Status of NICA Project

I. N. Meshkov[1, *]

[1] *Joint Institute for Nuclear Research, 141980 Dubna, Russia*

The project of Nuclotron-based Ion Collider fAcility NICA/MPD (+ MultiPurpose Detector) under development at JINR (Dubna) is presented. The general goals of the project are providing of colliding beams for experimental studies of both hot and dense strongly interacting baryonic matter and search for the mixed phase and critical endpoint and spin physics in collisions of polarized protons (deuterons). The first program requires providing of heavy ion collisions in the energy range of $\sqrt{s_{NN}} = 4$–11 GeV at average luminosity of $L = 1 \times 10^{27}$ cm^{-2} s^{-1} for $^{197}\mathrm{Au}^{79+}$. The polarized beams mode is proposed to be used in energy range of $\sqrt{s}$ =12–27 GeV (protons) at luminosity of $L \geq 1 \times 10^{30}$ cm^{-2} s^{-1} . The report contains description of the facility scheme and characteristics in heavy ion operation mode, status and plans of the project development.

1. NUCLOTRON-M & NICA PROJECT

The Nuclotron-based Ion Collider fAcility (NICA) is a new accelerator complex (Fig. 1) being constructed at JINR. It is aimed to provide collider experiments with

- heavy ions $^{197}\mathrm{Au}^{79+}$ at $\sqrt{s_{NN}} = 4$–11 GeV (1–4.5 GeV/u ion kinetic energy) at average luminosity of 1×10^{27} cm^{-2} 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 1×10^{30} cm^{-2} s^{-1}.

The proposed facility consists of the following elements (Fig. 1):

---

[*] Electronic address: `meshkov@jinr.ru`

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

- *"New" injector* (pos. 2, under construction): ESIS-type ion source that provides $^{197}\mathrm{Au}^{32+}$ ions of the intensity of 2×10^9 ions per pulse of about 7 μs duration at repetition rate up to 50 Hz and linear accelerator consisting of RFQ and RFQ Drift Tube Linac (RFQ DTL) sections. The linac accelerates the ions at $A/q \leq 8$ up to the energy of 6 MeV/u at efficiency not less than 80%.

- *Booster-synchrotron* housed inside Synchrophasotron yoke (pos. 3). The Booster (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 that allows to provide cooling of the ion beam in the energy range from injection energy up to 100 MeV/u. The maximum energy of $^{197}\mathrm{Au}^{32+}$ ions accelerated in the Booster is of 600 MeV/u. Stripping foil placed in the transfer line from the Booster to the Nuclotron allows to provide the stripping efficiency at the maximum Booster energy not less than 80%.

- *Nuclotron* — SC proton synchrotron (pos. 5) has maximum magnetic rigidity of 45 T·m and the circumference of 251.52 m provides the acceleration of completely stripped $^{197}\mathrm{Au}^{79+}$ ions up to the experiment energy in energy range of 1–4.5 GeV/u and protons up to maximum energy of 12.6 GeV.

- *Transfer line* (pos. 6) transports the particles from Nuclotron to Collider rings.

- *Two SC collider rings* (pos. 8) of racetrack shape have maximum magnetic rigidity of 45 T·m and the circumference of about 400 m. The maximum field of SC dipole magnets is 1.8 T. For luminosity preservation an electron and stochastic cooling systems will be constructed.

- *Two detectors* — MultiPurpose Detector (*MPD*, pos. 9) and Spin Physics Detector(*SPD*, pos. 10) are located in opposite straight sections of the racetrack rings.

- *Two transfer lines* transport particle beams extracted from Booster (pos. 11) and Nuclotron (pos. 12) to the new research area, where fixed target experiments both basic and applied character will be placed.

The NICA parameters (Table 1) allow us to reach the goals of the project formulated above.

One of NICA accelerators — Nuclotron is used presently for fixed target experiments on extracted beams (Fig. 1, pos. 7). This program is planned to be developed further and will be complementary to that one to be performed at Collider in heavy ions beam mode operation. The program includes experimental studies on relativistic nuclear physics, spin physics in few body nuclear systems (with polarized deuterons) and physics of flavours. At the same time, the Nuclotron beams are used for research in radiobiology and applied research.

2. COLLIDER LUMINOSITY

The collider design has to provide achievement of the project luminosity and its maintenance during a long time necessary for an experiment performance. That requires, correspondingly,

1) formation of ion beams of high intensity and sufficiently low emittance,
2) ion beam life time.

Beam intensity is limited, in principle, by beam space charge effects, which can be estimated by so called "tune shift criteria". First, and most strong of them usually, is so called betatron oscillation tune shift (or *"The Laslett tune shift"*):

$$\Delta Q = \frac{Z^2}{A}\frac{r_p\,N_i}{\beta^2\gamma^3\,4\pi\,\varepsilon_{\text{geom}}}\cdot k_{\text{bunch}}\,, \qquad k_{\text{bunch}} = \frac{C_{\text{Ring}}}{\sqrt{2\pi}\,\sigma_s}\,. \tag{1}$$

Here Ze and A are ion charge and mass number, r_p is proton classic radius, N_i is ion number per bunch in the bunched ion beam, β, γ are the ion Lorentz factors, k_{bunch} is bunch factor, C_{Ring} is the Collider ring circumference, σ_s is bunch length (σ – value for Gaussian beam). A special attention should be paid to ε parameter that is one-dimensional transverse emittance of the ion bunch (we consider the case of round beams). Eq. (1) is valid for so called "geometrical emittance" $\varepsilon_{\text{geom}} = \pi\,\langle x\rangle\,\langle x'\rangle$. Below we will use also "normalized emittance" $\varepsilon_{\text{norm}} = \beta\gamma\varepsilon_{\text{geom}}$ that is invariant of ion energy (if no beam distortion occurs at energy change).

Second criterion is so called beam-beam parameter that describes ion betatron tune shift related to scattering of ion on he electromagnetic field of encountering ion bunch:

$$\xi = \frac{Z^2}{A}\,\frac{r_p\,N_i(1+\beta^2)}{4\pi\,\gamma\,\beta^2\,\varepsilon_{\text{geom}}}\,. \tag{2}$$

For practical estimates one can use the numerical criterion for beam stability as follows:

$$\Delta Q_{\text{total}} \equiv \Delta Q + \xi \leq 0.05\,. \tag{3}$$

Then one can consider two cases of emittance dependence on ion energy:

$$1) \quad \varepsilon_{\text{geom}} = \text{const}, \qquad 2) \quad \varepsilon_{\text{norm}} = \beta\gamma\varepsilon_{\text{geom}} = \text{const}. \tag{4}$$

The first case corresponds to filling with ions the whole acceptance of the ring regardless of ion energy. The second one, more or less "idealistic", assumes $\varepsilon_{\text{geom}}$ variation with energy as $(\beta\gamma)^{-1}$. If criterion (3) is met one can express luminosity via ΔQ_{total}:

$$L = \beta^5\,\gamma^2\,\Delta Q_{\text{total}}^2\,\frac{A^2}{Z^4}\cdot\frac{4\pi\,\varepsilon_{\text{geom}}}{r_p^2\,\beta^*}\cdot\left(\frac{k_{\text{bunch}}}{\gamma^2}+1+\beta^2\right)^{-2}\cdot\frac{c\;n_{\text{bunch}}}{C_{\text{Ring}}}\cdot F_{\text{HG}}\,, \tag{5}$$

where β^* is betatron function value at interaction point (IP), F_{HG} is so called "hour-glass factor" accounting effect of beta-function variation at IP vicinity. Both cases (4) give us the luminosity dependence on ion central mass energy (CME), which coincide at low energy and differ by a few times at maximum energy of NICA collider (Fig. 2).

3. LUMINOSITY PRESERVATION

One of major problems of the NICA collider is suppression of intrabeam scattering (IBS) in intense ion bunches that defines mainly the beam life time. If ΔQ is fixed (as above) the beam life time limited by IBS is proportional to

$$\tau_{\text{IBS}} \propto \frac{A}{Z^2}\cdot\frac{\beta^2\gamma^2\,\varepsilon_{\text{geom}}\,(\Delta p/p)\,\sigma_s}{\Delta Q}\cdot f\left(\varepsilon_{\text{geom}},\sigma_s,\ \text{lattice functions}\right)\,. \tag{6}$$

A method of IBS increase is application of a "smooth" lattice of the collider ring. It was done during developing of the NICA collider lattice. Another and an efficient way of IBS suppression is use of beam cooling – stochastic and electron ones. As our analysis has shown, the problem can be resolved with application at the NICA collider stochastic cooling at the energy range of 2.5–4.5 GeV/u and electron cooling at 1.0–2.5 GeV/u. Both systems are under development in NICA project.

CONCLUSION

The main principle problems related to the NICA collider creation are considered in this report. Simultaneously other elements of the facility are under active development. The

NICA project as a whole has passed the phase of concept formulation and is presently under detailed simulation of accelerator elements parameters, development of the working project, manufacturing and construction of the prototypes, preparation of the project for state expertise in accordance with regulations of Russian Federation.

The project realization plan foresees a staged construction and commissioning of the accelerators that form the facility. The main goal is beginning of the facility commissioning in 2015.

Table 1. Parameters of NICA accelerators

	Booster	**Nuclotron**		**Collider**
Acceleration	*Project*	*Project*	*Status (Dec, 2010)*	
1. 1. Circumference, m	212.2	251.5		534
2. Max. magn. field, T	2.0	2.05	2.0	1.8
3. Magn. rigidity, T m	25.0	45	39.5	45
4. Cycle duration, s	4.0	4.0	5.0	≤3000
5. B-field ramp, T/s	1.0	1.0	1.0	<0.1
6. Accelerated/stored particles	$p \div \mathrm{Au}^{79+}$, $p\uparrow$, $d\uparrow$		$p{\div}\mathrm{Xe}$, $d\uparrow$	$p \div \mathrm{Au}^{79+}$, $p\uparrow$, $d\uparrow$
Maximum energy, GeV/u				
protons	—	12.6	—	12.6
deuterons	—	5.87	5.1	5.87
$^{197}\mathrm{Au}^{79+}$	0.6	4.5	1.0 ($^{238}\mathrm{Xe}^{24+}$)	4.5
Intensity, ion number per cycle (bunch)				
protons	$1. \cdot 10^{11}$	1×10^{11}	1×10^{11}	1×10^{11}
deuterons	1×10^{10}	1×10^{10}	1×10^{10}	1×10^{10}
$^{197}\mathrm{Au}^{79+}$	1×10^{9}	1×10^{9}	1×10^{6} (Xe^{24+})	1×10^{9}

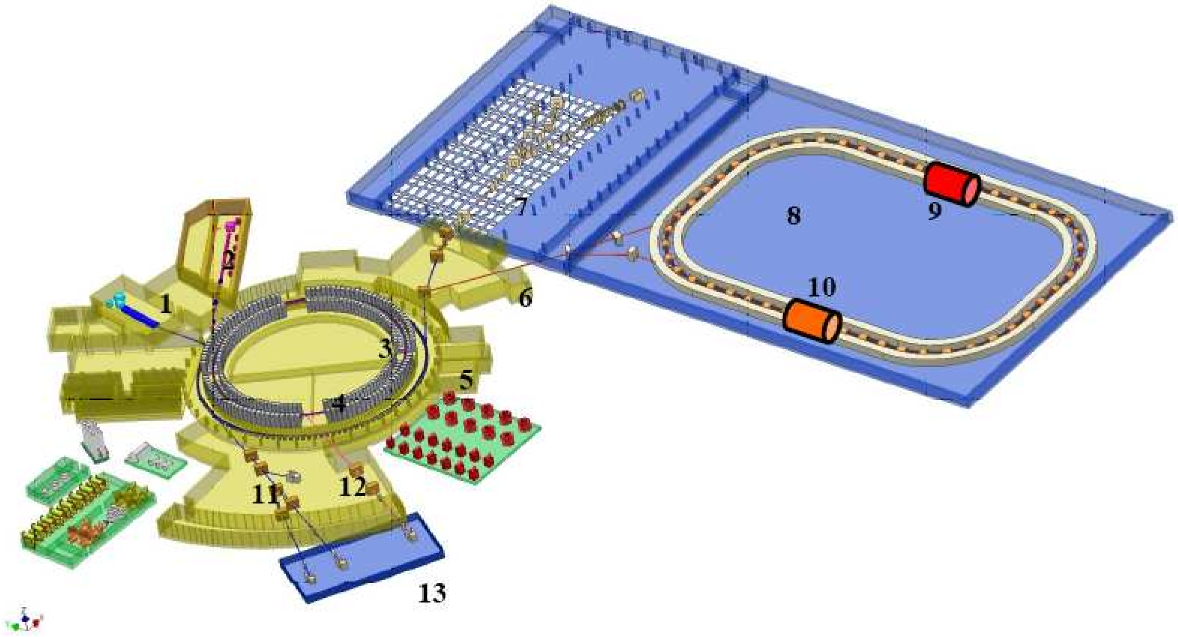

Figure 1. Scheme of NICA facility: 1 — light and polarized ion sources and “old” Alvarez-type linac; 2 — ESIS source and new RFQ linac; 3 — Synchrophasotron yoke; 4 — Booster; 5 — Nuclotron; 6 — beam transfer line; 7 — Nuclotron beam lines and fixed target experiments; 8 — Collider; 9 — MPD; 10 — SPD; 11, 12 — transfer channels; 13 — new research area.

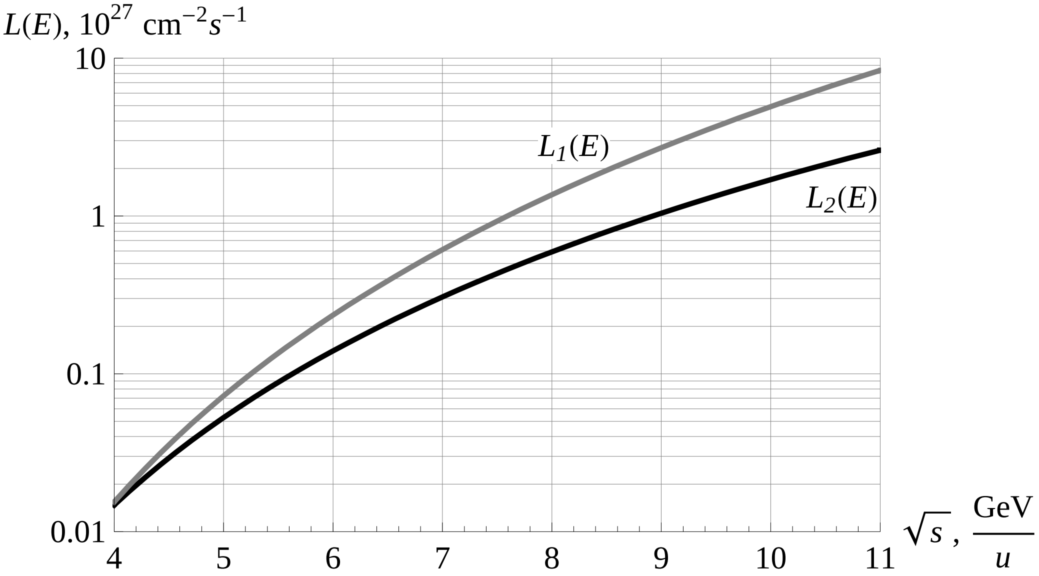

Figure 2. Luminosity of the NICA collider vs ion CME: $L_1(E) \approx \text{const}\, \beta^5\, \gamma^6$ if unnormalized ("geometrical") emittance is constant, $L_2(E) \approx \text{const}\, \beta^4\, \gamma^5$ if normalized emittance is constant.

FIGURE CAPTIONS

Fig.1: Scheme of NICA facility: 1 — light and polarized ion sources and “old” Alvarez-type linac; 2 — ESIS source and new RFQ linac; 3 — Synchrophasotron yoke; 4 — Booster; 5 — Nuclotron; 6 — beam transfer line; 7 — Nuclotron beam lines and fixed target experiments; 8 — Collider; 9 — MPD; 10 — SPD; 11, 12 — transfer channels; 13 — new research area.

Fig.2: Luminosity of the NICA collider vs ion CME: $L_1(E) \approx \mathrm{const}\,\beta^5\,\gamma^6$ if unnormalized (“geometrical”) emittance is constant, $L_2(E) \approx \mathrm{const}\,\beta^4\,\gamma^5$ if normalized emittance is constant.