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

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Abstract

The Nuclotron-based Ion Collider fAcility (NICA) is the 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 9 GeV/u. It includes new 6 Mev/u linac, 440 MeV/u booster, upgraded SC synchrotron Nuclotron and collider consisting of two SC rings, which provide average luminosity of $10^{27}cm^{-2}s^{-1}$. General goal of the project is to start in the coming 5-7 years experimental study of hot and dense strongly interacting QCD matter and search for possible manifestation of signs of the mixed phase and critical endpoint in heavy ion collisions. The NICA and the Multi Purpose Detector (MPD) are proposed for these purposes. Accelerator complex NICA is being built on the experience and technological developments at the Nuclotron facility and incorporates new technological concepts. 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. The scheme of the facility, its operation scenario and beam dynamics are presented in the report.

INTRODUCTION

The JINR basic facility for high-energy physics research is represented by the 6 AGeV Nuclotron [1] which has replaced the old weak focusing 10 GeV proton accelerator Synchrophasotron. The first relativistic nuclear beams with an energy of 4.2 AGeV were obtained at the Synchrophasotron in 1971. Since that time the study of relativistic heavy ion physics problems has been one of the main directions of the JINR research program. The new flagship of the Joint Institute for Nuclear Research is the NICA/MPD project [2]. The main goal of the project is to start in the coming years experimental study of hot and dense strongly interacting matter at the new JINR facility. This goal is proposed to be reached 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 (NICA) with maximum collision energy of 9GeV and averaged luminosity of $10^{27}cm^{-2}s^{-1}$. 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 it possible to study in-medium properties of hadrons and nuclear matter equation of state, including a search for possible signatures of deconfinement and/or chiral symmetry restoration phase transitions and critical endpoint by means of careful scanning in beam energy and centrality of excitation functions. The beam energy of the NICA is very much lower than the region of the RHIC (BNL) and the LHC (CERN) but it sits 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 the 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 reproduced at FAIR facility [4] after put the synchrotron SIS300 into operation, nevertheless, two different approaches — fixed target experiment CBM at FAIR and collider experiment MPD at NICA will allow 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. Alongside of proper physics meaning, it is 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]. Accelerator complex NICA is being built on 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 synchrotron based on low-field electromagnets with iron yoke and superconducting coils ("superferric magnets"). This accelerator named Nuclotron was built during 1987-1992. The main equipment of its magnetic system, and many other systems as well, was fabricated by the machinery workshops of JINR and LHE without invoking of specialized industry. The Nuclotron ring of 251.5 m in perimeter is mounted in the tunnel of cross-section of 2.5m x 3 m that was in the past a part of the Synchrophasotron infrastructure. After required modernization (that has been started last year in the frame of the Nuclotron upgrade program) 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 booster synchrotron will be designed and constructed. The booster magnetic system will be manufactured on the basis of the superferric magnets technology.

For the highly charged heavy ion generation the electron string ion source will be used. It has been developed in JINR during recent years. Such type the source "KRION-2" provides heavy ions for the operation of the Nuclotron facility. Highly charged heavy ions are produced in the electron string – new-discovered at JINR steady state of hot pure electron plasma, which provides excellent conditions for ion confinement and production of highly charged states. Ionization in the electron strings is produced by electron-ion impacts. The electron string is formed in the magnetic field of 1.2 ÷ 3.3 T. Electrons from an electron gun have energy in the range of 2 ÷ 6 keV. Traveling in the magnetic field they reach "the reflector" and return to the gun, reflect there again, and so bounce between the gun cathode and reflector forming "the string". Such a bouncing electron cloud produces the ionization of stored ions very efficiently.

Two new superconducting storage rings equipped with electron or stochastic cooling systems are aimed to provide collider experiment with heavy ions like Au, Pb or U at energy up to 3.5 x 3.5 GeV/u. The maximum magnetic rigidity of the collider rings is chosen to be equal to the Nuclotron one in order to have a possibility to increase center-of-mass energy of the heavy ion collisions up to about $\sqrt{s}$ = 11 GeV/u at the next stage of the project realization.

The proposed facility (Fig. 1) consists of:

1. ESIS-type ion source that provides 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 on the basis of linear accelerator consisting of RFQ and RFQ Drift Tube Linac (RFQ DTL) sections. The linac accelerates the ions at A/q ≤ 8 to the energy of 6 MeV/u at efficiency not less than 80%.
3. Booster synchrotron, which has maximum magnetic rigidity of 25 Tm and the circumference of about 215 m. The Booster 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 U^{32+} ions accelerated in the Booster is 440 MeV/u.
4. 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 40%.
5. The Nuclotron accelerator having maximum magnetic rigidity of 45 Tm and the circumference of 251.52 m provides the ion acceleration to the experiment energy.
6. Two collider rings with maximum magnetic rigidity of 45 Tm and the circumference of about 225 m. The maximum field of superconducting dipole magnets is about 5 T. For luminosity preservation an electron or stochastic cooling system is planned to be constructed.

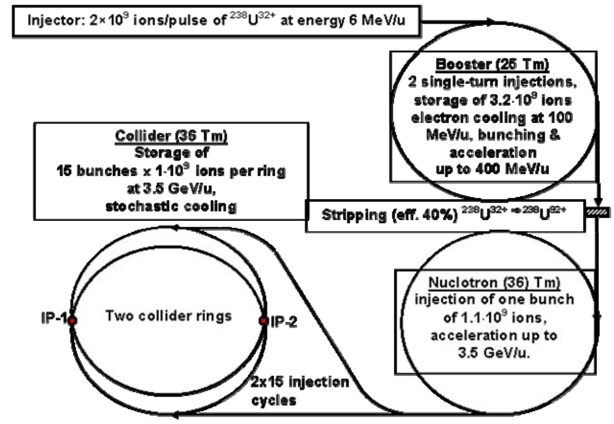

Fig. 1. Schematics of the NICA accelerator complex with parameters for U-U collisions.

The design of MPD detector is performed simultaneously 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." [6].

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 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 $\beta^2\gamma^3$. 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 is used. In equilibrium between intrabeam scattering and the cooling the luminosity life-time is limited mainly by the ion interaction with the 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 closed to the peak one.

The beam parameters and luminosity at the bunch intensity of 10^9 ions are listed in the Table 1.

Table 1. NICA parameters for U-U collisions.

Circumference, m	225
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	15
Incoherent tune shift	0.05
Rms beam emittance (unnormolized), π mm mrad at 1 GeV/u at 3.5 GeV/u	 3.8 0.26
Luminosity per one interaction point, $cm^{-2}s^{-1}$ at 1 GeV/u at 3.5 GeV/u	 $6.6 \cdot 10^{25}$ $1.1 \cdot 10^{27}$

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 increasing 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 2010-2012**

- 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 2011-2013**

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

• **Stage 4: year 2014**

– Commissioning of the NICA.

Technical design and construction of the injector will be done in co-operation with IHEP (Protvino). 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 BINP. High energy electron cooling system for collider will be designed and constructed in collaboration with BINP and FZ Juelich.

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

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