STATUS OF ACCELERATOR COMPLEX NICA

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Abstract

The Nuclotron-based Ion Collider fAcility (NICA) is under construction in JINR. The NICA goals are providing of colliding beams for studies of hot and dense strongly interacting baryonic matter and spin physics. The accelerator facility of collider NICA consists of following elements: acting Alvarez-type linac LU-20 of light ions at energy 5 MeV/u, constructed a new light ion linac at ion energy 7 MeV/u with additional acceleration section for protons at energy 13 MeV, acting heavy ion linac HILAC with RFQ and IH DTL sections at energy 3.2 MeV/u, superconducting booster synchrotron at energy up 600 MeV/u, acting superconducting synchrotron Nuclotron at gold ion energy 4.5 GeV/n and two collider storage rings with two interaction points. The status of acceleration complex NICA is under discussion.

INTRODUCTION

The NICA accelerator complex (Fig. 1) [1] is constructed and commissioned at JINR. NICA experiments shall be performed in search of the mixed phase of baryonic matter and nature of nucleon/particle spin. The new NICA accelerator complex will permit implementing experiments in the following modes: with the Nuclotron ion beams extracted at a fixed target; with colliding ion beams in the collider; with colliding ion-proton beams; with colliding beams of polarized protons and deuterons.

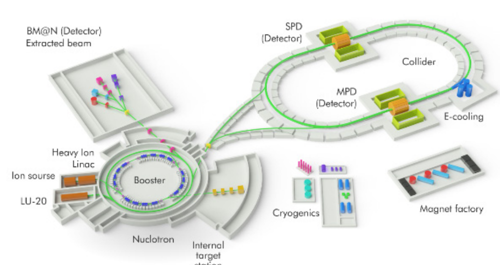

Figure 1: Layout of the NICA Accelerator complex.

The NICA complex (Fig. 1) includes the following main elements: an injection complex; a Booster; the superconducting synchrotron Nuclotron; a Collider composed of two superconducting rings with two beam interaction points; two detectors a Multi-Purpose Detector (MPD) and a detector for experiments in particle spin physics, the Spin Physics Detector (SPD); channels for beam transportation.

INJECTION ACCELERATOR COMPLEX NICA

The injection complex [2] includes a set of ion sources and two linear accelerators. The first one, the LU-20 linear accelerator, which is under operation since 1974, accelerates protons and ions from few sources: the laser source and the source of polarized ions (SPI) - protons and deuterons. SPI was constructed by JINR-INR RAS collaboration. The beam current of polarized deuterons corresponds to 2 mA. At the LU-20 exit, the energy of ions is 5 MeV/n. At present time, the LU-20 beam is injected directly into the Nuclotron. The HV injector of linac LU-20 has been replaced in 2016 by RFQ [2,3] with beam matching channels. The RFQ was constructed by JINR, ITEP of NRC “Kurchatov Institute”, NRNU MEPHI, VNIITF collaboration. The new buncher constructed by ITEP of NRC “Kurchatov Institute” was installed between RFQ and LU20 in 2017. Installation of new buncher permits to increase the heavy ion beam current in 5 times in Nuclotron 55 run in 2018.

The design of new Light Ion Linac (LILAc) was started in 2017 to replace the LU-20 in NICA injection complex. LILAc consists of three sections: warm injection section applied for acceleration of light ions and protons up to energy 7 MeV/n [2,4], warm medium energy section used for proton acceleration up to energy 13 MeV [3] and superconducting HWR sections [2, 5], which provides proton acceleration up to energy 20 MeV. The LILAC should provide beam current of 5 emA. The construction of first light ion section [4] at ion energy 7 MeV/n was started in 2018 by Bevatech GmbH (Germany), it should be delivered in JINR in 2021. The next step of the LILAc project – design of a middle energy section [3] and HWR superconducting sections [2, 5]. The increased beam energy of LILAc is required for future researches with polarized proton beams. The operating frequency of the LILAc is equal to 162.5 MHz for first two sections and 325 MHz for HWR section. The superconducting HWR are designed and constructed by Russian-Belarusian collaboration with participation of JINR, NRNU MEPhI, ITEP of NRC “Kurchatov Institute”, INP BSU, PTI NASB, BSUIR and SPMRC NASB.

The second accelerator of NICA injection complex— a new heavy-ion linear accelerator (Heavy Ion Linac, HILAc) [2] (Fig. 2) constructed by JINR-Bevatech collaboration is under exploitation since 2016. It will accelerate heavy ions ($^{197}Au^{31+}$ ions have been chosen as the base ions) injected from KRION-6T, a superconducting electron-string heavy ion source, constructed by JINR. At present time KRION-6T produces $5{\cdot}10^8$ Au^{31+} ions. This ion

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source will be used at injection in Booster in 2019. Upgraded version of KRION with $^{197}Au^{31+}$ ion intensity up 2×10^9 particles per pulse will be constructed in 2020 for collider experiments. The energy of ions at the exit from HILAc is 3.2 MeV/n, while the beam intensity amounts to 2×10^9 particles per pulse or 10 emA, repetition rate is 10 Hz. The HILAc consists of three sections: RFQ and two IH sections. The RFQ is a 4-rod structure operating at 100.625 MHz. The RFQ and each IH section are powered by 140 kW and 340 kW solid state amplifiers.

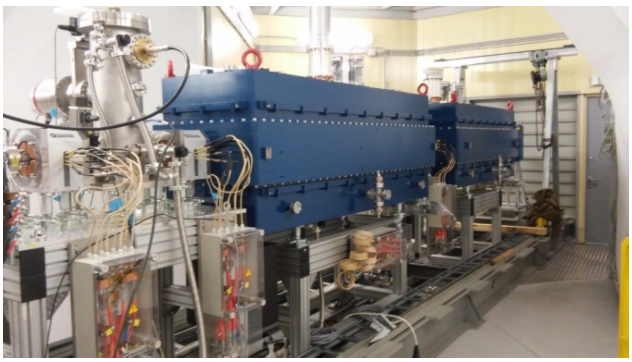

Figure 2: Heavy ion linear accelerator.

The transportation channel from HILAC to Booster [6] consists of 2 dipole magnets, 7 quadrupole lenses, 6 steerers magnets, debuncher, collimator, 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 collimation diaphragm in transport channel provides separation of ions with required charge $^{197}Au^{31+}$ from parasitic ions with another charges. The assembling of transportation channel from HILAC to Booster was started in autumn 2018 and it will be finished in April 2019.

The Booster [7] 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 established inside the yoke of the Synchrophasotron magnet. Main goals of the Booster are accumulation of $2\cdot10^9$ Au^{31+} ions; acceleration of the heavy ions up to energy 600 MeV/n required for effective stripping; forming of the required beam emittance with electron cooling system. The Booster has four-fold symmetry lattice with DFO periodic cells. Each quadrant of the Booster has 10 dipole magnets, 6 focusing, 6 defocusing quadrupole lenses and multipole corrector magnets

The all Booster dipole magnets (Fig. 3) and quadrupole lenses were fabricated in JINR. All dipole magnet and 70% of lenses were tested at JINR cryogenic test bench at present time [8].

For this purpose, specialized production line [9] of such magnets (Fig. 4) was organized at the LHEP. The equipment of the facility is allocated in separate building of 2600 m^2 and provides: SC cable production; windings production; assembling yokes of magnets and winding, welding and brazing cooling channels of magnets; room temperature magnetic measurements; check of vacuum tightness of cooling channels, beam pipes and cryostats; assembling magnets in cryostats; cryogenic tests of magnets at 6 benches.

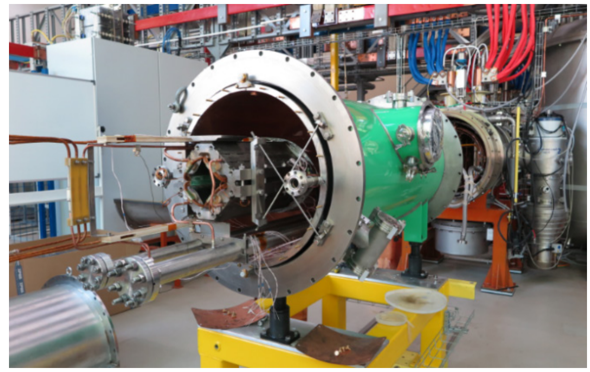

Figure 3: Booster dipole magnet.

Figure 4: Line for assembling and cryogenic testing of SC-magnets.

The Booster power supply system [7] provides consecutive connection of dipole magnets (total inductance 16.4 mH), quadrupole focusing (total inductance 0.6 mH) and defocusing (total inductance0.6 mH) lenses. The main powerful source of the power supply system forms a demanded current (up to 12.1 kA) with the required magnetic field ramp of 1 T/s. Two additional power supply sources of essentially smaller power are intended for flexible adjustment of the Booster working point. One of them allows varying simultaneously the magnetic field gradient in focusing and defocusing lenses, another only in defocusing ones. All Booster power supplies were constructed by Russian firm LM Invertor.

Missing dipole cells of the lattice are used for installation of injection, extraction, RF and electron cooling systems. The ion accumulation is provided by multi variant injection of ion beams into the Booster. Main methods of beam injection into the Booster are single turn, multi turn and multiple injection. 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 is room temperature while the kickers IK1 and IK3 are placed inside the Booster cryostat. The electrostatic septum and kicker IK2 is under fabrication by Russian firm Cryosystems and it

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will be delivered in JINR in autumn 2018. The electrostatic septum and kicker IK2 will be used for single turn injection. The kickers IK1 and IK3 constructed by firm Pink (Germany) will be delivered in JINR in March 2019.

The RF system [7] of the Booster is based on amorphous iron loaded cavities. Two RF stations are to provide10 kV of acceleration voltage. Frequency range of operation of the stations is from 587 kHz to 2526 kHz. The RF stations have been designed and created at BINP. They were delivered in JINR in 2016 and tested there.

The design and fabrication of electron cooling system [10,11] (Fig. 5) with maximal electron energy 60 keV was done by BINP SB RAS. The commissioning of electron cooling system in the booster position was performed by JINR and BINP teams in 2017. The electron cooling operation was tested in JINR at voltage 5 kV and electron beam current of 300 mA in June 2018. The vacuum in electron cooling system corresponds to 3×10^{-11} Torr. The relative transverse magnetic field in cooler solenoids is about $(1.5\text{-}2)\times10^{-5}$.

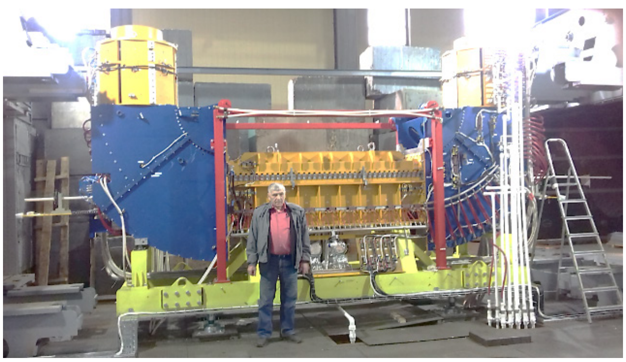

Figure 5: Booster electron cooling system.

The Booster beam extraction system [6] 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. Two septa, kicker and power supply is under fabrication in BINP SB RAS. This equipment will be delivered in JINR in 2019.

The installation of Booster cryomagnetic equipment (Fig. 6) was started in September 2018. The first technical Booster run is planned in 2019.

Figure 6: Installation of first booster magnets.

The Booster peculiarity is ultra-high vacuum of 10^{-11} Torr [12]. Poland firm Fracoterm fabricated the vacuum chambers for Booster magnets.

The ions accelerated in the Booster are extracted and transported along a magnetic channel [6], and on their way they cross a stripped target, inside which they are ionized to the maximum-charge state ($^{197}Au^{79+}$ in the case of gold). The ion stripping efficiency at energy of 580 MeV/u is very close to 100% of Au^{31+} which is striped in bare nucleus with efficiency of 80% $^{197}Au^{79+}$, and 20% in hydrogen type ions $^{197}Au^{78+}$. Due to high intensity of $^{197}Au^{78+}$ ions they have to be extracted to an absorber. BINP SB RAS performs the fabrication of transfer channel from Booster to Nuclotron [6]. The channel consists of 5 dipole magnets, 8 quadrupole lenses, 3 correctors, extraction septa, diagnostic and vacuum equipment. Commissioning of this channel in JINR is planned in December 2019.

The upgraded Nuclotron [13] accelerates protons, polarized deuterons and ions to a maximum energy depending of the sort of particles. The maximum ion energy corresponds to 5.6 GeV/n at present time. The polarized deuteron beams were obtained at intensity up 2×10^9 ppp in Nuclotron runs 53 and 54 with SPI in 2016-2018. The polarized proton beams were formed first time at intensity 10^8 ppp in Nuclotron 54 run in 2017. The injection with RF adiabatic capture at efficiency of 80%. was used in two last Nuclotron runs 54 and 55 in 2017 and 2018. The run 55 in 2018 was performed with acceleration of C^{6+}, Xe^{42+}, Kr^{26+} and Ar^{16+} ion beams. The resonant stochastic extraction (RF knockout technique) was realized in the run 55 in 2018 (Fig. 7). The working point was moved by the extraction quadrupole operated with feedback simultaneously with wide-band noise influence on the horizontal oscillations.

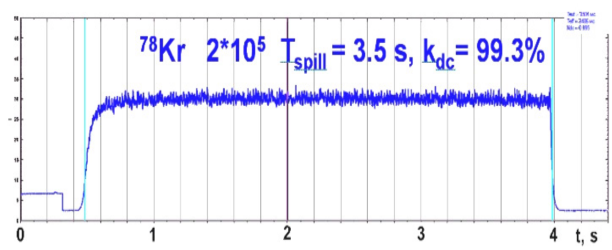

Figure 7: $^{78}Kr^{+26}$ beam spill 2 x 10^5 ppp.

The ion beam parameters obtained in Nuclotron until June 2018 are given in Table 1. The further increase of the ion intensity is connected with construction of new ESIS and Booster.

The installation in Nuclotron of beam injection system from the Booster and fast extraction system in Collider [6] 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. The Lambertson magnets are based on existing spare yokes for slow extraction system of Nuclotron. The concepts of Lamberson magnets were prepared and we plan to start its construction. The warm kicker prototype for mechanical

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tests has been manufactured. The design of the cold kickers is in progress.

Table 1: Main Parameters of Nuclotron Beams

Parameter	Project	Status, 2018
Max. magn. field, T	2	2 (1.7 routine)
B-field ramp, T/s	1	0.8 (0.7 routine)
particles	p–U, d↑	p↑, d↑, p – Xe
Maximum energy, GeV/u	12 (p), 5.8 (d) 4.5 $^{197}Au^{79+}$	5.6 (d, C), 3.6 (Ar^{16+})
Intensity, ions/cycle	10^{11} (p,d), 2×10^9 (A > 100)	d 4×10^{10} (2×10^{10} routine) $^7Li^{3+}3\times10^9$ C^{6+} 2×10^9 $Ar^{16+}1\times10^6$ $Kr^{26+}2\times10^5$ $Xe^{42+}1\times10^4$

The construction of room-temperature transfer channels from Nuclotron to collider rings [6] is under development and fabrication by French company SigmaPhi. The equipment deliveries will be started on summer of 2019. The channel lattice contains 27 dipoles, 28 quadrupoles, 33 steerers and set of beam diagnostics devices. There are two types of the dipoles and quadrupoles which differ by lengths. The channel magnets are powered in pulsed mode.

COLLIDER RINGS

The Collider [1] consists of two storage rings with two interaction points (IPs). Its main parameters (Table 2) are as follows: the magnetic rigidity is up to 45 T·m; the residual gas pressure in the beam chamber is not high than 10^{-10} Torr; the maximum field in 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 center of mass energy 11 GeV. The rings of the Collider are identical in shape to a racetrack — two arcs are connected by two long straight section (109 m each). The circumference of each ring is 503.04 m. The dipole magnets and lenses [8] 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 construction permits controlling the field in each of the rings separately. The total number of the lenses is equal to 86 in the arcs and the straight sections and 12 lenses of final focus sections. The design of the arc dipole magnets and dublet lenses was finished. The prototypes of dipole magnets (Fig. 8) and lenses were constructed. The construction of serial arc dipole magnets and duplet lenses was started in 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 along 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 final focus sections to provide that both beams are focused at the IP.

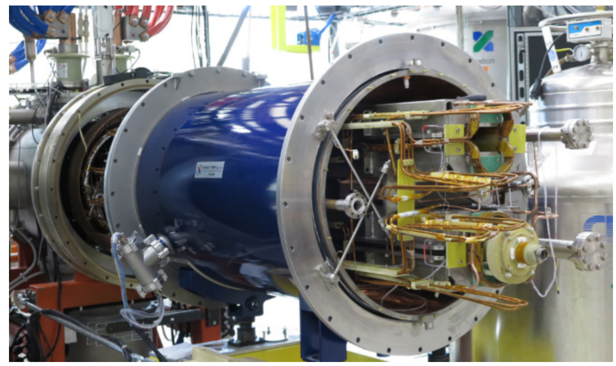

Figure 8: Prototype of collider dipole magnet.

Table 2: Main Parameters of the NICA Accelerator Complex

Parameter	Value		
Ring circumference, m	503,04		
Number of bunches	22		
Rms bunch length, m	0.6		
Beta-function in the IP, m	0.6		
Betatron tunes, Q_x/Q_y	9.44/9.44 9.1/9.1		
Ring acceptance π·mm·mrad	40		
Longitudinal acceptance	±0.01		
Ion energy, GeV/n	1	3	4.5
Ion number per bunch	$2\cdot10^8$	$2.4\cdot10^9$	$2.3\cdot10^9$
Rms dp/p, 10^{-3}	0.55	1.15	1.5
Rms emittance, π·mm·mrad	1.1/0.9	1.1/0.8	1.1/0.
Luminosity, $cm^{-2}s^{-1}$	$0.66\cdot10^{25}$	10^{27}	10^{27}
IBS growth time, sec	160	460	2000

The symmetric optic was designed for two beams in the rings. Betta function in IP was increased from 0.35 m up 0.6 m in 2017-2018 JINR-BINP SB RAS simulations to improve collider ring dynamic aperture. The dynamic aperture was increased from (4-5)$\sigma_{x,y}$ at β_*=0.35 m (it is less than geometrical aperture 6$\sigma_{x,y}$) up to 8$\sigma_{x,y}$ at β_*=0.6 m. Two working points 9.44 and 9.1 were choose for ring operation. Three power supplies are used in Collider for all dipole magnets and quadrupole lenses. The Collider main power supply provides consecutive connection of dipole magnets, quadrupole focusing and defocusing lenses at

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maximum current of 10.7 kA. The second power supply is used for all lenses, and third one is intended only for D lenses. The powers of second and third power supplies are by one order less than power of main power supply. At transition from working point 9.44 to 9.1 the power supply current is variated in all quadrupole lenses on -300 A (except lenses of final focuses) and on 9A for D-lenses. The length of each pair of quadrupole lenses was optimized in straight sections for this case. Additionally, each pair of lenses in straight section and each final focus lens has individual power supply with correction current up 300A.

Methods for cooling charged particle beams represent the key accelerator technologies, which are critical for achieving the design parameters of the complex. The electron cooling system [10] 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. The solenoid cooling section has the length of 6 m, the magnetic field is of 1 kG. The maximum electron beam current corresponds to 1 A. Construction of the electron cooling system was started in BINP SB RAS in 2016. The commissioning of cooling system in JINR will be in end of 2021 on two year early that it is planned.

The stochastic cooling system (SCS) [1] of the NICA Collider must provide ion cooling of up to 2.3×10^9 ions in a bunch, which corresponds to an effective number 8×10^{11} of ions. 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. The achievable output power of one solid-state amplifier is about 60–70 W. Therefore, to provide the total required output power of the system at a level of 500 W, 8 to 10 kickers will be switched on in parallel, and each one of them will have an individual supply.

Three RF systems with 26 cavities of the acceleration radio-frequency voltage will be applied for ion accumulation and formation of ion bunches [14] with the necessary parameters in the Collider. Accumulation of the beam of the required intensity is planned to be realized in the longitudinal phase space with the use of the ‘technique of barrier RF1 voltages’ and of stochastic or electron cooling of the particles being accumulated. The burrier bucket technique also will be used for ion acceleration in the rings. When the necessary intensity is achieved, the beam is bunched the RF2 system at voltage 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 permits 22 short bunches to be formed, which is necessary in order to achieve high luminosity. The maximal RF3 voltage corresponds to 125 kV. The RF2 and RF3 systems additionally will be used for an ion acceleration in rings from injection energy up to energy required for Collider experiments. The RF solid state amplifiers developed by Russian firm TRIADA are used for RF2 and RF3 systems. The construction of three RF systems was started in 2016-2017 in BINP SB RAS. Two RF1 and four RF2 cavities will be installed in JINR in 2020. Additional 4 RF2 and 16 RF3 cavities will be commissioned for extension collider version in 2021 on two years early that it is planned.

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