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Three Stages of The NICA Accelerator Complex Nuclotron-based Ion Collider fAcility

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Abstract. The project of Nuclotron-based Ion Collider fAcility (NICA) is under development at JINR (Dubna). The general goals of the project are providing of 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 requires running of heavy ion mode in the energy range of $\sqrt{s_{NN}} = 4 \div 11$ GeV at average luminosity of $L = 1 \cdot 10^{27}$ cm^{-2}·s^{-1} for ^{197}Au^{79+} nuclei. This stage of the project will be preceded with fixed target experiments on heavy ion beam extracted from *Nuclotron* at kinetic energy up to 4.5 GeV/u. The polarized beams mode is proposed to be used in energy range of $\sqrt{s_{NN}} = 12 \div 27$ GeV (protons) at luminosity up to $1{\cdot}10^{32}$ cm^{-2}·s^{-1}. The report contains a brief description of the facility scheme and characteristics in heavy ion operation mode, the description of the MultiPurpose Detector (*MPD*) and characteristics of the reactions of the colliding ions, which allow us to detect the mixed phase formation. Status and plans of the project development are presented.

INTRODUCTION: THE NICA PROJECT AT JINR

The NICA project is aimed to develop, construct and commission at Joint Institute for Nuclear Research (Dubna, Russia) a modern accelerator complex Nuclotron-based Ion Collider fAcility (NICA) equipped with two detectors MultiPurpose Detector (*MPD*) & Spin Physics Detector (*SPD*) and perform experiments on search of the mixed phase of baryonic matter state and nature of nucleon/particle spin.

A study of hot and dense baryonic matter should shed light on: in-medium properties of hadrons and nuclear matter equation of state; onset of deconfinement and/or chiral symmetry restoration; phase transition, mixed phase and critical end-point; possible local parity violation in strong interactions [1]. It is indicated in series of theoretical works, in particular, in [2] that heavy ion collisions at $\sqrt{s_{NN}} \leq 11$ GeV in the lab system allow to reach the highest possible baryon density.

A project NICA aimed to study hot and dense baryonic matter and spin physics is under development as a flagship project at JINR in high energy physics. In addition to the beams extracted from the *Nuclotron* the project foresees a construction of collider facility providing experiments in collider mode at the energy range of $\sqrt{s_{NN}} = 4 \div 11$ GeV for ^{197}Au^{79+} with the luminosity up to $L = 1 \cdot 10^{27}$ cm^{-2}·s^{-1}.

The NICA will also provide the polarized proton and deuteron beams up to the c.m.s. energy of 27 GeV for *pp* collisions with the luminosity higher than $L = 1 \cdot 10^{32}$ cm^{-2}·s^{-1}. The high intensity and high polarization (> 50%) of the colliding beams open up 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.

The comparison of the parameters of the NICA accelerator complex with the existing and being developed machines of heavy ions and polarized beams shows that NICA does fit to the research goals formulated above.

NICA — STAGE I

Nuclotron facility consists today of the *“Old injector”* and the *Nuclotron*.

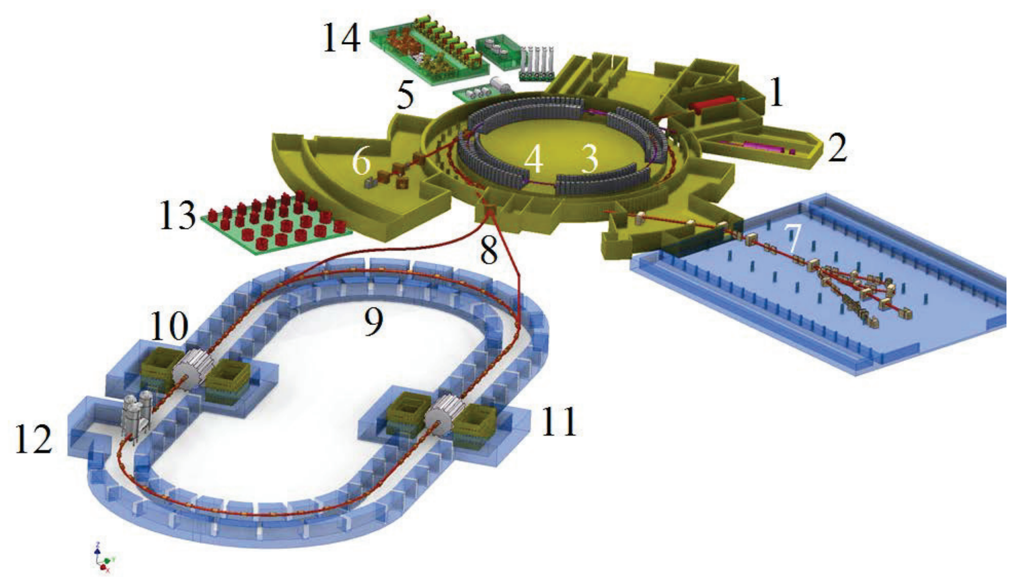

FIGURE 1. Scheme of NICA facility. Description on the text

The *"Old injector"* contains set of light ion sources including source of polarized protons and deuterons and Alvarez-type linac LU-20 (Fig. 1, pos. 1).

Nuclotron is SC proton synchrotron (Fig. 1, pos. 5) that has maximum magnetic rigidity of 45 T·m and the circumference of 251.52 m. It can provide the acceleration of completely stripped $^{197}Au^{79+}$ ions up to the experiment energy in the range of 1÷4.5 GeV/u and protons up to maximum energy of 12.6 GeV. It is used presently for fixed target experiments with extracted beams and experiments with internal target. The program includes experimental studies on relativistic nuclear physics, spin physics in few body nuclear systems (with polarized deuterons) and physics of flavours. The part of this program, *"The Baryonic Matter at Nuclotron"* (BM@N) is under development presently.

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

"New injector" (Fig. 1, pos. 2) is under construction. It contains ESIS-type ion source that provides $^{197}Au^{31+}$ ions of the intensity of $2 \cdot 10^9$ ions per pulse of about 7 μs duration at repetition rate of 10 Hz and heavy ioin 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 3.2 MeV/u at efficiency not less than 80% (A, Z are ion mass and charge numbers). It has been delivered by BEVATECH Company (Germany) in 2014–2015 and is under commissioning presently. It will be complementary to that one to be performed at *Collider* in heavy ion beam mode.

Housed inside the Synchrophasotron yoke (Fig. 1, pos. 3), the *Booster-synchrotron* (Fig. 1, pos. 4) has superconducting (SC) magnetic system that provides maximum magnetic rigidity of 25 T·m at the ring circumference of 215 m. It is equipped with electron cooling system constructed by Budker INP. It allows us to provide cooling of the ion beam in the energy range from 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 not less than 80%. The *Booster* elements are under manufacturing and machine is planned to be commissioned in 2017.

Besides, the *Nuclotron* beams are used for research in radiobiology and applied research. Moreover, the *Nuclotron* is very good facility for testing of the *Collider* equipment and operational regimes, elements and prototypes for the *MPD* using extracted beams ($^{12}C^{6+}$ ions at 3.5 GeV/u and deuterons at 4 GeV/u presently). Particularly, in the run #45 (Feb. 2012) the circulation of 3.5 GeV/u deuteron beam during 1000 seconds was demonstrated. During 2011-2013 the first version of stochastic cooling system was designed, constructed and tested at *Nuclotron* at 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 Julich. The results will be used also for design of the stochastic cooling system for the High-Energy Storage Ring (HESR, FAIR).

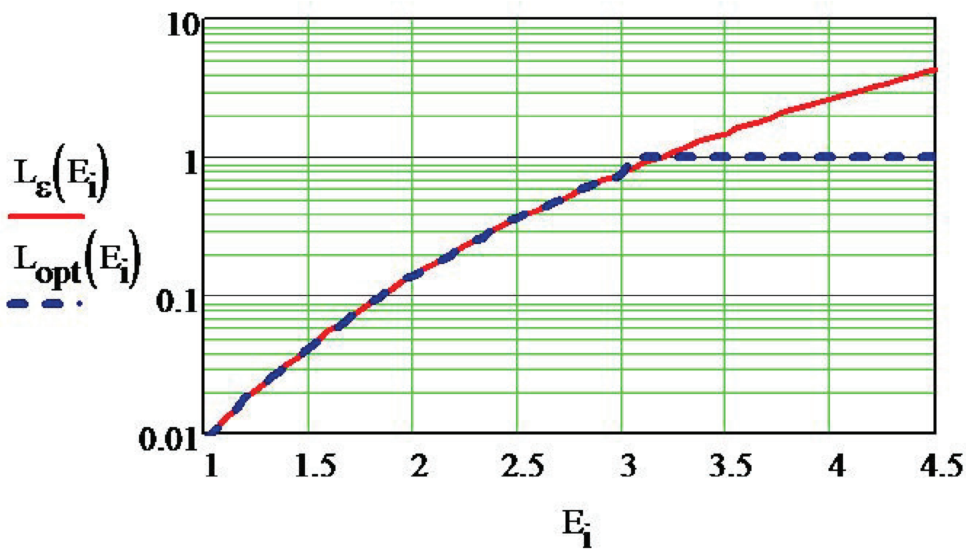

FIGURE 2. Project luminosity (10^{27} cm^{-2}·s^{-1}) of the NICA *Collider* vs ion kinetic energy per nucleon (GeV/u); two modes: ion number per bunch is limited by the ion bunch space charge ($L_\epsilon(E_i)$, solid curve) and is optimized (dashed line, $L_{opt}(E_i)$)

Two transfer lines transport particle beams extracted from *Booster* (Fig. 1, pos. 6) and *Nuclotron* (Fig. 1, pos. 7) to research areas, where fixed target experiments both of basic and applied character will be set.

NICA — STAGE II

The Stage II of the NICA project includes construction of the *Collider*, the beam transfer line from *Nuclotron* to *Collider* and the MultiPurpose Detector (*MPD*). *The transfer line* (Fig. 1, pos. 8) will transports the particles from *Nuclotron* to *Collider* rings. The line is at the design stage presently.

Two SC Collider rings (Fig. 1, pos. 9) of racetrack shape have maximum magnetic rigidity of 45 T·m and the circumference of 503 m. The maximum field of SC dipole magnets is of 1.8 T. For luminosity preservation electron and stochastic cooling systems are constructed. The *Collider* design is in progress; the prototypes of its magnets have been fabricated and tested in 2013; the mass production is scheduled for 2016–2018.

Two detectors — the MultiPurpose Detector (*MPD*, Fig. 1, pos. 10) and the Spin Physics Detector (*SPD*, Fig. 1, pos. 11) are located in the opposite straight sections of the racetrack rings. The *MPD* is being designed presently; prototypes of the subdetectors are under construction and testing. The *SPD* is under conceptual design and is planned to be constructed at Stage III.

The electron cooler of electron energy of 0.5 ÷ 2.5 MeV will be placed in special building (Fig. 1, pos. 12).

Cryogenics and auxiliary equipment supply facility (Fig. 1, pos. 13, 14) provides LHe, LN2, electric power and cooling water to feed the accelerator complex and detectors.

The NICA parameters allow us to reach the project luminosity (Fig. 2).

THE *MPD*

The *MPD* [4] is a typical collider detector based on the solenoidal superconducting magnet (Fig. 3): 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); inner tracker (IT); time-of-flight (TOF) system; electromagnetic calorimeter (ECal); end cap tracker (ECT), and two forward spectrometers based on toroidal magnets (optional). Three stages of putting *MPD* into operation are foreseen. The first stage of operation involves the magnet, TPC, TOF, ECal and IT (partially).

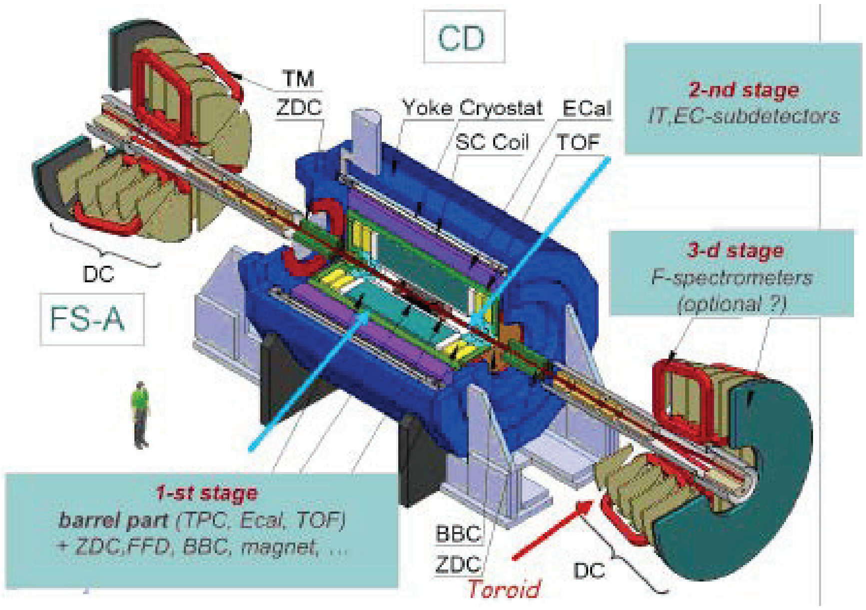

FIGURE 3. General view of the *MPD*, and sets of sub-detectors to be put in operation at different stages

The *MPD* experiment should be competitive and at the same time complementary to ones carried out at RHIC [5], and constructed in the frame work of FAIR [6] project.

There are several *MPD* detection tasks that should be fulfilled first [1]. Observation of the *elliptic flow of the secondary particles in the momentum space* does manifest a collective behavior of the *central fireball matter*.

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

A lot of information can be obtained from detection of leptons and photons. Leptons result from decays of mesons like π, ρ, ω, φ, J/ψ, and others, which give rise to e^+e, $\mu^+\mu^-$, ν_e, ν_μ (the latter are undetectable for the *MPD*). They provide the information about the QGP-phase structure. Detection of photons gives us the QGP temperature.

Very convincing are the fluctuations of the collision products parameters. They are "a sign" 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 experimental data, e.g. dispersion and higher momenta of $R(0)$: $D = \langle (R - \langle R \rangle)^2 \rangle$, $M_{3R} = \langle (R - \langle R \rangle)^3 \rangle$ and higher, and fluctuations of other parameters of the collision reactions. None that the experiment at RHIC at a high ion energy $\sqrt{s_{NN}} = 200$ GeV/u gave zero result: $D_R = M_{3R} = \ldots = M_{6R} = 0$. An attempt to detect the fluctuations at low energy (Beam Energy Scan, BES) failed due to lack of statistics (low luminosity of the RHIC).

The measurement of the charge asymmetry WRT reaction plane characterizes *electric dipole moment of QCD matter* and is a possible signature of *strong parity violation*.

Processes studied with *MPD* were simulated using the dedicated software framework (MpdRoot). Evaluated rate in Au+Au collisions at $\sqrt{s_{NN}} = 7$ GeV (10% central interactions) at the luminosity of 10^{27} cm$^{-2}\cdot$s^{-1} is of the order of 7 kHz. The *MPD* performance meets in general the required parameters for proposed experimental program.

THE STAGE III — POLARIZED IONS AND *SPD*

The polarized beam mode of NICA is being implemented in two steps. The first is 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 the new Source of Polarized Particles by the end of 2015. The second step is development of the *Collider* lattice for storing polarized beams and keeping them circulating in the collider mode. This work is at the design stage.

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

START-UP VERSION OF THE NICA PROJECT

Very important and hard task of the NICA project development is to begin its commissioning at the end of 2019. It is planned to be done in a reduced version of the facility and its elements parameters. Nevertheless, this will allow us to start experiments in 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 $\sigma_{bunch} = 0.6$ m that provides the "concentration" of the luminosity at the inner tracker area of the *MPD*.
2. Maximum ion number per bunch is limited by the value of the betatron tune shift $\Delta Q \leq 0.05$.
3. Maximum emittance of the colliding bunches does not exceed 1.1 π mm·mrad; 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 presence of the intrabeam scattering (IBS).
4. The bunch number per ring is limited by the requirement of avoiding of the parasitic collisions and is equal to $n_{bunch} = 22$.
5. RF systems consist of the barrier voltage system ("RF-1") and the RF system of the 3^{rd} 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 formation of the bunched ion beams where each 3rd separatrix is filled with the ions. The square of the separatrix of the RF-2 is by 25 times larger of the longitudinal r.m.s. emittance of the bunch.
6. For suppression of the IBS one colling system will be constructed — namely, stochastic cooling system for longitudinal degree of freedom (the "filter method").

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

CONCLUSION

The main characteristics of NICA project, its status and principle problems related to the NICA creation are considered in this report. The NICA project as a whole has passed the phase of design and is presently in stage of accelerator elements manufacturing and construction.

The project realization plan foresees a staged construction and commissioning of the accelerators which form the facility.

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