ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOPT001

NICA ION COLLIDER AND PLANS OF ITS FIRST OPERATIONS

E .Syresin†, O. Brovko, A. Butenko, A. Galimov, E. Gorbachev, V. Kekelidze, H. Khodzhibagiyan, S. Kostromin, V. Lebedev, I. Meshkov, A. Philippov, A. Sidorin, G. Trubnikov, A. Tuzikov
Joint Institute for Nuclear Research, Dubna, Russia

Abstract

The Nuclotron-based Ion Collider fAcility (NICA) is in assembling phase at JINR. The NICA goal is to provide colliding beams for studies of hot and dense strongly interacting baryonic matter and spin physics. The heavy ion injection complex of the NICA Collider consists of the following accelerators: a 3.2 MeV/u new heavy ion linac (HILAC) with RFQ and IH DTL sections, a new 600 MeV/u superconducting Booster synchrotron, and the upgraded Nuclotron - 3.9 GeV/n superconducting synchrotron. The heavy ion injection complex started operations with the first ion beams in beginning of 2022. Assembling of two Collider storage rings with two interaction points began in December 2021. The status of the NICA accelerator complex and plans for its first operation is discussed in the paper.

TWO STAGES OF NICA PROJECT

The NICA accelerator complex [1,2] is under assembling at JINR. Its commissioning is expected to start in 2023. The first phase of NICA experiments will be aimed on research of the mixed phase of baryonic matter, and the second phase - on the nature of the nucleon/particle spin. The NICA accelerator complex will operate in two modes: the Nuclotron ion beams extracted to a fixed target, and support of colliding ion beams in the Collider. The main elements of the NICA complex are the injection complex, the beam transfer lines and the Collider. The injection complex includes a set of ion sources, two linear accelerators, a new superconducting Booster and the superconducting upgraded synchrotron – Nuclotron. The Collider consists of two superconducting rings with two interaction points, which contain two detectors: the Multi-Purpose Detector and the Spin Physics Detector.

The project NICA will be performed in two stages. The stage I was complete at the end of March 2022. It involved construction and operation of the new heavy ion injection complex and the first fixed target experiments carried out in the Baryonic Matter at Nuclotron (BM@N) detector. The stage IIa is under implementation now. The construction of basic Collider systems is mainly finished, and the mounting of the Collider equipment for the basic configuration is started. The first colliding beam experiments are planned for the end of 2023. The stage IIb is related to formation of colliding beams with the design luminosity at operation of RF-3 cavities and the electron cooling system at the end of 2024.

HEAVY ION INJECTION COMPLEX

The heavy ion linac HILAC constructed by the JINR-Bevatech collaboration has been operating since 2016. The efficiency of beam transport through the second and third IH sections is ~78%. The maximum ion beam current at the HILAC entrance during the first Booster runs corresponded to the design value of 10 mA. The current of 4 mA obtained at the HILAC exit is 3 times larger than the design value. The $^{4}He^{1+}$, $^{12}C^{4+}$ and $^{56}Fe^{14+}$ ions produced in the plasma and the laser ion sources were accelerated in HILAC and then injected into the Booster.

For the collider program the main project goal for the injection complex [1-3] (Fig.1) is accumulation of $2\cdot10^9$ $^{209}Bi^{35+}$ ions in the Booster with subsequent acceleration of heavy ions up to the energy of 578 MeV/n required for effective stripping which happens in Booster-to-Nuclotron transfers. Additionally, the electron cooling at 65 MeV/n helps to form the required beam emittances. The 211 m long Booster is located inside the yoke of the Synchrophasotron dipoles. All Booster dipoles and quadrupoles were fabricated and tested at JINR.

Figure 1: Booster ring inside Synchrophasotron yoke.

The first Booster run was carried out in November-December 2020. After the orbit correction and tuning of the injection system the intensity of the circulating $^{4}He^{1+}$ beam grew up to 7×10^{10} ions. The total charge of these ions in the beam is equal to the design charge of the beam required for the Collider: 2×10^9 $^{209}Bi^{35+}$ ions.

During the first three runs the $^{4}He^{1+}$, $^{56}Fe^{14+}$ and $^{12}C^{4+}$ beams with the intensities of up to 4×10^{10}, 2.5×10^8 and 2×10^9, respectively, were accelerated in the Booster.

The following main results of the second Booster run with $^{56}Fe^{14+}$ ion beams (Fig.2) were achieved: the beam injection efficiency with adiabatic capture at the 5th harmonic higher than 95%; acceleration up to the energy of 65 MeV/u with the efficiency of recapturing from the 1st to the 5th harmonic close to 100%; acceleration up to the energy of 578 MeV/u with dB/dt = 1.2 T/s; vacuum ion

†esyresin@jinr.ru

13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand JACoW Publishing
ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOPT001

lifetime about 10 s at the beam energy of 3.2 MeV/n, which corresponds to the equivalent residual gas pressure of about 5×10^{-9} Pa; electron cooling of ions at the energy of 3.2 MeV/n; the beam extraction to the Booster-Nuclotron transfer line with subsequent beam stripping and transport to Nuclotron with the total transfer efficiency of 75%.

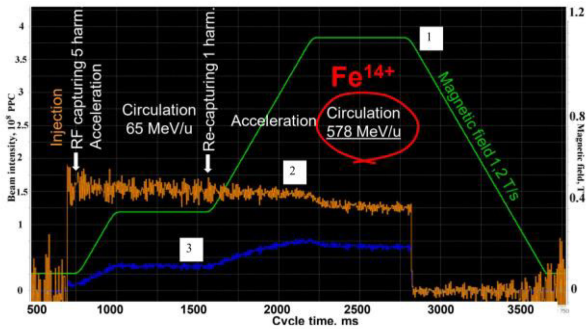

Figure 2: Dependence on time for: 1 -magnetic field, 2 – number of circulated $^{56}Fe^{14+}$ions, 3 – beam current parametric transformer signal.

The cryomagnetic and power supply systems were tested with the design magnetic cycle. The cycle has three plateaus: injection, electron cooling and beam extraction. The achieved magnetic field ramping rate of 1.2 T/s corresponds to the design value. The achieved maximum magnetic field of 1.8 T also corresponds to the design value.

The electron cooling of $^{56}Fe^{14+}$ ions was first performed during the second Booster run. The FWHM relative momentum spread of uncooled beam was equal to $1.2\cdot10^{-3}$. The FWHM relative momentum spread of cooled ions was 4×10^{-4} (Fig. 3).

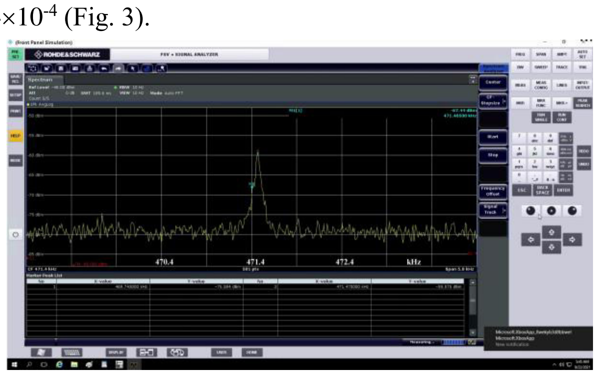

Figure 3: Schottky noise signal at 4th harmonic of revolution frequency and $^{56}Fe^{14+}$ ion energy 3.2 MeV/u.

Formation of cooled ion beams in the Booster with small transverse and longitudinal emittances is one of the crucial tasks to be resolved to achieve the design Collider luminosity.

The Nuclotron [4] accelerates protons, polarized deuterons and heavy ions to a maximum energy depending on the sort of particles. The maximum light ion energy corresponds to 5.2 GeV/n at the magnetic rigidity of 38.5 T m.

The kicker and the Lambertson septum magnet of the beam injection system were installed in the Nuclotron in December 2021. The first beam acceleration in Booster-Nuclotron chain was performed during the January-March 2022 run with carbon ion beams slow extracted from the Nuclotron. The intensity of the circulated $^{12}C^{4+}$ ion beam in Booster is equal to 3×10^{9} particles. The $^{12}C^{4+}$ ions were accelerated in the Booster up to the energy of 263 MeV/n and then extracted, fully stripped and directed to the new Booster-Nuclotron transfer line. Next the ions were injected to Nuclotron and accelerated up to the energy of 2.8 GeV/n. Finally, the ions were extracted with slow extraction and directed to the fixed target of the Short-Range Correlation (SRC) experiment (Fig.4) which studied collisions of $^{12}C^{6+}$ nuclei with the hydrogen target in BM@N. The next Booster-Nuclotron beam run is planned for September 2022 with $^{40}Ar^{16+}$ and $^{83}Kr^{26+}$ ion beams.

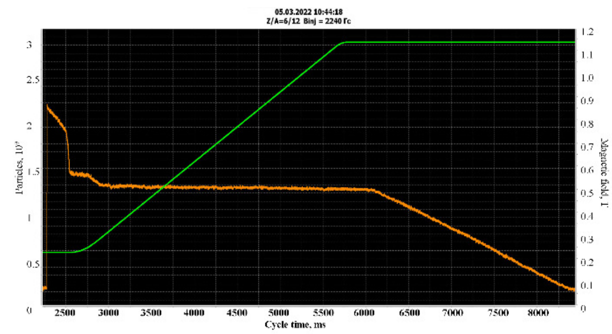

Figure 4: Dependences of Nuclotron ion beam current transformer signal (orange) and dipole field (green) on time after injection $^{12}C^{6+}$ beam from Booster; the injection plateau, acceleration and slow extraction are shown.

The first Collider beam run is planned with $^{209}Bi^{83}$ ions. The KRION-6T ion source should provide a $^{209}Bi^{35+}$ ion beam with the intensity of 5×10^{8} ppp. The present transfer efficiency at acceleration from the ion source to the Nuclotron exit is about 25%. During 2022-2023 Booster-Nuclotron runs, we plan to increase this efficiency to above 40%.

COLLIDER

The Collider [1-2,5] consists of two storage rings with two interaction points (IPs). Its main parameters are as follows: the magnetic rigidity is up to 45 T·m; the residual gas pressure in the beam chamber is below 10^{-8} Pa; the maximum field in the dipole magnets is 1.8 T; the kinetic energy of bismuth nuclei ranges from 1 to 4.5 GeV/n; the head-on collisions; and the luminosity at maximal energy is 10^{27} $cm^{-2}\,s^{-1}$. The Collider rings are identical with vertical beam separation and shape of racetrack (two 109 m straight sections connected by two arcs; straight sections are separated by 79.84 m). The circumference of each ring is 503.04 m.

An installation of the NICA dipoles started in December 2021 (Fig. 5). The initial configuration does not include the RF-3 system with 16 RF cavities and the electron cooling system. Two RF-1 and eight RF-2 cavities of the radio-frequency system will be used for ion accumulation and bunching in this initial configuration [1,5]. Accumulation of the beam is planned to be carried out in the longitudinal phase space using the barrier backet RF-1. The bunching in each Collider ring will be performed by RF-2 cavities having the maximum accelerating voltage of 100 kV in

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOPT001

each ring. It is planned to complete the installation in the summer of 2023 with subsequent start of the first technological run without beam to test cryogenics, SC magnets, power supplies, vacuum, controls and other systems.

Figure 5: Installation of magnets in NICA tunnel.

The first run with colliding $^{209}Bi^{83+}$ ion beams is planned to start at the end of 2023 with beam energy of 1-2 GeV/n. The intensity of the ion beam injected into each Collider ring is estimated to be 2×10^8 ppp. A single bunch injected from the Nuclotron can be captured directly into the RF-2 bucket with rms length of 2.5 – 1.8 m. The luminosity in this mode corresponds to $(1-2)\times10^{24}$ cm^{-2} s^{-1} (Fig.6).

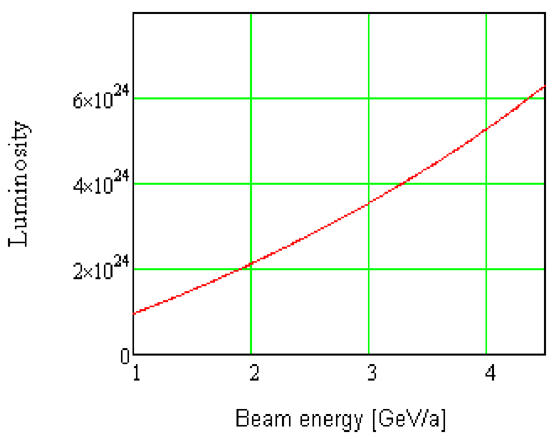

Figure 6: Dependence of luminosity with single bunch collisions on the ion energy.

During the first Collider run we plan to use the RF-1 barrier voltage for ion accumulation. The number of ion injections from the Nuclotron to the Collider ring is governed by the longitudinal emittance set by the Booster electron cooling and the longitudinal acceptance of the RF-1 barriers. The Collider electron cooling system will not operate during the first beam run, and the number of Nuclotron injections is estimated up to ~25 before filling the RF-1 barrier acceptance. The number of ions per bunch in RF-2 bunching is about $2\cdot10^8$. The luminosity of colliding ion beams at the ion energy of 1 – 2 GeV/n is expected to be 5×10^{24} – 2×10^{25} cm^{-2} s^{-1} (Fig.7). This luminosity is quite close to the design value for stage IIa of the NICA project.

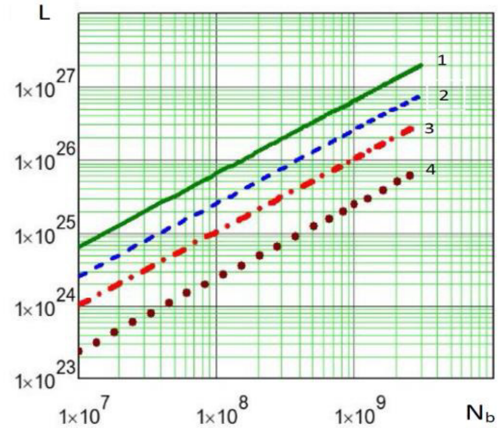

Figure 7: Dependence of luminosity on number particles per bunch at different ion energies: (1) 4.5 GeV/u, (2) 3 GeV/u, (3) 2 GeV/u, (4) 1 GeV/u.

Operation of 16 RF-3 cavities and the 2.5 MeV electron cooling system is planned to start at the end of 2024 within the stage IIb of NICA project. In this run the beam energy will be increased to its design value of 4.5 GeV/n. The use of electron cooling and the RF-3 system should yield the dense and short ion bunches enabling an achievement of the design luminosity of 10^{27} cm^{-2} s^{-1}.

CONCLUSION

Operation of the NICA Collider injection chain is confirmed by three successful beam runs with different ion types. The construction of the NICA Collider is at its final stage. The first experiments with colliding beams are planned for late 2023.

REFERENCES

[1] Technical Project of NICA Acceleration Complex, Dubna, 2015.

[2] V. D. Kekelidze R. Lednicky, V. A. Matveev *et al.*, "Three stages of the NICA accelerator complex", *Eur. Phys. J. A*, vol. 52, no. 211, p. 390, 2016. doi:10.1088/1742-6596/668/1/012023

[3] A. Butenko, N. Agapov, A. Alfeev *et al.*, "First Experiments with Accelerated Ion Beams in the Booster of NICA Accelerator Complex", *in Proc. 12th Int. Particle Accelerator Conf. (IPAC'21)*, Campinas, Brazil, May 2021, pp.123-125. doi:10.18429/JACoW-IPAC2021-MOPAB025

[4] E. M. Syresin, N. N. Agapov, A. V. Alfeev *et al.*, "Nuclotron Development for NICA Acceleration Complex", in *Proc. IPAC 19*, Melbourne, Australia, May 2019, paper THXXPLM1, pp. 3396-3398. doi:10.18429/JACoW-IPAC2019-THXXPLM1

[5] E. Syresin, O. Brovko, A. Butenko *et al.*, "Status of Accelerator Complex NICA", in *Proc. 26th Russian Particle Accelerator Conf. (RuPAC'18)*, Protvino, Russia, Oct. 2018, pp. 12-16. doi:10.18429/JACoW-RUPAC2018-MOXMH03