ISBN: 978-3-95450-198-4 doi:10.18429/JACoW-COOL2017-THM21

NICA PROJECT: THREE STAGES AND THREE COOLERS

I. N. Meshkov†[1, 2], G.V. Trubnikov[1, 2]
[1]Joint Institute for Nuclear Research, Dubna, Russia
[2]Sankt-Petersburg State University, Sankt-Petersburg, Russia

Abstract

The Nuclotron-based Ion Collider fAcility (NICA) project is being developed at JINR in three stages. The 1st stage, is a fixed target experiment with ions accelerated in the linac and tandem of two superconducting (SC) synchrotrons providing for ions $^{197}Au^{79+}$ maximum kinetic energy of 4.5 GeV/u ($\sqrt{s}$NN = 3.45 GeV/u). The 2nd stage extends $\sqrt{s}$NN to 11 GeV/u in colliding beams' mode. Both stages have a goal of experimental study of both hot and dense baryonic matter to search for so-called Mixed Phase formation in collisions of heavy relativistic ions and search for "new physics". The third stage is spin physics studies in collisions of polarized protons ($\sqrt{s}$NN = 27 GeV) and deuterons. The report focuses on beam dynamics in the NICA and the cooling methods application.

INTRODUCTION: THE NICA PROJECT AT JINR

The NICA project aims to design, construction and commissioning at the Joint Institute for Nuclear Research (Dubna, Russia) a modern accelerator complex Nuclotron-based Ion Collider fAcility (NICA) equipped with two detectors: the MultiPurpose Detector (MPD) and the Spin Physics Detector (SPD). Experimental studies planned at NICA will be dedicated to search of the mixed phase of baryonic matter and the nature of nucleon/particle spin. The project development has three stages:

Stage I: the fixed target experiment on heavy ions generated in the ion source and accelerated in the chain Heavy-Ion Linac (HILAc) – Booster synchrotron – Nuclotron.

Stage II: development of the same accelerator chain and transfer of the accelerated ions to the Collider rings and performance of the experiments on the ion beams in collider mode.

Stage III: generation and acceleration of polarized protons and deuterons and performance of the experiments on the colliding beams of the polarized particles.

A study of hot and dense baryonic matter should shed light on in-medium properties of hadrons and the nuclear matter equation of state; onset of deconfinement and/or chiral symmetry restoration; phase transition, mixed phase and the critical end-point; and possible local parity violation in strong interactions [1]. It has been indicated in series of theoretical works, in particular, in [2], that heavy-ion collisions at the nucleon-nucleon center-of-mass energy $\sqrt{s}$NN ~ 10 GeV allow one to reach the highest possible net baryon density.

The NICA project is under development as a flagship JINR project [3] in high-energy physics. Its main goal is construction of a collider facility providing ion collisions in collider mode at the energy range of $\sqrt{s}$NN = 4 – 11 GeV for Au^{79+} with luminosities up to $L = 10^{27}$ cm^{-2} s^{-1}. NICA will also provide the polarized proton and deuteron beams up to $\sqrt{s}$NN = 27 GeV for pp collisions with luminosity up to $L = 10^{32}$ $cm^{-2}\cdot s^{-1}$. The high intensity and high polarization (> 50 %) of the colliding beams will present a unique possibility for spin physics research, which is of crucial importance for the solution of the nucleon spin problem ("spin puzzle") - one of the main tasks of the modern hadron physics.

NICA – STAGE I

The program "The Baryonic Matter at Nuclotron" (BM@N) is complementary to that one of the Stage II. It is presently under active development and uses presently for testing experiment the existing Nuclotron facility. The last one currently consists of the "Old injector", new Heavy Ion Linac (HILAc) and the Nuclotron. The "Old injector" contains a set of light ion sources including a source of polarized protons and deuterons and an Alvarez-type linac LU-20 (Fig. 1, pos. 1). In this year the old fore-injector of LU-20 – electrostatic generator of 625 kV voltage has been replaced by new RFQ fore-injector that provides output energy of 156 keV for all ions. The LU-20 is capable to accelerate protons at the second harmonics only. Therefore the output proton energy, as well as other ions at A/Z = 2, is of 5 MeV.

The "New injector" (pos. 2) contains the ESIS-type ion source, which provides $^{197}Au^{32+}$ ions of intensity of $2\cdot10^9$ ions per pulse of about 7 μs duration at a repetition rate of 10 Hz, and the heavy ion linear accelerator (HILAc), consisting of RFQ and RFQ Drift Tube Linac sections. The HILAc accelerates the ions at $A/Z \leq 8$ up to the energy of 3 MeV/u, at efficiency no less than 80% (A, Z are ion mass and charge numbers). It was fabricated by the BEVATECH Company (Germany) in 2014 - 2015 and has been commissioned at JINR in 2016.

The Stage I will be commissioned for experiments after construction of the Booster-synchrotron (pos. 4), transfer channels from HILAC to the Booster and from Booster to existing Nuclotron, and the BM@N detector.

The NICA Booster

The ring of the SC Booster-synchrotron of the circumference of 215 m is housed inside the Synchrophasotron yoke (pos. 3). Its SC magnetic system provides a maximum magnetic rigidity of 25 Tm that allows us to accelerate ions $^{197}Au^{31+}$ to the energy of 578 MeV/u. It is sufficient for stripping these ions up to state of bare nuclei. Then, after transfer to Nuclotron (see below) the nuclei can be accelerated up to maximum project energy of 4.5 GeV/u. This

---

† meshkov@jinr.ru

ISBN: 978-3-95450-198-4 doi:10.18429/JACoW-COOL2017-THM21

is the main reason for the Booster construction. Another reason is rather evident. A good vacuum, as high as 10 pTorr achievable in the Booster, allows one to reduce fast ion losses in collisions with residual gas atoms at low energy injection. In Nuclotron regular vacuum pressure is about 0.3 nTorr that leads to fast losses of injected ions.

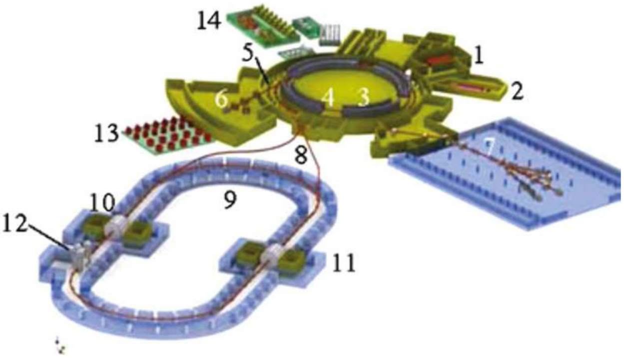

Figure 1: Scheme of the NICA facility. The description is given in the text.

The Booster SC magnets and other elements are being manufactured and passing through a “cold test” when necessary (Table 1).

Table 1: Booster SC Magnets’ Fabrication and Test

Magnet	Total number	Plan/Tested 12.09.2017
Dipole	40	28/25
Quad	48	20/26

The beginning of the machine commissioning is planned at the turn of 2018.

Electron Cooler for the Booster Electron cooling system (E-cooler) for the Booster is constructed by Budker INP [4] and is under commissioning presently at JINR/NICA (Fig. 2).

Figure 2: The BINP team with its leader V. Parkhomchuk (is taking photo) at E-cooler mounted at the Booster (May 2017).

The E-cooler will “compress” 6D emittance of the ion beam in the energy range from the injection energy up to 100MeV/u. The first regime of the lowest energy will be used for multiturn and/or multicycle injection of the ion beam from HILAc. The highest cooling energy allows us preparing low emittance ion beam for injection into Nuclotron and have the emittance low at acceleration. It gives, particularly, some advantage at the beam slow extraction from Nuclotron (see below).

Ion Stripping and Beam Transfer Line to Nuclotron The ions are stripped at crossing a copper foil placed in the ion beam transfer line from the Booster to the Nuclotron. The stripping efficiency at the maximum Booster energy is no less than 80%. The Ion Beam Transfer Line (BTL), including ion stripping station, is under final design and fabrication at BINP. It is scheduled for commissioning in February 2019.

Nuclotron in the NICA Project

The Nuclotron itself is a SC proton synchrotron (Fig.1, pos. 5) that has a maximum magnetic rigidity of 45 Tm and a circumference of 251.52 m. It can provide acceleration of completely stripped $^{197}Au^{79+}$ ions up to a kinetic energy in the range of 1 – 4.5 GeV/u, and of protons up to a maximum kinetic energy of 12.6 GeV. It is used presently for fixed target experiments with extracted beams and experiments with an internal target. The experiments’ program includes experimental studies on relativistic nuclear physics, spin physics in few-body nuclear systems (with polarized deuterons), and physics of flavours.

The Applied Research on Nuclotron Beams is carried out presently in radiobiology and other subjects. Besides, the Nuclotron is used for testing the collider equipment and operational regimes of the elements and prototypes of the MPD at extracted beams ($^{12}C^{6+}$ ions at 3.5 GeV/u and deuterons at 4 GeV/u). With the Booster commissioned the program of applied research at NICA will be enlarged significantly.

Both the applied researches and BM@N experiment require an efficient slow extraction of the particles accelerated in Nuclotron.

Slow Resonant Extraction from Nuclotron is accomplished using classical scheme of excitation of nonlinear resonance $(Q_x)_{res} = n + 1/3$. For Nuclotron $n = 7$, $Q_y = 7.4$. The flux of extracted particles $J(t)$ is determined by speed of variation of the betatron tune shift $\delta(t)$:

$$\delta(t) = Q_x - (Q_x)_{res}\,, \quad J(t) = \frac{dN}{d\delta}\cdot\frac{d\delta}{dt}\,. \tag{1}$$

Usually for experiment, the stretching in time of a slow extraction is preferably to be as long, as possible (Fig. 3).

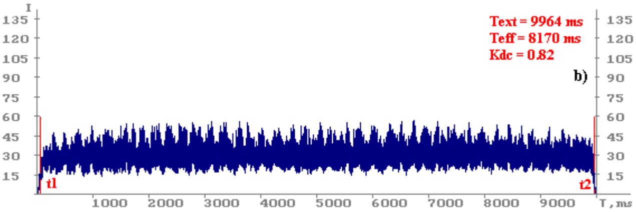

Figure 3: The spill of deuteron ions extracted from the Nuclotron; duration about 10 s.

Another "desire" of experimenters is constant value of the extracted particle flux. A gain in this characteristic can be achieved at application of electron cooling in the Booster. It reduces the ion beam emittance that leads finally to a smaller emittance of the beam after its acceleration in Nuclotron. The numerical simulation of particle dynamics at slow resonant extraction (based on Ref. [5]) shows the increase of extraction time at constant flux of extracted particles when beam emittance is reduced. Besides the tune dependence on time δ(t) is described with a definite function obtained by numerical simulation (Fig. 4). Details of these simulations will be published later.

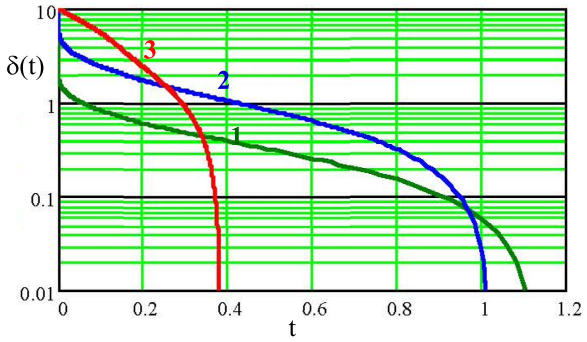

Figure 4: Dependence of δ(t) on time at constant particle flux J(δ) (arb. units) at slow resonant extraction of Gaussian beam of different values of the beam transverse (σ_x) and longitudinal (σ_p) emittances:

$\sigma_x = \sigma_p = 0.1$ (1), 0.3 (2), 1.0 (3) (arb. units).

Thus, electron cooling gives us an additional control of parameters of an extracted ion flux.

BM@N Detector

Presently the BM@N Detector is stage of fabrication and mounting its elements - subdetectors (Fig. 5), and testing them on ion beam from the Nuclotron.

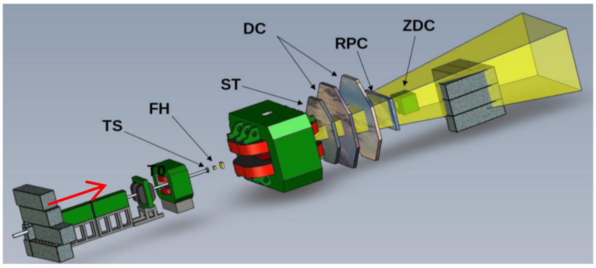

Figure 5: Scheme of the BM@N detector: TS – Target Station, FH – Forward Hodoscopes, ST – Straw tube Tracker, DC – Drift Chambers, RPC – Resistive Plate Chamber, ZDC – Zero Degree Calorimeter; arrow indicates the direction of the primary ion beam.

Full scale of BM@N experiment is scheduled for 2019. To be accomplished in time it demands construction and commissioning the Booster, BTL from the Booster to the Nuclotron and upgrading BTL from Nuclotron to BM@N experiment.

NICA – STAGE II

Stage II of the NICA project includes the construction of the Collider, the BTL from the Nuclotron to the Collider, and the MultiPurpose Detector (MPD).

The BTL from Nuclotron to the Collider Rings after preliminary design by NICA group was, for ordered to SigmaPhi Co (France) for its final (working) design, fabrication and commissioning, with the request of the work completion at the 2019 end.

The NICA Collider

NICA Collider consists of two SC rings (Fig. 1, pos. 9) of the racetrack shape have maximum magnetic rigidity of 45 Tm and a circumference of 503 m. The maximum field of SC dipole magnets is of 1.8 T. The final design of the Collider is close to the completion and allows us to obtain its major parameters (Table 2).

Table 2: NICA Collider Major Parameters

Parameter	Value
Circumference, m	503.04
Heavy ions	
Energy range for Au^{79+}, $\sqrt{s_{NN}}$, GeV	4 - 11
Min. beta-function in IP, m	0.35
Max. luminosity, $cm^{-2}\cdot s^{-1}$	$1\cdot10^{27}$
Polarized particles	
Max. proton energy, $\sqrt{s_{NN}}$, GeV	27.0
Max. luminosity, $cm^{-2}\cdot s^{-1}$	$1\cdot10^{32}$

Collider Magnets The first preserial prototype of the Collider "twin" dipole magnets (Fig. 6) was constructed and passed the "cold" test, where it has shown quality in accordance with the specification. Beginning of the magnet mass production is scheduled for the 2017 end.

Figure 6: Serial dipole magnet and quadrupole lens doublet for Booster and preserial "twin" dipole magnet for Collider Full energy range two parts of energy range.

Collider RF System consists of three different devices. RF-1 provides the "barrier" voltage for storage in the collider rings of the injected ions. The RF-2 and RF-3 providing the harmonic voltage of the 22nd and 66th harmonics of the ion revolution frequency correspondingly are used for the formation of the bunched ion beams consisting of 22 bunches. The bunch number of 22 per ring is limited by the requirement of avoiding parasitic collisions in common parts of both rings in the large straight sections. Project length of a bunch in colliding beams is of 0.6 m (one sigma).

A possibility of slow acceleration/ deceleration of the ions stored in the Collider is foreseen. It may be necessary if the regime of ion storage will be optimized at certain fixed ion energy. Then ion energy change will be implemented with RF-1 system that has variable frequency.

Collider Luminosity For project luminosity achievement, the electron and stochastic cooling systems are constructed. Full energy range of Collider operation is divided in two parts of ion kinetic energy – so called "Space Charge Dominated Mode" (SCDM), for 1 to 3 GeV/u, and "IBS Dominated Mode" (IBS DM), from 3 to 4.5 GeV/u. To maintain Collider luminosity at project level the both electron and stochastic cooling methods are planned to be used. At SCD regime the electron cooling will be used alone, whereas at IBS DR both methods are applicable. Details of these regimes can be found in [6, 7].

Electron Cooling for the Collider (ECC) The electron cooler with the electron kinetic energy of 0.5–2.5MeV will be placed in a special building at the Northern straight section of the Collider (Fig.1, pos. 12). Its design, construction, mounting on Collider and commissioning, including using in c the regime of the colliding ion beams, is entrusted to BINP team [8].

Stochastic Cooling at the Collider The development of the stochastic cooling system for the Collider is in stage of design and construction at JINR. This work is performed in close collaboration with the Forschungszentrum Juelich.

During 2011 – 2013, the first working version of the stochastic cooling system was designed, constructed, and tested at the Nuclotron at an ion kinetic energy of 3.5 GeV/u with deuteron and carbon ($^{12}C^{+6}$) ion beams.

The MPD

The MPD [6, 7] is located in the "North" straight section of NICA Collide (Fig. 1, pos.10). It is based on the superconducting solenoid (Fig. 7), with a magnetic field of 0.66T (6.623m in diameter and 9.010m in length). The major sub-detectors of the MPD are the time projection chamber (TPC), the inner tracker (IT), the time-of-flight (TOF) system, the electromagnetic calorimeter (ECal), the end cap tracker (ECT), and two forward spectrometers based on toroidal magnets (optional). Fast Forward Detector (FFD) and Fast Hadron Calorimeter (FHC). Two last ones will be used for tuning of the Collider luminosity. The MPD is under final design presently; prototypes of the sub-detectors are under construction and testing.

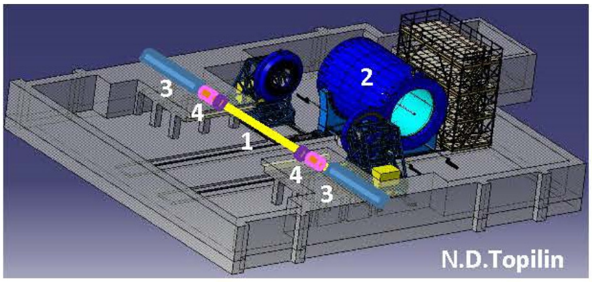

Figure 7: The MPD before final assembling: 1 - beam pipe, 2 – solenoid, 3 - final focus lenses, 4 - FFD and FHC for Collider luminosity tuning.

NICA – STAGE III

The implementation of the Stage III of the NICA facility requires two significant developments.

1. Adopting of the NICA accelerator facility to acceleration in Nuclotron and Collider of polarized particles, protons and deuterons. It demands renewal the lattice of the collider inserting in both machines spin rotators allowing to provide a stable spin dynamics and control of the spin direction in the Collider.

Recently a group of expert from BINP joined the NICA team for fulfilment of these tasks.

2. Design and construction of Spin Physics Detector (SPD). The SPD is located in "Southern" straight section of the racetrack rings (Fig. 1, pos. 11). It is under conceptual design since 2012. To intensify the design process a new group of experts has been formed August 17, 2017 at the seminar at BVLHEP JINR with intention to spread it to international collaboration.

CIVIL CONSTRUCTION AND INFRASTRUCTURE

The main civil construction works at NICA complex are carried out for building of the tunnels BTL NC and Collider and "rooms" for MPD, SPD and ECC. Strabag Co (Germany/Austria) and subcontractors from Russia started these works in November 2015. The Company execute the works in accordance with schedule. The mounting of the collider elements, transfer channel and MPD parts is planned to be started at the middle of 2019 when the corresponding parts of the collider building will be ready.

Cryogenics and the auxiliary equipment supply facility (Fig.1, pos. 13, 14) to provide LHe, LN2, electric power and cooling water for the accelerator complex and detectors is under construction.

BASIC AND FINAL CONFIGURATIONS OF THE NICA STAGE II

The very important and difficult task of the NICA project development is to begin its commissioning in 2020. It is planned to be done in a reduced version of the facility and element parameters. Nevertheless, this will allow us to start experiments in the colliding beams' mode, with the test and tuning of the MPD detector and the majority of the accelerators' elements.

The basic configuration of the NICA assumes the following:

1. An increased length of colliding beams' bunches equal to bunch = 0.6 m has been chosen to provide the "concentration" of the luminosity at the inner tracker area of the MPD.
2. The maximum ion number per bunch is limited by the value of the betatron tune shift Q ≤ 0.05.
3. The maximum emittance of the colliding bunches is less than 1.1 π·mm·mrad; the ratio of the horizontal emittance to the vertical one and the momentum spread of the ions is defined by the equilibrium state of the bunches in the presence of the intrabeam scattering (IBS).
4. The square of the separatrix for the RF-2 is 25 times larger than the longitudinal r.m.s. emittance of the bunch.
5. For suppression of the IBS, a stochastic cooling system of the Collider (SCSC) for each ring will be constructed in a reduced version: for longitudinal degree of freedom only (the "filter method").

As a result, the maximum peak luminosity can be provided at the level of $5 \cdot 10^{25}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at the kinetic energy of the $^{197}\mathrm{Au}^{79+}$ ions in the range of 3–4.5 GeV/u.

The Final Configuration of the NICA requires the construction of the third RF system of the 66th harmonics of the revolution frequency and high RF amplitude (RF-3). It will squeeze 22 bunches kept in the separatrices of RF-2 to the length of 60 cm. At that, each third separatrix is filled with ions when the two others remain empty.

The construction of the ECC and the completion of the SCSC will be produced.

The full configuration of the MPD will be commissioned as well.

SUMMARY

The main characteristics of the NICA project, its status, and the principle problems related to the NICA creation have been considered in this report.

The BM@N and MPD experiments are competitive and, at the same time, complementary to experiments carried out at RHIC [9] and those planned within the FAIR project [10].

The NICA project as a whole has passed the phase of design and is currently in the stage of manufacturing and construction of the elements of accelerators and MPD and BM@N detectors.

The project realization plan foresees a staged construction and commissioning of the accelerator facility and the detector MPD and SPD.

ACKNOWLEDGEMENT

Authors express the gratitude to the colleagues of the NICA accelerator team – A. Butenko, G. Khodzhibagiyan, T. Katayama, S. Kostromin, O. Kozlov, A. Sidorin, A. Smirnov, R. Stassen, E. Syresin, A. Philippov, and A. Tuzikov - for longstanding intense common work on the NICA project and (I. M.) to E. Levichev (BINP) for fruitful advises on nonlinear particle dynamics in cyclic accelerators.

REFERENCES

[1] `http://theor.jinr.ru/twiki-cgi/view/NICA/WebHome`

[2] J. Cleymans and J. Randrup, *Phys. Rev.* C 74, 047901 (2006).

[3] I. Meshkov, *Phys. At. Nucl.* 75, 594 (2012).

[4] A. V. Bublei *et al.*, "Low Energy Electron Cooler for the NICA Booster", presented at COOL'17, Bonn, Germany, paper TUM11, this conference.

[5] E. B. Levichev, "Lectures on Particle Nonlinear Dynamics in Cyclic Accelerators", Novosibirsk State Technical University (2009) (in Russian).

[6] V. D. Kekelidze, R. Lednicky, V. A. Matveev, I. N. Meshkov, A. S. Sorin, and G. V. Trubnikov, *Eur. Phys.* J. A 52, 211 (2016).

[7] V. D. Kekelidze, V. A. Matveev, I. N. Meshkov, A.S. Sorin, and G. V. Trubnikov, PEPAN 48, 727 (2017).

[8] V.B. Reva *et al.*, "The High Voltage cooler for NICA, Status and Ideas", presented at COOL'17, Bonn, Germany, paper TUM21, this conference.

[9] G.S. Stephans, *J. Phys.* G 32, 447 (2006) nucl-ex/0607030.

[10] P. Senger, *J. Phys.* G 30, 1087 (2004).