool bunched beam at large bunching factor. So the peak linear density of the ions corresponds to a coasting beam at the ion number of about $8\cdot10^{11}$. At such conditions it is important to minimize "unwanted" mixing from pickup to kicker and maximize "wanted" mixing from kicker to pickup in order to have minimum cooling time at reasonable system bandwidth.

The NICA energy range and the chosen lattice of the collider give a unique possibility to provide isochronous mode for the ion motion from pickup to kicker.

In the total ion energy range the collider is operated below transition energy (γ_{tr} = 7.091). However the partial slip factor of the arc section is negative over about 3 GeV/u. The sign of the total slip factor of the ring is dominated by the positive slip factor of the straight section, which value is larger than absolute value of the arc slip factor. Optimum pickup position corresponds to beginning of the arc section. The kicker has to be located in the downstream straight section. Depending of the distance from the end of the arc to the kicker the partial slip factor η_{pk} will have zero value at some energy in the range from 3 to 4.5 GeV/u.

This property can be illustrated by the example of the longitudinal degree of freedom. For the Palmer method the pickup is located at the entrance into the arc section near maximum of the dispersion function. If the kicker is located in the long straight section at 132 m downstream from the pickup (Fig. 2) the partial slip factor is equal zero at about 4 GeV/u.

As result we have small negative η_{pk} at maximum energy and small positive at minimum energy (Fig. 3). In this case we exclude practically the unwanted mixing in the all energy range and sufficiently increase in the wanted one.

To provide the cooling time by two-three times shorter than the IBS ones (to have a technical reserve) the SC system bandwidth can be chosen from 3 to 6 GHz [8].

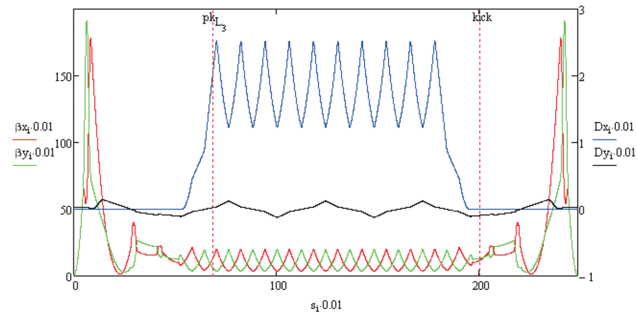

Figure 2: Lattice functions at the half of the collider circumference with positions of pickup and kicker for longitudinal cooling.

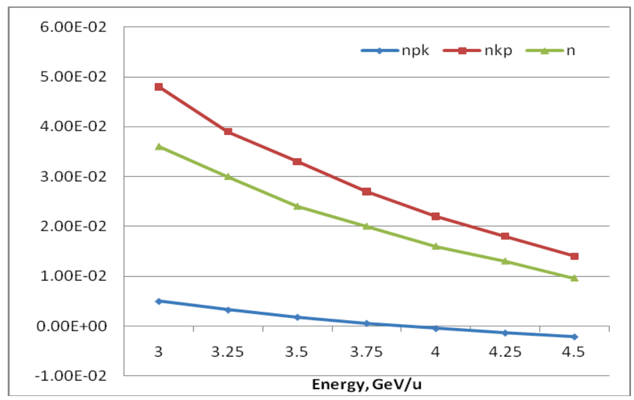

Figure 3: Total (green) and partial (red and blue) slip-factors of the ring as the function of the ion energy.

Since the stochastic cooling had never been used before at JINR, it was decided to perform an experiment at Nuclotron for learning by the NICA team the SC technique and demonstrating the system ability for the cooling of a bunched beam.

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. At large energy the collider working point is chosen below half-integer resonance (fractional part of the betatron tunes is of 0.49) that is optimum for stochastic cooling application. In this case the synchrotron and betatron Shottky bands are separated maximally. However at this working point the maximum acceptable tune shift is about 0.05 only. For the electron cooling the working point can be located below integer resonance where the acceptable tune shift can reach value of about 0.1. Correspondingly the luminosity (that scales as ΔQ^2) can be increased by about 4 times in comparison with IBS-D regime.

For the cooling section at reasonable technical parameters (Table 3) the cooling time values at small energy are about 20 times shorter than IBS heating times and the electron cooling is sufficiently strong to provide SCD regime of the collider operation. In IBS-D mode the required cooling time is rather long and electron cooling can provide suppression of IBS even at high energy.

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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	0.8
Magnetic field in the cooling section, T	0.2
Magnetic field imperfection in cooling section	2×10^{-5}
Longitudinal electron temperature, meV	5.0

NUCLOTRON AS TEST FACILITY FOR NICA

One of NICA accelerators – the superconducting synchrotron Nuclotron is used presently for fixed target experiments on extracted beams and experiments with internal target. This program is planned to be developed further and will be complementary to that one to be performed at Collider in heavy ion mode operation. The program includes experimental studies on relativistic nuclear physics, spin physics in few body nuclear systems (with polarized deuterons) and physics of flavors. At the same time, the Nuclotron beams are used for radiobiology and applied researches.

In addition to the implementation of the current physics program 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 operation regimes.

Development works for NICA performed during recent Nuclotron runs include the testing of elements and prototypes for the MPD using extracted deuteron beams; the transportation of the extracted beam (C^{6+} ions at 3.5 GeV/u and deuterons at 4 GeV/u) to the point of the future BM@N detector location; operational tests of the automatic control system based on the TANGO platform, which has been chosen for the NICA facility.

Simulation of the collider magnetic system operation conditions was performed at the Nuclotron during runs #45-47 (in years 2012-2013). This presumed test of the Nuclotron systems in the operation mode with long plateau of the magnetic field. In the run #45 the circulation of the deuteron beam accelerated up to 3.5 GeV/u was demonstrated during 1000 seconds. During the runs #46 and #47 such a regime was used for test of stochastic cooling at the Nuclotron that is an important phase of the NICA collider cooling system design.

During 2011-2013 the elements of the stochastic cooling system for test at the Nuclotron were designed, constructed and installed into the ring. This work performed in close collaboration with the Forschungszentrum Jülich (FZJ) is also important to IKP FZJ for testing elements of the stochastic cooling system being developed for the High-Energy Storage Ring (HESR, FAIR) [10]. In March 2013 the effect of the longitudinal cooling using notch-filter method had been demonstrated at the Nuclotron for the first time [11]. We plan to investigate gradually longitudinal and transverse stochastic cooling of coasting and bunched beams.

The experimental investigation of stochastic cooling was a complex test of machine performance. During the experiment, the cryogenic and magnetic systems, power supply and quench-protection systems, cycle control and diagnostic equipment were operated stably in a mode of the gradual increase of the accelerated beam circulation time on the flat-top of the magnetic field from a few tens of seconds up to eight minutes.

CONCLUSION

The NICA project as a whole has passed the phase of concept formulation and is presently under development of the working project, manufacturing and construction of the complex elements. The project realization plan foresees a staged construction and commissioning of the accelerators which form the facility. The main goal of the project is beginning of the facility commissioning in 2017.

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REFERENCES

[1] G. Trubnikov, et.al. Project of the Nuclotron-based ion collider facility (NICA) at JINR, Proc. of EPAC08, Genoa, Italy.
[2] BM@N project at JINR, http://nica.jinr.ru/
[3] A.V.Butenko, et al. Development of NICA injection facility, Proc. of IPAC2013, Shanghai, China.
[4] H. Khodzhibagiyan, et al. Prototype superconducting magnets for the NICA accelerator complex, Proc. of IPAC2013, Shanghai, China.
[5] N. Agapov, et al. Cryogenics for the Future Accelerator Complex NICA at JINR, JINR RC 2012.
[6] M. Bryzgunov, at al., Low energy cooler for NICA Booster, Proc. of RUPAC2012, Saint-Petersburg, Russia.
[7] I.Meshkov, et al. NICA project at JINR, Proc. of COOL'11, Alushta, Ukraine.
[8] I.Meshkov, et. al. Application of cooling methods to NICA project, Proc. of COOL'11, Alushta, Ukraine.
[9] A.V.Smirnov, et al. Stacking Modes with Barrier Buckets Method in NICA Collider, Proc. of COOL13 Mürren, Switzerland.
[10] R. Stassen, et al. Recent developments of the HESR stochastic cooling system, Proceedings of COOL07, Bad Kreuznach, Germany.
[11] N.Shurkhno, et al. Stochastic cooling at the Nuclotron, Proc. of COOL13 Mürren, Switzerland.

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