IL NUOVO CIMENTO **42 C** (2019) 58
DOI 10.1393/ncc/i2019-19058-1

Colloquia: EuNPC 2018

NICA project: Challenges for heavy ion collider

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received 5 February 2019

Summary. — The global scientific goal of the NICA/MPD (Nuclotron-based Ion Collider fAcility/Multy Purpose Detector) project realizing at JINR is to explore the phase diagram of strongly interacting matter in the region of high compression. The proposed program allows to search for possible signs of the phase transitions and critical phenomena in heavy ion (up to Au) collisions at centre-of-mass energies up to 11 GeV/u. The collider experiment provides optimum conditions for efficient measurements at energy scan. However, to reach required average luminosity of the order of 10^{27} cm$^{-2} \cdot$ s^{-1} is a complicated accelerator task. In difference to high energy collider the luminosity is limited by Lasslet tune shift mainly, the beam-beam parameter is almost negligible. A flexible procedure of the beam storage and short bunch formation is to be applied to provide maximum peak luminosity in a wide energy range. To suppress luminosity dilution due to intra-beam scattering (IBS) an application of beam cooling methods is mandatory. A solution of these and other problems is presented on example of the NICA collider design.

1. – Introduction

NICA [1] is an international project realizing by international intergovernmental organization – the Joint Institute for Nuclear Research and brings the efforts of 18 member states and 6 associated countries. In 2017 the project was included into ESFRI road map. NICA, a modern accelerator facility, will support world-leading programs in long base line fundamental, applied research and education. The project comprises experimental studies of fundamental character in the fields of the following directions:
- relativistic nuclear physics [2],
- spin physics in high and middle energy range of interacting particles,
- radiobiology.

Applied researches based on particle beams generated at NICA are dedicated to development of novel technologies in material science, environmental problems resolution, energy generation, particle beam therapy and others.

The NICA complex (Fig. 1) includes:

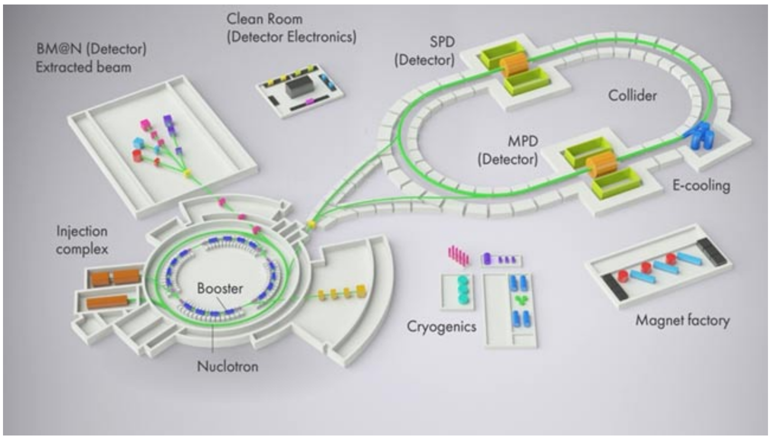

Fig. 1. – Sketch of the NICA complex.

- set of accelerators providing the particle beams for fixed target and collider experiments,
- experimental facilities,
- factory for superconducting magnet fabrication,
- workshops for construction of the detector elements,
- NICA innovation center,
- required infrastructure.

Main accelerator of the NICA complex is the Nuclotron (250 m long superconducting ion synchrotron at magnetic rigidity of about 42 $T{\cdot}m$) equipped with two injection chains: for heavy (including small superconducting synchrotron – the Booster) and for light ions. The collider experiments will be provided at two storage rings with two interaction points at zero beam crossing angle. The Collider ring has a racetrack shape and is based on double-aperture (top-to-bottom) superconducting magnets. Main experimental facilities are:

- Multi Purpose Detector (MPD) aiming to study of hot and dense strongly interacting matter in heavy ion (up to Au) collisions at the centre-of-mass energy range of max baryonic density (up to 11 GeV).
- Spin Physics Detector (SPD) aiming to study of spin physics with colliding beams of polarized deuterons and protons at the energies up to 27 GeV (for protons).
- Baryonic Matter at Nuclotron (BM@N) – fixed target experiment at the Nuclotron extracted beams which main goals are investigations of strange/multi-strange hyperon, hypernuclei production and short range correlations.

Peculiarity of a heavy ion collider operation at small ion kinetic energy is discussed in this article.

2. – Challenges for heavy ion collider

2˙1. *Luminosity of the Collider*. – In the frame of the NICA project the phase diagram of strongly interacting matter in the region of high compression will be explored in the collider experiment with MPD detector. General requirement to the collider is to provide optimum operation of the detector. MPD design presumes investigation of the collisions at zero beam crossing angle in the interaction point, the luminosity has to be concentrated inside vertex detector in the vicinity of the interaction point. For the vertex detector geometry it means that the collider has to be operated with a bunched beam at the root mean square bunch length σ_s not longer than 60 cm [3]. Only this case will be discussed below.

The peak luminosity is limited from the upper side by necessity to avoid overload the detector electronics. The maximum achievable event count rate $\dot{N}_{event}$ is limited by MPD electronics at the level of about 7 kHz. In the NICA energy region the reaction cross-section σ is about $7 \cdot 10^{-24}$ cm^2.

By definition the corresponding luminosity L is given by

$$L \le \dot{N}_{event}/\sigma, \tag{1}$$

that for our parameters corresponds to $L \le 10^{27}$ $cm^{-2} \cdot s^{-1}$. Such a level is typical for other heavy ion colliders: RHIC for $Au - Au$ collisions at maximum energy and LHC for $Pb - Pb$ collisions. However at the NICA the ion kinetic energy below 4.5 GeV/u is sufficiently smaller that leads to specific limitations for the collider parameters.

The collider working cycle has to be designed to provide a mean luminosity as close as possible to the peak one. Upper technical limit of the mean luminosity is determined by the ion production rate $\dot{N}_{pr}$ provided by the injection chain. During operation all produced ions are lost in accelerator or detector and for the loss rate we have $\dot{N}_{loss} = \dot{N}_{pr}$. Some part of the losses is related to the investigating reactions, another part to different parasitic processes: losses at injection into the collider, scattering with residual gas atoms and so on, thus $\dot{N}_{loss} = \dot{N}_{event} + \dot{N}_{other\ loss}$. As result the mean luminosity cannot exceed the following value

$$L \le \dot{N}_{pr}/\sigma. \tag{2}$$

This limit can be of great importance for experiments with exotic particles: antiprotons or radioactive ions. The NICA collider heavy ion injection chain is designed to provide 10^9 Au nuclei each 5 sec. That corresponds to the limitation of the mean luminosity at the level of about $3 \cdot 10^{31}$ $cm^{-2} \cdot s^{-1}$. Four orders of magnitude of the technical reserve permit to use the NICA injection chain for a few experiments in parallel that presumed by the experimental program. At large ion production rate the collider mean and peak luminosity is limited by particle dynamics. For identical round beams the peak luminosity is given by the following well known formula:

$$L = \frac{n_b N^2}{4\pi\epsilon\beta^* T_{rev}} f(x) \text{ here } f(x) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \frac{e^{-u^2} du}{1 + u^2 x^2} \text{ and } x = \frac{\sigma_s}{\beta^*}, \tag{3}$$

where T_{rev} is the ion revolution period in the collider; $f(x)$ is so called "hour-glass" factor related to the finite bunch length, all other parameters are discussed below; n_b is the number of bunches circulating in each collider ring. To reach maximum luminosity it has to be chosen as large as possible, but the inter-bunch distance is to be large enough to avoid parasitic collisions inside the detector. The beta function in the collision point β^* has to be as small as possible, but comparable with bunch length to avoid luminosity reduction due to "hour-glass" factor.

At high energies of the colliding beams (Tevatron, RHIC, LHC) the collider is used for the beam acceleration also. In this case a train of bunches (or a few trains) injecting into collider at minimum energy is prepared by the injection chain. That leads to obvious recommendation for the beam parameters to reach maximum luminosity:

- the bunch intensity N has to be as large as possible,

- the growth of the beam emittance ϵ has to be minimized in all elements of injection chain.

Both the recommendation can be combined together: to increase the luminosity one has to increase the bunch brightness N/ϵ at the exit of the injection chain.

2˙2. *Space charge effects at low energy.* – The bunch brightness is limited in the collider by two main space charge effects.

Repulsion between ions with the same sign of the electric charge leads to incoherent shift of the betatron oscillation frequency. Change of the betatron oscillation number Q is given by Laslett tune shift formula:

$$\Delta Q = -\frac{Z^2 r_p}{A}\frac{N}{4\pi\epsilon\beta^2\gamma^3}F_{SC}F_b \text{ here } F_b = \frac{C}{\sqrt{2\pi}\sigma_s}, \tag{4}$$

where A, Z – the ion atomic and charge numbers; r_p – proton classical radius; β and γ – relativistic parameters; F_{SC} – the image force correction factor depending on the vacuum chamber design and for estimations can be set to unity; F_b – bunching factor; C – the ring circumference.

Second space charge effect is usually characterized by so called beam-beam parameter (linear part of the tune shift due to fields of opposite bunch in the collision point) calculated in accordance with the following formula

$$\xi = \frac{Z^2 r_p}{A}\frac{N}{4\pi\epsilon\beta^2\gamma}\frac{1+\beta^2}{2}. \tag{5}$$

Acceptable displacement of the ring working point (don't leading to the particle loss or fast emittance growth) due to both these effects determines maximum achievable bunch brightness. If the injection chain cannot provide the limit value, the bunch brightness can be increased by beam cooling application in the collider, for instance stochastic cooling realized at RHIC.

The Lasslett tune shift fast decreases with increase of the beam energy (as γ^3, see formula (4)), because the magnetic field of the beam compensates electrical repulsion between the ions. The beam-beam parameter decreases with energy as γ (formula (5)), because the magnetic field of the opposite bunch leads to increase of the repulsion. As result at high energy (RHIC, LHC) the Lasslett tune shift is negligible and the luminosity is limited by beam-beam parameter. At low energy the beam-beam parameter and Laslett tune shift can be comparable (that is typical for RHIC operation during Beam Energy Scan program) or Laslett tune shift dominates (for the NICA parameters the beam-beam parameter is about one order of magnitude less than the Laslett tune shift). There is another important difference between these two effects: x does not depend on the ring circumference C and determined by number of collision point, while the Laslett tune shift is linearly proportional to C (via bunching factor in formula (4)).

At low energy when the Laslett tune shift dominates the beam brightness can be expressed from maximum achievable tune shift ΔQ that gives for the luminosity:

$$L = \frac{A}{Z^2 r_p}\frac{n_b N c}{\beta^*}\frac{\sqrt{2\pi}\sigma_s}{C^2}\gamma^3\beta^3 f(x)\,\Delta Q. \tag{6}$$

This formula permits to calculate maximum achievable peak luminosity in the case when the maximum bunch intensity is constant and determined by injection chain performance. To reach this maximum value the beam emittance must be varied with energy as follows:

$$\epsilon = \frac{Z^2 r_p}{A} \frac{N}{4\pi\beta^2\gamma^3\Delta Q} \frac{C}{\sqrt{2\pi}\sigma_s}, \tag{7}$$

that can be achieved at active formation of the beam phase volume only that can be provided by a beam cooling application.

A possibility to vary the bunch intensity with energy can give additional increase of the luminosity. In this case one can exclude the bunch intensity from the formula (8) and to obtain:

$$L = \left(\frac{A}{Z^2 r_p}\right)^2 \frac{\epsilon}{\beta^*} \frac{8\pi^2\sigma_s^2 c}{C^2 l_{bb}} \gamma^6 \beta^5 f(x) \Delta Q^2. \tag{8}$$

To have a mean luminosity close to this limiting value one needs to minimize processes leading to the luminosity dilution during experiment. Large bunch brightness at small energy leads to fast growth of the beam phase volume due to IBS process. In difference to a high energy collider the IBS is most important process. For instance at the NICA parameters the characteristic time of the emittance grows is below 30 *min*. To maximize this time the bunch parameters have to be provided near thermo-dynamical equilibrium between longitudinal and transverse degrees of freedom (to avoid fast relaxation). To suppress the IBS process a beam cooling during experiment is mandatory.

2˙3. *Requirements to low energy collider*. – Keeping most important parameters in the formula (8), one can conclude that the maximum peak luminosity is proportional to

$$L \propto \frac{\epsilon \Delta Q^2}{C^2}. \tag{9}$$

In difference to a high energy collider (when the beam-beam parameter is dominated) to reach maximum peak luminosity one needs to follow the recommendations:

- the bunch intensity should be varied with energy to provide required bunch brightness,
- the beam emittance has to be as large as possible (close to an acceptance limit),
- a beam cooling is mandatory during the bunch formation,
- the ring circumference has to be as small as possible,
- the working point has to be far from low order resonances to reach maximum tune shift.

The first recommendation leads to necessity of a preliminary beam storage and bunch formation. At the NICA collider the particle storage is provided in the longitudinal phase plane that leads to complicated structure of the RF system. The ring optic structure has to provide large dynamic aperture value to achieve a large beam emittance. At large emittance the RF system of the collider should provide large momentum spread of the bunch corresponding to minimum IBS grows rates. It complicates the RF system design and requires adequate chromaticity correction system to provide large acceptance on momentum deviation. An octupole correction system is necessary to control of the tune spread to achieve maximum ΔQ. Necessity of the beam cooling during storage, bunch

Table I. – *Parameters of the NICA collider for gold-gold collisions.*

Circumference of the ring, m		503.04	
Number of bunches		22	
Rms bunch length, m		0.6	
β-function in IP, m		0.35	
Betatron frequencies, Q_x/Q_y		9.44/9.44	
Natural chromaticity, Q'_x/Q'_y		-33/-28	
Acceptance, $\pi\ mm \cdot mrad$		40	
Momentum acceptance, $\Delta p/p$		± 0.01	
Energy of Au^{79+}, GeV/u	1	3	4.5
Number of ions per bunch	$2 \cdot 10^8$	$2.4 \cdot 10^9$	$2.3 \cdot 10^9$
Rms momentum spread, $\Delta p/p$	$0.55 \cdot 10^{-3}$	$1.15 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$
Rms emittance, $\pi\ mm \cdot mrad$	1.1/0.95	1.1/0.85	1.1/0.75
Luminosity, $cm^{-2} \cdot s^{-1}$	$0.6 \cdot 10^{25}$	$1 \cdot 10^{27}$	$1 \cdot 10^{27}$
IBS growth time, *sec*	160	460	1800

formation and experiment requires a development of a high energy electron cooling system and stochastic cooling of bunched beam. A compromise between these requirements and the minimization of collider circumference chosen during the NICA collider design is presented in the Table I [3] where the beam parameters and luminosity are given for three differnt ion kinetic energies.

3. – Outlook

NICA is a flagship project of JINR presently. It was started as a part of the JINR Roadmap for 2009-2016 described in the JINR 7-years Program and approved by Scientific Council of JINR and The Committee of Plenipotentiaries of JINR in 2009. In 2016 between Russian Federation government and JINR was signed a contract presuming additional funding of the NICA construction as an international mega-science facility. For the moment the modernization of the Nuclotron light ion injection chain was provided. New linear accelerator of the heavy ion injection chain was constructed and commissioned in 2016. All superconducting magnets for the Booster were fabricated at JINR, the Booster assembly is scheduled for 2018. Construction of the NICA collider building started in 2016 is in progress. First experiments at BM@N detector and radiobiology experiments in the frames of the NICA research program were performed in spring of 2018 with carbon, argon and krypton beams.

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