PROJECT OF THE NUCLOTRON-BASED ION COLLIDER FACILITY (NICA) AT JINR

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Abstract

The Nuclotron-based Ion Collider fAcility (NICA) is a new accelerator complex being constructed at JINR aimed to provide collider experiments with heavy ions up to uranium at maximum energy (center of mass) equal to $\sqrt{s} \sim 11$ GeV/u. It includes new 6.2 Mev/u linac, 440 MeV/u booster, upgraded SC synchrotron Nuclotron and collider consisting of two SC rings, which provide average luminosity of $10^{27}cm^{-2}s^{-1}$. The new facility will allow also an effective acceleration of light ions to the Nuclotron maximum energy and an increase of intensity of polarized deuteron beams up to the level above 10^{10} particles/cycle. Accelerator complex NICA is being built on the experience and technological developments at the Nuclotron facility and incorporates new technological concepts. The scheme of the facility, its operation scenario and beam dynamics are presented in the report.

INTRODUCTION

The proposal of heavy ion collider NICA is based on experience earned at the Joint Institute for Nuclear Research since 1971 when the first relativistic nuclear beams of the energy of 4.2 GeV/u were obtained at the Synchrophasotron - weak focusing 10 GeV proton synchrotron. Presently the JINR basic facility for high-energy physics research is represented by the synchrotron of 45 Tm of the magnetic rigidity – the Nuclotron [1], which replaced the Synchrophasotron. The new flagship of the JINR is the NICA/MPD project [2]. General goal of the project is to start in the coming 5-7 years experimental study of hot and dense strongly interacting QCD matter at the new JINR facility. This goal is proposed to reach by:

1) development of the existing Nuclotron accelerator facility as a basis for generation of intense beams over atomic mass range from protons to uranium and light polarized ions;
2) design and construction of heavy ion collider with maximum collision energy of $\sqrt{s} \sim 11$ GeV/u for heavy ions and mean luminosity of $10^{27}cm^{-2}s^{-1}$;
3) design and construction of Multi Purpose Detector (MPD).

The investigations are relevant to understanding of the evolution of the Early Universe after Big Bang, formation of neutron stars, and the physics of heavy ion collisions. The new JINR facility will make possible to study in-medium properties of hadrons and nuclear matter equation of state, including a search for possible signatures of deconfinement, phase transition and/or partial chiral symmetry restoration as well as the critical end point by careful scanning the excitation functions in beam energy and centrality. The beam energy of the NICA is very much lower than the region of the RHIC (BNL) and the LHC (CERN) but it is situated right on top of the region where the baryon density is expected to be the highest. In this energy range the system occupies a maximal space-time volume in a mixed quark-hadron phase (the phase of coexistence of hadron and quark-qluon matter). It is expected [3] that the energy region of NICA will allow analyzing the highest baryonic density under laboratory conditions. The conditions similar to NICA are expected to be reached at FAIR facility [4] when the synchrotron SIS 300 will be put into operation. Nevertheless, two different approaches — fixed target experiment CBM at FAIR and collider experiment MPD at NICA will allow one a wide variety of methods to be used in these studies. It is proposed that along with heavy ions NICA will provide proton and light ion beams including polarized beams. The possibility of asymmetric collisions, for example pA, is considered also, being a quite important as a reference point for comparison with heavy ion collision data. In future, as a next stage of the Project, the NICA keeps a possibility for electron-ion collisions.

STRUCTURE OF THE FACILITY

The NICA Conceptual Design Report was prepared and published in January 2008 [5]. The choice of an optimum facility structure and parameters was based on the following criteria:

- avoiding technical not-yet-tested solutions in order to provide technical design of the facility without a long R&D stage,
- maximum application of technologies developed in JINR and experience of the JINR personnel,
- optimal usage of the existing equipment and the existing buildings, where the facility has to be located,
- wide co-operation with JINR Member State institutions and active participation of Russian institutions,
- costs optimization in accordance with the JINR budget.

Accelerator complex NICA is being built using the experience and technological developments at the Nuclotron facility operated at JINR. The Veksler and Baldin Laboratory of High Energies (VB LHE) of JINR is a pioneer in design and construction of the world's first superferric synchrotron. The magnetic system of the accelerator is based on 2 T fast-pulsed electromagnets with iron yoke and superconducting coils made of hollow NbTi composite cable cooled with two-phase helium flow at 4.5 K. This accelerator named Nuclotron was built during 1987-1992. The Nuclotron ring of the 251.5 m circumference is mounted in the tunnel of 2.5 m x 3 m cross-section that in the past was a part of the Synchrophasotron infrastructure. After a required modernization (that has been started last year in the frame of the Nuclotron upgrade program [6]) the Nuclotron will be used as a key element of the NICA injection chain. To increase the Nuclotron ability for the heavy ion acceleration a new linac as injector and intermediate booster synchrotron will be designed and constructed. Two new superconducting storage rings are aimed to provide collider experiment with heavy ions like Au, Pb or U at kinetic energy up to 4.3 x 4.3 GeV/u.

The proposed facility (Fig. 1) consists of:

1. Electron string ion source (ESIS) developed at JINR that will provide U^{32+} ions at intensity of $2{\cdot}10^9$ ions per pulse of about 7 μs duration at repetition rate up to 50 Hz.
2. Injector based on linear accelerator consisting of RFQ and RFQ Drift Tube Linac (RFQ DTL) sections. The linac accelerates the ions at $A/q \leq 8$ to the energy of 6.2 MeV/u with efficiency not less than 80%. The accelerator will be designed and constructed in co-operation with IHEP (Protvino) on the basis of the long experience in the design, construction and exploitation of the RFQ structures.
3. Booster synchrotron, which has maximum magnetic rigidity of 25 Tm and the circumference of about 215 m. The Booster is equipped with an electron cooling system that allows to provide cooling of the ion beam in the energy range from the injection energy up to 100 MeV/u. The maximum energy of U^{32+} ions accelerated in the Booster is 440 MeV/u. The Booster magnetic system will be manufactured on the basis of the superferric magnet technology.
4. Stripping foil placed in the transfer line from the Booster to the Nuclotron allows one to achieve the stripping efficiency at the maximum Booster energy not less than 40%.
5. The Nuclotron accelerator having maximum magnetic rigidity of 45 Tm and the circumference of 251.52 m that provides the ion acceleration up to the energy of the experiment.
6. Two collider rings having a maximum magnetic rigidity of 45 Tm that is equal to the Nuclotron one. The maximum field of superconducting dipole magnets has to be about 4 T. For luminosity preservation an electron or stochastic cooling system is planned to be constructed.

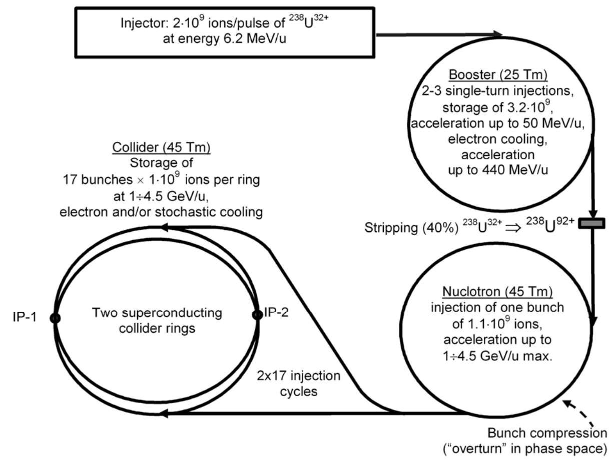

Fig. 1. Schematics of the NICA accelerator complex with parameters for U-U collisions.

The design of MPD detector is performed together with the accelerator complex R&D and the necessary upgrade of the infrastructure. Basic approach to the particle detector design and construction are published in the "MPD Letter of Intent." [7].

LUMINOSITY OF THE COLLIDER

The collider operation at luminosity of between 10^{26} and 10^{27} cm^{-2} s^{-1} allows to perform experiments which should measure all hadrons comprising multi-strange hyperons, their phase-space distributions and collective flows. This includes also event-by-event observables.

It is suggested to achieve the required luminosity level at the ion bunch intensity (10^9 ions per bunch) already used at RHIC in routine operation. The luminosity by two orders of magnitude larger than the luminosity in RHIC at low energy operation will be reached by means of the following peculiarities of the NICA design.

1. **Collider operation at low beta function in the interaction point.** This is possible due to a short interaction region (of about 10 m) that allows to have maximum beta functions in the triplets of about 90 m at the beta function of 0.5 m in the collision point. At such conditions the beam radius in the lenses of the low beta insertion section is about 4 cm that requires reasonable aperture of the lenses.
2. **Short bunch length.** The rms bunch length of about 30 cm makes possible to avoid "the hour glass effect" and to concentrate 80% of the luminosity inside the inner tracker of the detector.
3. **Collider operation at the beam emittance corresponding to the space charge limit.** In the NICA energy range the luminosity is limited by the incoherent tune shift value. If the ion number per bunch and the tune shift are fixed, the luminosity is scaled with the energy as $\beta^3\gamma^3$. The formation and preservation of low emittance value, corresponding to achievable tune shift, is produced by beam cooling application at the experiment energy.
4. **Large collision repetition rate.** The collider is operated at the bunch number of 10 ÷ 20 in each ring.

This is achieved at well established injection kicker parameters (the kicker pulse duration is about 100 ns) by means of injection into the collider of bunches of short length. The bunch of the required length is formed in the Nuclotron after the acceleration. Small longitudinal emittance value, required for the bunch compression in the Nuclotron, is provided by the electron cooling of the ion beam in the Booster.

5. **Long luminosity life-time.** For luminosity preservation the electron or stochastic cooling system will be used. In equilibrium between intrabeam scattering and the cooling, the luminosity life-time is limited mainly by the ion interaction with residual gas atoms. The vacuum conditions in the collider rings are chosen to provide the beam life time of a few hours. The beam preparation time is designed to be between 2 and 3 minutes. Therefore, the mean luminosity value is concentrated in the peak one.

The beam parameters and luminosity at the bunch intensity of 10^9 ions are listed in the Table 1 for two kinetic energy values – 1 and 4.3 GeV/u.

Table 1. NICA parameters for U-U collisions.

Circumference, m	250
Number of collision points	2
Beta function in the collision point, m	0.5
Rms momentum spread	0.001
Rms bunch length, m	0.3
Number of ions in the bunch	10^9
Number of bunches	17
Incoherent tune shift	0.05
Rms beam emittance, π mm mrad at 1 GeV/u at 4.3 GeV/u	 4.3 0.17
Luminosity per interaction point, $cm^{-2}s^{-1}$ at 1 GeV/u at 4.3 GeV/u	 $6\cdot10^{25}$ $1.7\cdot10^{27}$

During a technical design of the facility, the bunch parameters will be optimized depending on the experiment energy and ion specie. So, an increase of the bunch intensity allows one to increase the luminosity at the same value of the tune shift. To keep the constant tune shift the beam emittance has to be increased proportionally to the bunch intensity and the luminosity is scaled linearly with the ion number.

PLANS FOR REALIZATION

The proposed timetable of the NICA design and construction are the following:

• **Stage 1: years 2007-2009**

– R&D works on development of heavy ion source of ESIS-type.

- Upgrade of the Nuclotron facility.
- R&D works.

– Preparation of the Technical Design Report.

– Prototyping of the NICA elements.

- Design and construction of the injector.
- Disassembling of the Synchrophasotron magnet coils.
- Beginning of civil construction

• **Stage 2: years 2010-2011**

- Construction of operational ion source and achievement of the specified parameters.

– Completion of the injector fabrication.

- Construction of the Booster.
- Fabrication of the superconducting magnets for the Collider rings.
- Completion of civil construction.

• **Stage 3: years 2011-2012**

– Assembling of the injector, the Booster and the Collider rings.

• **Stage 4: year 2013**

– Commissioning of the NICA.

Technical design and construction of the injector will be done in co-operation with IHEP (Protvino) [8]. Design and construction of RF systems for the NICA rings and the Booster electron cooling system will be provided in co-operation with BINP (Novosibirsk). Design and construction of the superconducting magnetic system of the collider will be performed in collaboration with IHEP and Budker INP. High energy electron cooling system for collider will be designed and constructed in collaboration with Budker INP and FZ Juelich.

Participation of other scientific centers in the design and construction of the NICA elements is under negotiation now.

REFERENCES

[1] A.A.Smirnov, A.D.Kovalenko, “Nuclotron superconducting accelerator of nuclei at LHE JINR (Creation, Operation, Development)” Particles and Nuclei, Letters, 2004, v.1, №6 (123), p.11-40,

[2] A.N.Sissakian et al., “The Project NICA/MPD at JINR: Search for the Mixed Phase of Strongly Interacting Matter at Nuclotron-based Ion Collider fAcility” XXIII Int. Symp. on Lepton and Photon Inter. at High Energy, LP07, Daegu, Korea. (2007).

[3] A.N. Sissakian, A.S. Sorin, V.D. Toneev, In ”High Energy Physics IHEP’06”, Proc.of the 33-rd Int. Conf., Moscow, 2006, ed. by A. Sissakian et al., JINR, Russua, Vol.1, p.421; arXiv: nucl-th/0608032.

[4] P. Senger, J. Phys G30, 1087 (2004). FAIR Baseline Technical Report, Eds. H.H. Gutbtod, I. Augustin, H. Eickhoff, K.-D. Gross, W.F. Henning, D.Krämer, G. Wolter, V.1, GSI, 2006.

[5] NICA Conceptual Design Report, http://www.jinr.ru/

[6] A.Butenko et al., “Status of the Nuclotron. “Nuclotron-M” project”, These Proceedings.

[7] MPD Letter of Intent, http://www.jinr/ru/.

[8] O.Belyaev, V.Kobets, et al., “Heavy ion injector for NICA/MPD project”, These Proceedings.