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ФИЗИКА И ТЕХНИКА УСКОРИТЕЛЕЙ

NICA PROJECT AT JINR

V. Kekelidze, R. Lednický, V. Matveev, I. Meshkov, A. Sorin, G. Trubnikov

Joint Institute for Nuclear Research, Dubna

The project of the 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 spin physics (in collisions of polarized protons and deuterons). The first program requires providing of heavy-ion collisions in the energy range of $\sqrt{s_{NN}} = 4-11$ GeV [1] at average luminosity $L = 1 \cdot 10^{27}$ cm$^{-2}\cdot$ s^{-1} for ^{197}Au^{79+} nuclei. The polarized beams mode is proposed to be used in the energy range of $\sqrt{s_{NN}} = 12-27$ GeV (protons at luminosity $L \geqslant 1 \cdot 10^{30}$ cm$^{-2}\cdot$ s^{-1}. The key issue of the project is application of cooling methods — stochastic and electron ones. The report contains description of the facility scheme and characteristics in heavy ion operation mode, status and plans of the project development.

Представлен проект NICA/MPD, разрабатываемый в ОИЯИ (Дубна). Главная цель проекта — создание ускорительного комплекса для экспериментальных исследований на встречных пучках тяжелых ионов физики горячей и сильно сжатой барионной материи, а также физики спина в столкновениях поляризованных протонов и дейтронов. Первая программа требует создания коллайдера тяжелых ионов в диапазоне энергий $\sqrt{s_{NN}} = 4-11$ ГэВ со средней светимостью $L = 1 \cdot 10^{27}$ см$^{-2}\cdot$ с$^{-1}$ для ядра ^{197}Au^{79+}. Режим с поляризованными пучками предполагается использовать в диапазоне энергий $\sqrt{s_{NN}} = 12-27$ ГэВ (протоны со светимостью $L \geqslant 1 \cdot 10^{30}$ см$^{-2}\cdot$ с$^{-1}$). Осуществление первой программы возможно только при условии применения методов охлаждения — стохастического и электронного. Доклад содержит описание схемы установки и характеристик режимов работы в варианте тяжелоионного коллайдера, статус и планы по развитию проекта.

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NUCLOTRON-M & NICA PROJECT

The Nuclotron-based Ion Collider fAcility (NICA) [1] is a new accelerator complex (Fig. 1) being constructed at JINR. 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 an average luminosity of $1 \cdot 10^{27}$ 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 at $\sqrt{s_{NN}} = 4-13.8$ GeV ($2-5.9$ GeV/u ion kinetic energy) at an average luminosity of $\geqslant 1 \cdot 10^{30}$ cm$^{-2}\cdot$ s^{-1}.

[1] We remind $\sqrt{s_{NN}}$ is the ion total energy per nucleon («invariant mass») in ion center mass rest frame; for colliding beams of equal energy it coincides with laboratory reference frame.

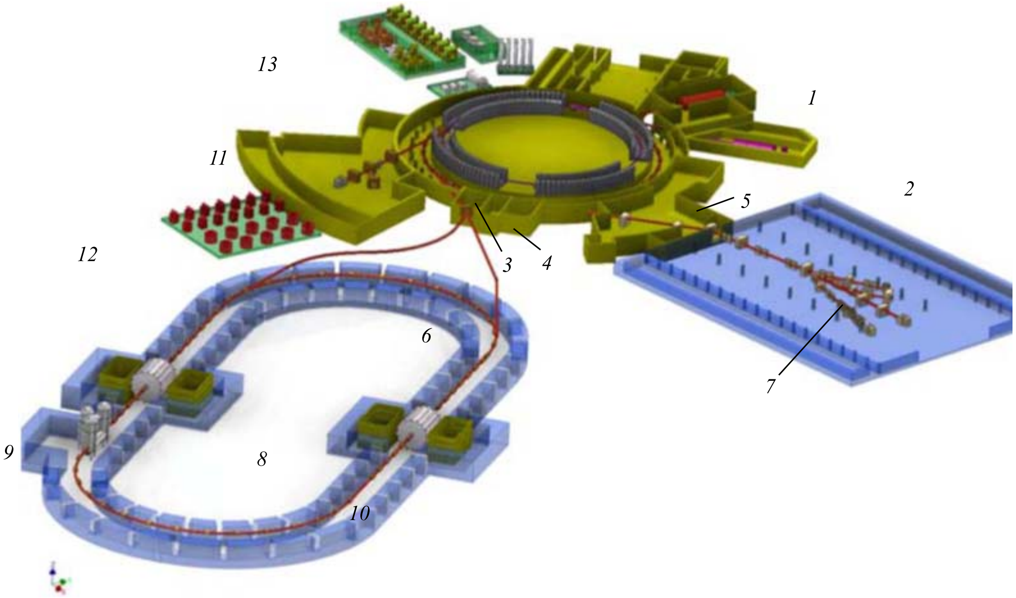

Fig. 1. Scheme of the NICA facility: *1* — light and polarized ion sources and «old» Alvarez-type linac; *2* — ESIS source and new RFQ linac; *3* — Synchrophasotron yoke; *4* — booster; *5* — Nuclotron; *6* — beam transfer lines; *7* — Nuclotron beam lines and fixed target experiments; *8* — collider; *9* — MPD; *10* — SPD; *11* — new research area; *12* — cryogenic plant; *13* — auxiliary equipment

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

— *«Old» injector* (*1*): a set of light ion sources including a source of polarized protons and deuterons and an Alvarez-type linac LU-20;

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

— *Booster-synchrotron* housed inside the Synchrophasotron yoke (*3*). The booster (*4*) has superconducting (SC) magnetic system that provides a maximum magnetic rigidity of 25 T $\cdot$ m at a ring circumference of 215 m. It is equipped with electron cooling system that allows cooling of the ion beam in the energy range from injection energy up to 100 MeV/u. The maximum energy of ^{197}Au^{32+} ions accelerated in the booster is 600 MeV/u. Stripping foil placed in the transfer line from the booster to the Nuclotron allows the stripping efficiency at the maximum booster energy not less than 80%.

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

— *Transfer line* (*6*) transports the particles from the Nuclotron to the collider rings.

— *Two SC collider rings* (*8*) of racetrack shape have a maximum magnetic rigidity of 45 T $\cdot$ m and a circumference of about 400 m. The maximum field of SC dipole magnets is 1.8 T. For luminosity preservation, electron and stochastic cooling systems will be constructed.

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

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

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

Parameters of NICA accelerators

Acceleration	Booster project	Nuclotron		Collider project
		Project	Status (April 2011)	
Circumference, m	212.2	251.5		503.0
Max. magn. field, T	2.0	2.0	2.0	1.8
Magn. rigidity, T · m	25.0	45	39.5	45
Cycle duration, s	4.0	4.02	5.0	$\geqslant 2000$
B-field ramp, T/s	1.0	1.0	1.0	< 0.1
Accelerated/stored particles	p–$^{197}Au^{79+}$, $p\uparrow, d\uparrow$, p–Xe, $d\uparrow$			p–$^{197}Au^{79+}$, $p\uparrow, d\uparrow$
Maximum energy, GeV/u				
Protons	—	12.6	—	12.6
Deuterons	—	5.87	5.1	5.87
Ions, GeV/u	$^{197}Au^{32+}$ 0.4	$^{197}Au^{79}$ 4.5	$^{54}Xe^{24+}$ 1.0	$^{197}Au^{79}$ 4.5
Intensity, ion number per cycle (bunch)				
Protons	$1 \cdot 10^{11}$	$1 \cdot 10^{11}$	$1 \cdot 10^{11}$	$1 \cdot 10^{11}$
Deuterons	$1 \cdot 10^{10}$	$1 \cdot 10^{10}$	$1 \cdot 10^{10}$	$1 \cdot 10^{10}$
$^{197}Au^{79}$	$2 \cdot 10^{9}$	$2 \cdot 10^{9}$	$1 \cdot 10^{6}$ ($^{54}Xe^{24+}$)	$1 \cdot 10^{9}$

One of the NICA accelerators, the Nuclotron, is used presently for fixed target experiments on extracted beams (Fig. 1, *7*).

This program is planned to be developed further and will be complementary to that one to be performed at the collider in heavy-ion 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.

COLLIDER LUMINOSITY AND COOLING ISSUES

The collider design has to provide 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 the so-called «tune shift criteria». *The first one*, and usually strongest of them, is the so-called betatron oscillation tune shift (or «The Laslett tune shift»):

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

Here Z 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; $k_{\rm bunch}$ is bunch factor; $C_{\rm ring}$ is the collider ring circumference; σ_s is bunch length (σ-value for Gaussian beam); $\varepsilon_{\rm geom}$ is the ion bunch «geometrical» transverse emittance (to distinguish it from «normalized» one $\varepsilon_{\rm norm}$ used below). *The second criterion* is the so-called *beam–beam parameter* that describes ion betatron tune shift related to ion scattering by the electromagnetic field of colliding ion bunch:

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

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

$$\Delta Q_{\rm tot} \equiv \Delta Q + n_\xi \xi \leqslant 0.05. \tag{3}$$

Here n_ξ is the number of interaction points.

One of instabilities and major problems of the NICA collider is suppression of intrabeam scattering (IBS) in intense ion bunches. The last one defines mainly the beam life time. For this purpose we have proposed to use both the electron cooling [2] and stochastic cooling [3] methods. In the first case we assume achievement of an equilibrium between cooling and space charge forces when space charge tune shift $\Delta Q_{\rm tot}$ reaches a resonant value (e.g., 0.05). We call it *space charge dominated regime* (SCD regime). Then using formulae (1), (2) and well-known expression for luminosity of round colliding beams, one can derive simple relations between parameters:

$$L \propto \Delta Q_{\rm tot}^2\, \varepsilon_{\rm geom}\, f_L(E_{\rm ion}) f_{\rm HG}, \quad N_i \propto \Delta Q_{\rm tot}\, \varepsilon_{\rm geom}\, f_N(E_{\rm ion}), \tag{4}$$

where E_i is ion energy, f_L, f_n are the functions describing energy dependence of parameters, $f_{\rm HG}$ is hour-glass effect function. We see that maximum luminosity is achieved if beam emittance $\varepsilon_{\rm geom}$ has maximum, i.e., coincides with the ring acceptance. At some circumstances the luminosity can be limited by «not the beam reasons» (e.g., detector performance). Then one can optimize the SCD regime decreasing equilibrium emittance and N_i (Fig. 2). Such an optimization can be done with variation of N_i number. In the case of limited luminosity one can also avoid SCD regime decreasing ion number and allowing, by weakening cooling force, the beam emittance keeping $\Delta Q_{\rm tot}$ below resonant value. We call it *IBS dominated regime* (IBS DR) when equilibrium state is provided with equality of IBS and cooling rates:

$$R_{\rm IBS} = R_{\rm cool}. \tag{5}$$

Then, at fixed luminosity, similar to formulae (4), one can write

$$L = {\rm const}, \quad N_i \propto \sqrt{L\varepsilon_{\rm geom}}\varphi_L(E_i), \quad \Delta Q_{\rm tot} \propto \sqrt{\frac{L}{\varepsilon_{\rm geom}}}\psi_L(E_i) < \Delta Q_{\rm max}. \tag{6}$$

As we see, minimum $\Delta Q_{\rm tot}$ corresponds to maximum emittance, i.e., full acceptance filling with ions. Simultaneously, it gives us maximum $\tau_{\rm IBS}$ at relatively increased ion number (Fig. 3). We should mention that at IBS DR ion number dependence of energy is rather weak — proportional to $(N_{\rm ion}/{\rm C})^{-1/2}$.

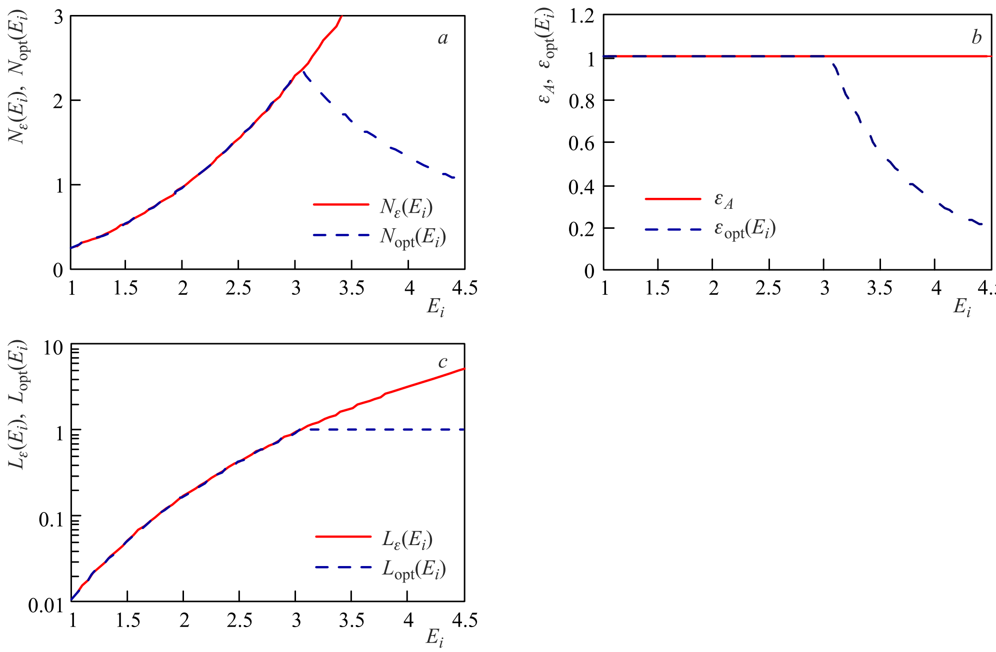

Fig. 2. Space charge dominated regime; ion number per bunch (*a*), emmitance (*b*) and luminosity (*c*) versus ion energy in two cases: full acceptance if filled with ions (red solid curve) and luminosity is limited (blue dashed curve); the ring acceptance = 40 $\pi\cdot$mm$\cdot$mrad, parameter units: $[N_i] = 10^9$, $[\varepsilon] = \pi\cdot$mm$\cdot$mrad, $[L] = 10^{27}$ cm$^{-2}\cdot$s^{-1}

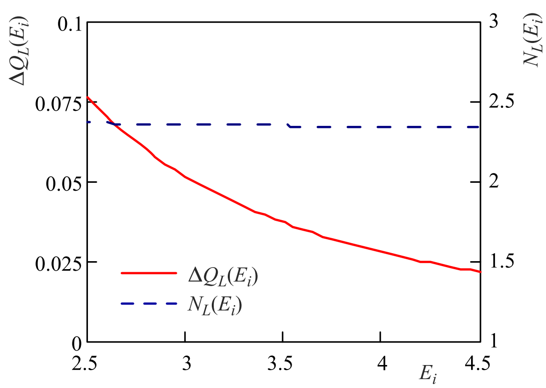

Fig. 3. IBS dominated regime; beam tune shift $\Delta Q_{\rm tot}$ (red solid curve) and ion number per bunch N_i (blue dashed curve) at constant luminosity $L = 1\cdot 10^{27}$ cm$^{-2}\cdot$s^{-1} and beam emittance of 1.0 $\pi\cdot$mm$\cdot$mrad; $[N_i] = 10^9$

For NICA parameters, as it follows from Fig. 3, IBS DR can be used at $E_i > 3$ GeV/u where $\Delta Q < 0.05$. At the same energy range we plan to use stochastic cooling. At lower energy, electron cooling application is preferable (if not to say more realizable) [2, 3]. However, then another problem appears: ion recombination with cooling electrons. This effect can be significantly diminished by increase of cooling electrons temperature [4].

The described approach (SC and IBS dominated regimes) can be developed even further. One can, for instance, increase luminosity in low energy range (below 3 GeV/u) by enlarging minimum beta functions in IP area. That will be followed by decrease of beta functions in the lenses of final focus and lead correspondingly to increase of the ring acceptance. Those steps are planned for future development.

CONCLUSION

The status main characteristics of the NICA project and principle problems related to the NICA collider creation are considered in this report. The NICA project as a whole has passed the phase of concept formulation, and the working project, manufacturing and construction of the prototypes are presently under development.

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 2017.

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