ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPMP014

NICA ACCELERATOR COMPLEX AT JINR

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Abstract

The status of the NICA accelerator complex which is under construction at JINR (Dubna, Russia), is presented. The main goal of the project is to provide ion beams for experimental studies of hot and dense baryonic matter and spin physics. The NICA collider will provide heavy ion collisions in the energy range of $\sqrt{s_{NN}}=4\div11$ GeV at the the average luminosity of $L=1\times10^{27}cm^{-2}\cdot s^{-1}$ for $^{197}Au^{79+}$ nuclei and polarized proton collisions in the energy range of $\sqrt{s_{NN}}=12\div27$ GeV at the luminosity $L \geq 10^{31}cm^{-2}\cdot s^{-1}$. The NICA accelerator complex will consist of two injector chains, a 578 MeV/u superconducting (SC) Booster synchrotron, the existing SC synchrotron (Nuclotron), and a new SC collider that has two storage rings with the circumference of 503 m. Construction of the facility is based on the Nuclotron technology of SC magnets with an iron yoke. A hollow SC cable cooled by two-phase He flux is used for operation with 10 kA currents and 1Hz cycling rate. Both stochastic and electron cooling methods are used for the beam accumulation and stability maintenance.

INTRODUCTION

The NICA accelerator complex [1, 2] is constructed and commissioned at JINR. NICA experiments will be aimed at searching for the mixed phase of baryonic matter and nature of nucleon/particle spin. The new NICA accelerator complex will permit performing experiments in the following modes: with the Nuclotron ion beams extracted to a fixed target; with colliding ion beams in the collider; and with colliding ion-proton beams; with colliding beams of polarized protons and deuterons.

The main elements of the NICA complex are an injection complex, a Booster, the superconducting synchrotron Nuclotron, a Collider composed of two superconducting rings with two beam interaction points, a Multi-Purpose Detector (MPD) and a Spin Physics Detector (SPD) and beam transport channels.

INJECTION COMPLEX

The injection complex [1] includes a set of ion sources and two linear accelerators. One, the LU-20 linear accelerator, which has been under operation since 1974, accelerates protons and ions from the laser source and the source of polarized ions (SPI) of protons and deuterons. The SPI was constructed by the JINR-INR RAS collaboration. The beam current of polarized deuterons corresponds to 3 mA. At the LU-20 exit, the energy of ions is 5 MeV/n. At the present time, the LU-20 beam is injected directly into the Nuclotron. The HV injector of the LU-20 was replaced in 2016 by an RFQ [2,3] with beam matching channels. The RFQ and the new buncher were constructed by the JINR - ITEP of NRC “Kurchatov Institute”, NRNU MEPHI, VNIITF collaboration. The new debuncher was constructed in 2019 by INR for the LU-20-Nuclotron injection channel.

The design of a new Light Ion Linac (LILAc) was started in 2017 to replace the LU-20 in the NICA injection complex. LILAc consists of three sections: a warm injection section used for acceleration of light ions and protons up to the energy of 7 MeV/n, a warm medium energy section used for proton acceleration up to the energy of 13 MeV, and a superconducting HWR section used for proton acceleration up to the energy of 20 MeV. The LILAc should provide the beam current of 5 emA.

The second accelerator of the NICA injection complex, a new Heavy-Ion Linac (HILAc) (Fig. 1) constructed by the JINR-Bevatech, collaboration, has been operating since 2016. It will accelerate heavy ions ($^{197}Au^{31+}$ have been chosen as the base ions) injected from KRION-6T, a superconducting electron-string heavy ion source constructed by JINR. At the present time KRION-6T produces $5\cdot10^8$ Au^{31+} ions. An upgraded version of KRION with the $^{197}Au^{31+}$ ion intensity of up 2×10^9 particles per pulse will be constructed in 2020 for collider experiments. The ion energy at the exit from HILAc is 3.2 MeV/n, while the beam intensity amounts to 2×10^9 particles per pulse, and the repetition rate is 10 Hz. HILAc consists of three sections, the RFQ and two IH sections. The RFQ is a 4-rod structure operating at 100.625 MHz. The 140 kW and 340 kW solid-state amplifiers power the RFQ and each IH section.

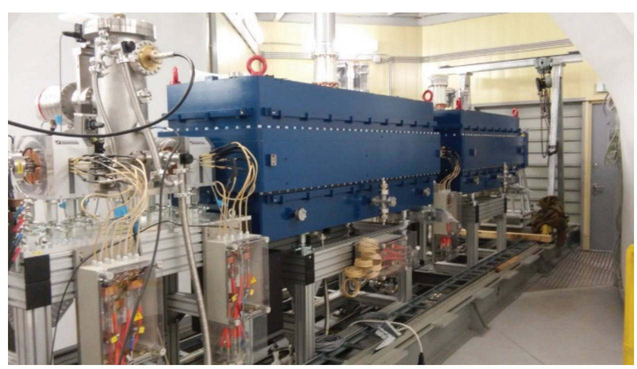

Figure 1: Heavy ion linear accelerator.

The transport channel from HILAC to Booster consists of two dipole magnets, seven quadrupole lenses, six steerers magnets, a debuncher, a collimator, and vacuum and diagnostic equipment. The debuncher constructed by Bevatech GmBH reduces relative ion momentum spread after HILAc from 5×10^{-3} to 10^{-3}. The assembling of the transport channel from HILAC to Booster was started in autumn 2018 and will be finished in spring 2019.

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The Booster [1] is a superconducting synchrotron intended for accelerating heavy ions to an energy of 600 MeV/n. The magnetic structure of the Booster with a 211-m-long circumference is mounted inside the yoke of the Synchrophasotron magnet. The main goals of the Booster are accumulation of $2\cdot10^9$ Au^{31+} ions, acceleration of heavy ions up to the energy 600 MeV/n required for effective stripping, and forming of the required beam emittance with the electron cooling system. The Booster has a four-fold symmetry lattice with DFO periodic cells. Each quadrant of the Booster has ten dipole magnets, six focusing and six defocusing quadrupole lenses, and multipole corrector magnets

All Booster dipole magnets and quadrupole lenses were fabricated and tested at JINR. For this purpose, a specialized production line was organized at LHEP.

Installation of the Booster cryomagnetic equipment (Fig. 2) was started in September 2018. The first technical Booster run with this equipment is planned for 2019.

Figure 2: Installation of the first Booster magnets.

The Booster power supply system provides consecutive connection of dipole magnets, quadrupole focusing and defocusing lenses. The main powerful source of the power supply system forms a current of up to 12.1 kA with the required magnetic field ramp of 1 T/s. Two additional power supply sources are intended for flexible adjustment of the Booster working point. All Booster power supplies were constructed by the LM Invertor (Russia).

The beam injection system of the Booster consists of an electrostatic septum and three electric kickers. The section has a bypass of cryogenic and superconducting communications, and the largest part of the section including the septum and the kicker IK2 has a room temperature while the kickers IK1 and IK3 are placed inside the Booster cryostat. The electrostatic septum, kicker IK2 produced by the Cryosystems (Russia) and kickers IK1 constructed by the Pink (Germany) will be delivered in JINR in spring 2019.

The Booster RF system is based on amorphous iron loaded cavities. Two RF stations provide 10 kV of acceleration voltage. The operating frequency range of the stations is from 587 kHz to 2526 kHz. The RF stations have been designed and created at BINP. They were delivered to JINR and tested there in 2014.

The electron cooling system with the maximal electron energy of 60 keV was designed and fabricated by the BINP. The JINR and BINP teams performed the commissioning of electron cooling system in the Booster position in 2017.

The Booster beam extraction system consists of a magnetic kicker, two magnetic septa, a stripping station and, a closed orbit bump subsystem including four lattice dipoles with five additional HTS current leads. The ions accelerated in the Booster are extracted and transported along a magnetic channel, and on their way, they cross a stripped target. The channel consists of five dipole magnets, eight quadrupole lenses, three correctors, extraction septa, and diagnostic and vacuum equipment.

Two septa, a kicker, magnets of the transfer channel, and power supplies are under fabrication at BINP. This equipment will be delivered to JINR between autumn 2019 and spring 2020.

The Booster peculiarity is ultrahigh vacuum of 10^{-11} Torr. Fracoterm (Poland) fabricated the vacuum chambers for Booster magnets.

The upgraded Nuclotron [1, 2] accelerates protons, polarized deuterons, and ions to a maximum energy depending on the sort of particles. The maximum ion energy corresponds to 5.6 GeV/n at the present time. Polarized deuteron beams were obtained at the intensity of up to 2×10^9 ppp in the Nuclotron. The polarized proton beams were first formed at the intensity of 10^8 ppp in 2017. The injection with RF adiabatic capture at the efficiency of 80% was used in the Nuclotron runs. The last Nuclotron run was performed with acceleration of C^{6+}, Xe^{42+}, Kr^{26+} and Ar^{16+} ion beams. The resonant stochastic extraction (RF knock-out technique) was realized in that run.

The installation in the Nuclotron of the Booster beam injection system and the Collider fast extraction system are required for its operation as the main synchrotron of the NICA complex. The kickers and Lamberson magnets should be constructed for injection and extraction sections.

Construction of room-temperature transfer channels from the Nuclotron to the Collider rings is under development and fabrication by SigmaPhi (France). The equipment deliveries will start in summer 2019. The channel lattice contains 27 dipoles, 28 quadrupoles, 33 steerers, and a set of beam diagnostics devices. There are two types of dipoles and quadrupoles which differ by length. The channel magnets are powered in the pulsed mode.

COLLIDER

The Collider [1, 2] 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 not higher than 10^{-10} Torr; the maximum field in the dipole magnets is 1.8 T; the kinetic energy of gold nuclei ranges from 1 to 4.5 GeV/n; the beam axes coincide at the interaction section (zero intersection angle); and the average luminosity is 10^{27} cm^{-2} s^{-1} for gold ions at the center - of - mass energy of 11 GeV. The rings of the Collider are identical in shape to a racetrack — two arcs are connected by two 109 m straight sec-

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tions. The circumference of each ring is 503.04 m. The dipole magnets and lenses in the arcs are combined into 12 cells of the so-called FODO structure separated by straight sections. The total number of the horizontal dipole magnets in the arcs of both rings corresponds to 80 and 8 vertical dipole magnets for two IP regions. The magnets of both rings in the arcs are situated one above another; their axes are separated vertically by 320 mm. The magnets in the arcs have common yokes, but their design permits controlling the field in each of the rings separately. The total number of the lenses is 86 in the arcs and the straight sections and 12 lenses of the final focus sections. The design of the arc dipole magnets and dublet lenses was finished. Prototypes of the dipole magnets and lenses were constructed. The construction of serial arc dipole magnets and duplet lenses was started at JINR in autumn 2018. The beams are brought together and separated in the vertical plane. Upon passing the section bringing them together, the particle bunches in the upper and lower rings travel along a common straight trajectory toward each other to collide at two interaction points (IPs). Single-aperture lenses are installed along the final focus sections to provide that both beams are focused at the IP.

The symmetric optic was designed for two beams in the rings. The betta function at the IP was increased from 0.35 m to 0.6 m in 2017-2018 to improve the Collider ring dynamic aperture. Two working points 9.44 and 9.1 were chosen for ring operation.

Three power supplies are used in the Collider for all dipole magnets and quadrupole lenses. The Collider main power supply provides in-series connection of dipole magnets, quadrupole focusing and defocusing lenses at the maximum current of 10.7 kA. The second power supply is used for all lenses, and the third one is intended only for D lenses.

The cooling of charged particle beams are critical for achieving the design parameters of the complex. The electron cooling system for the NICA Collider at an electron energy of 2.5 MeV is intended for accumulation and bunch formation at the ion kinetic energies in the range of 1.0–4.5 GeV/n. Construction of the electron cooling system was started at BINP in 2016. The commissioning of the cooling system at JINR will be at the end of 2021, two years ahead of schedule.

The stochastic cooling system (SCS) of the NICA Collider must provide ion cooling of up to 2.3×10^9 ions in a bunch. To achieve the design cooling time, an SCS with the frequency bandwidth 2–4 GHz is necessary. The Collider SCS uses pickup electrodes and kickers. The main elements of the stochastic cooling system also include signal delay system blocks, solid-state amplifier and preamplifier cascades, and a rejector (comb) filter system.

Three RF systems with 26 cavities of the acceleration radio-frequency voltage will be used for ion accumulation and formation of ion bunches with the necessary parameters in the Collider. Accumulation of the beam of the required intensity is planned to be performed in the longitudinal phase space using the ''technique of barrier RF1 voltages'' (Fig. 3) and stochastic or electron cooling of the particles being accumulated. The barrier bucket technique will also be used for ion acceleration in the Collider rings.

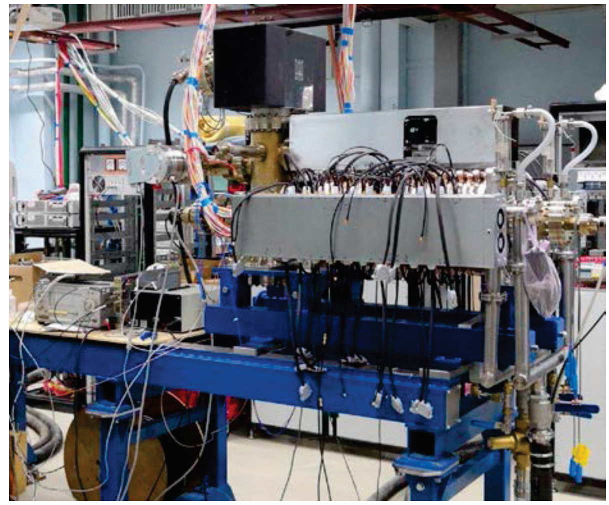

Figure 3: Barrier bucket RF1 station.

When the necessary intensity is achieved, the beam is bunched by the RF2 system at the voltage of up to 25 kV of the 22nd harmonics of the rotation frequency with the subsequent takeover by the RF3 system of the 66th harmonics. This permit 22 short bunches to be formed, which is necessary to achieve high luminosity. The maximal RF3 voltage corresponds to 125 kV. The RF2 and RF3 systems will additionally be used for ion acceleration in the rings from the injection energy to the energy required for Collider experiments. The RF solid - state amplifiers developed by Triada (Russia) are used for RF2 and RF3 systems. Construction of three RF systems was started in 2016-2017 at BINP. Two RF1 and four RF2 cavities will be installed at JINR in 2020. Additional four RF2 and sixteen RF3 cavities will be commissioned for extension Collider version in 2021, two years ahead of schedule planned.

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