Review

Three stages of the NICA accelerator complex[*]

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Abstract. The Nuclotron-based Ion Collider fAcility (NICA) project is under development at JINR (Dubna). The general goals of the project are to provide colliding beams for experimental studies of both hot and dense strongly interacting baryonic matter and spin physics (in collisions of polarized protons and deuterons). The first program will require the running of heavy-ion mode in the energy range of $\sqrt{s_{NN}} =$ 4–11 GeV at luminosities up to $L = 1 \cdot 10^{27}$ cm^{-2} s^{-1} for ^{197}Au^{79} nuclei (see details in sect. 4. This stage of the project will be preceded by fixed target experiments with the heavy-ion beam to be extracted from the Nuclotron at kinetic energies up to 4.5 GeV/u. The polarized beam mode is proposed to be used in the energy range of $\sqrt{s_{NN}} = 12$–27 GeV (protons) at luminosities up to $1 \cdot 10^{32}$ cm^{-2} s^{-1}. This report contains a brief description of the facility scheme and characteristics in the heavy-ion operation mode, the description of the MultiPurpose Detector (MPD), and characteristics of the reactions of the colliding ions, which will allow us to detect the mixed phase formation. The plans and status of the project development are presented.

1 Introduction: the NICA Project at JINR

The NICA project is aimed to be developed, constructed, and commissioned 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). Experiments shall be performed in search of the mixed phase of baryonic matter and the nature of nucleon/particle spin.

The project is developed in 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: completion of the same chain of heavy-ions' generation and acceleration by the ions' transfer 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.

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[*] Contribution to the Topical Issue "Exploring strongly interacting matter at high densities - NICA White Paper" edited by David Blaschke *et al.*
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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 $\sqrt{s_{NN}} \sim 10$ 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. In addition to the beams extracted from the Nuclotron, the project foresees the 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 the c.m.s. energy of 27 GeV for pp collisions with luminosity up to $L = 10^{32}$ cm^{-2} · 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.
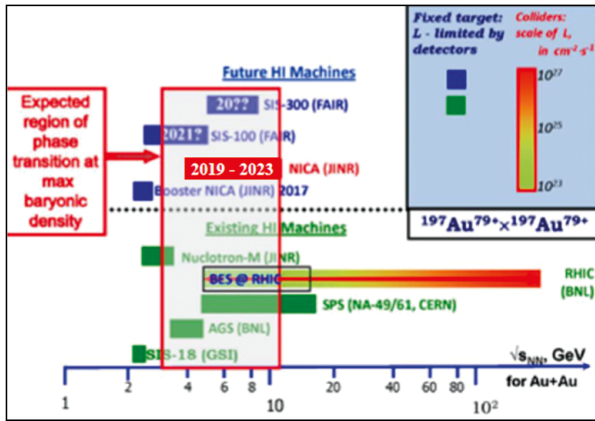
Fig. 1. The energy ranges of heavy-ion machines in operation (lower part in green) and under construction (upper part in blue and red); the rectangular frame indicates the region of maximum net baryonic density.
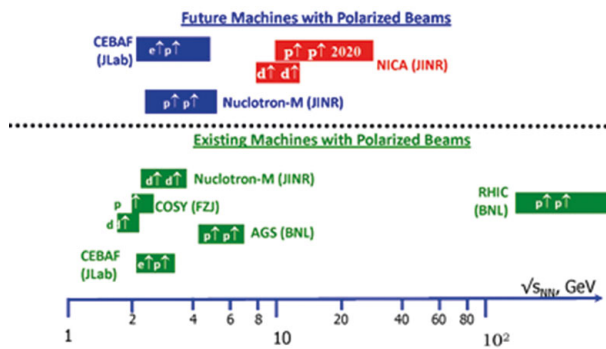

Fig. 2. Machines with polarized beams: existing (lower part in green) and under construction (upper part in blue and red).

2 Accelerators and colliders in the NICA energy range

The comparison of the parameters of the NICA accelerator complex with existing and currently developing machines of heavy ions and polarized beams (see figs. 1, 2) shows that NICA is perfectly situated to approach the research goals formulated above.

3 NICA —Stage I

The Nuclotron facility currently consists of the "Old injector" 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. 3, pos. 1).

The Nuclotron itself is a SC proton synchrotron (pos. 5) that has a maximum magnetic rigidity of 45 T m 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 (table 1). It is used presently for fixed target experiments with extracted beams and experiments with an internal target.
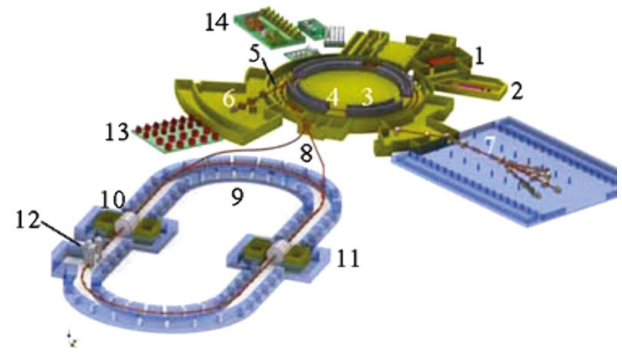

Fig. 3. Scheme of the NICA facility. The description is given in the text.

Table 1. Nuclotron beams.

Parameter	Project (2017)	
Magnetic field, T	2.0 ($B_\rho = 42.8$ T m)	
Field ramp, T/s	1.0	
Repetition period, s	5.0	
	Energy, Gev/u	Ions/cycle
Light ions $\Rightarrow d$	7.0	$5 \cdot 10^{10}$
Heavy ions	With KRION-6T & Booster	
$^{40}Ar^{18+}$	5.9	$2 \cdot 10^{10}$
$^{56}Fe^{26+}$	6.4	$1 \cdot 10^{10}$
$^{124}Xe^{48/42+}$	5.0	$2 \cdot 10^{9}$
$^{197}Au^{79+}$	5.5	$2 \cdot 10^{9}$
Polarized beams	With SPI	
$p \uparrow$	12.6	$1 \cdot 10^{10}$
$d \uparrow$	6.6	$1 \cdot 10^{10}$

The program includes experimental studies on relativistic nuclear physics, spin physics in few-body nuclear systems (with polarized deuterons), and physics of flavours. This part of the program, "The Baryonic Matter at Nuclotron" (BM@N), is under active development.

The development of Stage I of the NICA project will be completed after the construction of the "New injector" and the Booster-synchrotron and after the commissioning of the BM@N detector.

The "New injector" (pos. 2) is under construction. It contains the ESIS-type ion source, which will provide $^{197}Au^{32+}$ ions of intensity of $2 \cdot 10^9$ ions per pulse of about $7\,\mu s$ 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 linac 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 delivered by the BEVATECH Company (Germany) in 2014-2015 and is presently being commissioned. This stage is intended to be complementary to the stage to be realized with Collider in heavy-ion beam mode.

Housed inside the Synchrophasotron yoke (pos. 3), the Booster-synchrotron (pos. 4) has a superconducting (SC) magnetic system that provides a maximum magnetic

rigidity of 25 T m at the ring circumference of 215 m. It is equipped with an electron cooling system, constructed by Budker INP, which will provide cooling for the ion beam in the energy range from the injection energy up to 100 MeV/u. The maximum energy of $^{197}Au^{31+}$ ions, accelerated in the Booster, is of 600 MeV/u. Stripping foil placed in the ion transfer line from the Booster to the Nuclotron provides the stripping efficiency at the maximum Booster energy, no less than 80%. The Booster elements are being manufactured, and the machine is planned to be commissioned in 2017.

The Nuclotron beams also find use in radiobiology research and other applied research. Moreover, the Nuclotron is used for testing the collider equipment and operational regimes, elements and prototypes for the MPD using extracted beams (C^{6+} ions at 3.5 GeV/u and deuterons at 4 GeV/u presently). Particularly, in the run #45 (Feb. 2012), the circulation of a 3.5 GeV/u deuteron beam for 1000 seconds was demonstrated. During 2011–2013, the first 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. This work was performed in close collaboration with the Forschungszentrum Jülich. The results will also be used for the design of the stochastic cooling system for the High-Energy Storage Ring (HESR, FAIR).

Two transfer lines, in order to transport particle beams extracted from the Booster (pos. 6), and the Nuclotron (pos. 7), in order to research areas for both basic and applied research using fixed target experiments, will be constructed.

4 NICA —Stage II

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

The transfer line (pos. 8) will transport the particles from Nuclotron to the Collider rings. The line is currently in the design stage.

Two SC collider rings (pos. 9) of racetrack shape have maximum magnetic rigidity of 45 T m and a circumference of 503 m. The maximum field of SC dipole magnets is of 1.8 T. For luminosity preservation, the electron and stochastic cooling systems will be constructed. The collider design is in progress; the prototypes of its magnets were fabricated and tested in 2013; the mass production is scheduled for 2016–2018.

Two detectors, the MultiPurpose Detector (MPD, pos. 10) and the Spin Physics Detector (SPD, pos. 11), are located in opposite straight sections of the racetrack rings. The MPD is being designed presently; prototypes of the sub-detectors are under construction and testing. The SPD is under conceptual design and is planned to be constructed during Stage III.

The electron cooler with the electron kinetic energy of 0.5–2.5 MeV will be placed in a special building (pos. 12). Cryogenics and the auxiliary equipment supply facility (pos. 13, 14) provide LHe, LN2, electric power and
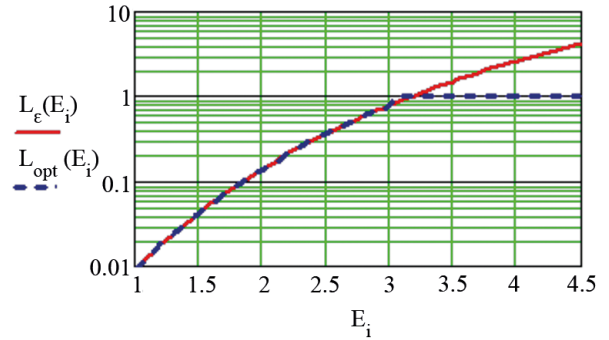

Fig. 4. Project luminosity ($10^{27}\,cm^{-2}\,s^{-1}$) of the NICA collider *versus* ion kinetic energy per nucleon (GeV/u); two modes: ion number per bunch is limited by the ion bunch space charge ($L_\varepsilon(E_i)$, solid curve) and is optimized (dashed line, $L_{opt}(E_i)$).

Table 2. NICA collider major parameters.

Ring circumference, m	503.04
Heavy ions	
β^*, m	0.35
Energy range for Au^{79+}, $\sqrt{s_{NN}}$, GeV	4–11
r.m.s. $\Delta p/p$, 10^{-3}	1.6
Luminosity for Au^{79+}, $cm^{-2}\,s^{-1}$	$1 \cdot 10^{27}$
Polarized particle	
Max. energy range for polarized p, $\sqrt{s_{NN}}$, GeV	27
Luminosity for p, $cm^{-2}\,s^{-1}$	$1 \cdot 10^{32}$

cooling water to feed the accelerator complex and detectors. The NICA parameters allow us to reach the project luminosity at the ion kinetic energy higher than 3 GeV/u (fig. 4 and table 2).

5 The MPD

The MPD [4] is a typical collider detector based on the solenoidal superconducting magnet (fig. 5), with a magnetic field of 0.66 T (6.623 m in diameter and 9.010 m 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). Three stages are foreseen in order to bring MPD into operation. The first stage of operation involves the magnet, TPC, TOF, ECal, and IT (partially).

The MPD experiment should be competitive and, at the same time, complementary to experiments carried out at RHIC [5] and those planned within the FAIR project [6].

There are several MPD detection tasks that should be fulfilled first [1]. A study of the elliptic flow of the secondary particles in the momentum space, in order to quantify the collective behavior of the central fireball matter.
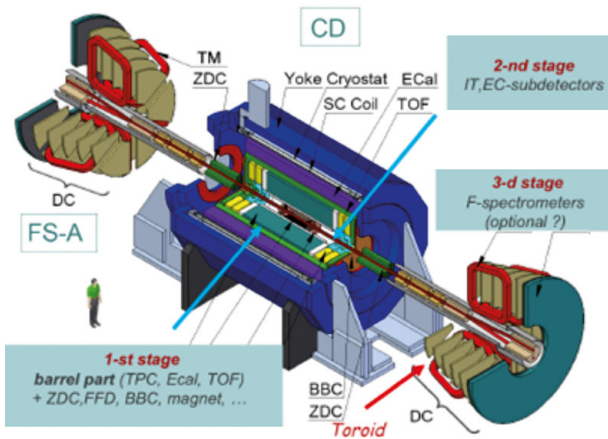
Fig. 5. General view of the MPD and sets of sub-detectors to be put in operation at different stages.

A detailed measurement of the well-known "Horn effect" can give information about peculiarity of the heavy-ion collisions. The effect has been observed in experiments where energy dependence of the multiplicity ratio $R = \langle K^+ \rangle / \langle \pi^+ \rangle$ was measured at the pseudorapidity $y^* \approx 0$ (i.e., at the scattering angle $\theta \approx \pi/2$). The non-monotonic dependence of the $R(0)$ ratio on energy can be regarded as an indication of the onset of deconfinement and/or the onset of a meson-dominated production regime.

A lot of information can be obtained from the detection of leptons and photons. Leptons result from decays of mesons, such as the π, ρ, ω, ϕ, J/Ψ, etc., which give rise to $e^+ e^-$, $\mu^+ \mu^-$, ν_e, ν_μ (the latter are undetectable in the MPD). They provide information about the QGP-phase structure. The detection of photons allows one to estimate the QGP temperature.

The fluctuation studies of the collision products parameters are very informative. Large fluctuations can be considered as a signature of the mixed phase formation. Indeed, the system becomes unstable at the two-phase stage (as in a classic process of boiling water —a flow of bubbles fluctuates tremendously). The idea is to locate the critical point using correlation/fluctuation of particle characteristics, e.g., dispersion and higher moments of $R(0)$: $D_R = \langle (R - \langle R \rangle)^2 \rangle$, $M_{3R} = \langle (R - \langle R \rangle)^3 \rangle$. An attempt to detect the fluctuations in the Beam Energy Scan at RHIC likely failed because of a lack of statistics, i.e., a low luminosity of the RHIC at lower energies.

An important signal for the onset of deconfinement, 1st-order phase transition, is a substantial increase of the evolution time of the excited matter. This signal can be revealed with the help of femtoscopic momentum correlations as a tail in the reconstructed space-time separation of particle emitters.

The measurement of the charge asymmetry with respect to the reaction plane characterizes the electric dipole moment of QCD matter and is a possible signature of local parity violation.

Processes studied with MPD were simulated using the dedicated software framework (MpdRoot). The evaluated

rate in Au + Au collisions, at $\sqrt{s_{NN}} = 9\,\mathrm{GeV}$ (10% central interactions) for the luminosity of $10^{27}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, is of the order of $7\,\mathrm{kHz}$. The MPD performance in general meets the required parameters for the proposed experimental program.

6 The Stage III —polarized ions and SPD

The polarized beam mode of NICA is being implemented in two steps. The first is the acceleration of polarized deuterons at the Nuclotron, which has been performed since the 1990s. This beam is used in fixed target experiments, and the beam intensity will be increased with commissioning of the new Source of Polarized Particles in 2016. The second step is the development of the collider lattice for storing polarized beams and keeping them circulating in the collider mode. This work is in the design stage. The project luminosity of the collider is up to $10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

The SPD will be constructed in the second IP. Its elaboration is also postponed to the third phase of the NICA project. Nevertheless, the SPD concept has been formulated and the creation of a motivated international collaboration has begun.

7 Start-up version of the NICA project

The very important and difficult task of the NICA project development is to begin its commissioning by the end of 2019. 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 start-up version of the NICA assumes the following:

1) An increased length of colliding beams' bunches equal to $\sigma_{\mathrm{bunch}} = 0.6\,\mathrm{m}$ 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 $\Delta Q \leq 0.05$.

3) The maximum emittance of the colliding bunches is less than $1.1\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$; 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 bunch number per ring is limited by the requirement of avoiding parasitic collisions in common parts of both rings in the large straight sections and is equal to $n_{\mathrm{bunch}} = 22$.

5) RF systems consist of the barrier voltage system (RF-1) and the RF system of the 22nd harmonics of the revolution frequency (RF-2). RF-1 is used for storage in the collider rings of the injected ions; RF-2 is used for the formation of the bunched ion beams. The square of the separatrix for the RF-2 is 25 times larger than the longitudinal r.m.s. emittance of the bunch.
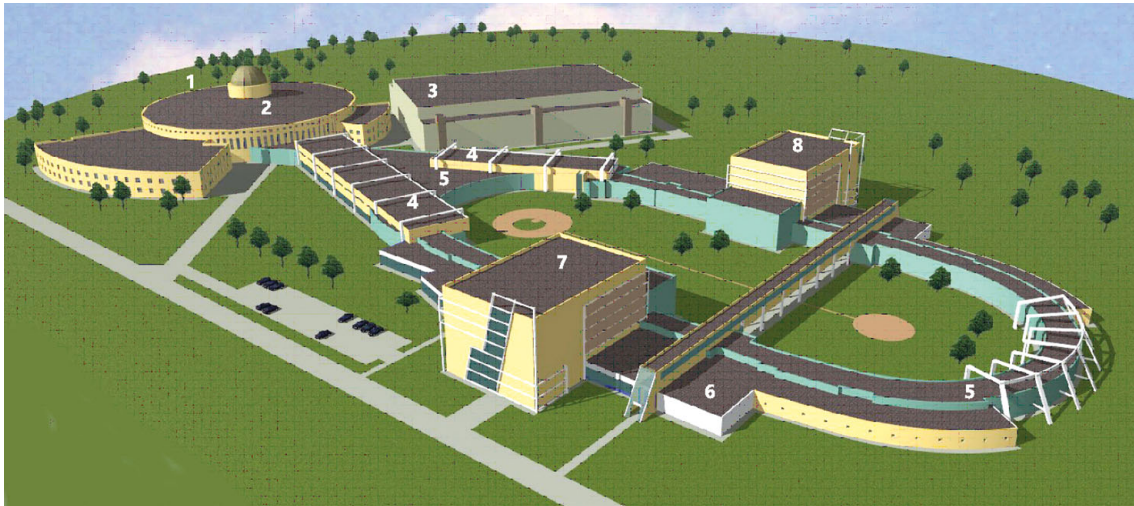
Fig. 6. The buildings for the NICA accelerators. 1: "old" and "new" injectors; 2: Booster-synchrotron and Nuclotron; 3: hall for the fixed target experiments; 4: beam transfer channels; 5: collider rings; 6: electron cooler; 7: MPD; 8: SPD.

6) For suppression of the IBS, a stochastic cooling system, for longitudinal degrees of freedom (the "filter method"), will be constructed.

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

The construction work of the buildings of the collider and transfer channels (see fig. 6) was started in November 2015. The mounting of the collider elements, transfer channel and MPD parts is planned to be started at the beginning of 2019 when the corresponding parts of the collider building will be ready. The start-up version of the project is planned for the end of 2019 and the completion of the NICA commissioning in the project mode is planned for 2023 [7].

The completion of this project version of the NICA project 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 an electron cooler and the completion of the stochastic cooling system are assumed also. The full project version of MPD will be commissioned as well.

8 Conclusion

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 NICA project as a whole has passed the phase of design and is currently in the stage of accelerator element manufacturing and construction.

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

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