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NICA ION COLLIDER AND ITS ACCELERATION COMPLEX

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Abstract

The Nuclotron-based Ion Collider fAcility (NICA) [1] is under construction at JINR. The NICA project goal is to provide colliding beams for studies of hot and dense strongly interacting baryonic matter and spin physics. The NICA Collider includes two rings with 503 m circumference each and the injection complex. For the heavy ion mode, the injection complex consists of following accelerators: 3.2 MeV/u linac (HILAC), 600 MeV/u (A/Z=6) superconducting booster synchrotron (Booster) and main superconducting synchrotron (Nuclotron) with kinetic energy up to 3.9 GeV/u (A/Z=2.5). The injection complex has been under commissioning for more than 2 years. The latest half-year Run ended in February of 2023. It was devoted to preparations for the collider operation and also delivered slowly extracted 3.9 GeV/u xenon beam to the BM&N experiment [2].

Now the injection complex is shut down for its further development and an assembly of the collider. Cryogenic tests of the collider magnetic structure are expected at the end of 2023. The next run of the injection complex is aimed at an increase of ion flux by more than an order of magnitude and will be started at 2024.

INTRODUCTION

The Run IV of the injection complex was carried out from Sep. 20 of 2022 to Feb. 3 of 2023. The main goals of the Run were commissioning of the complex in the collider configuration and delivery of the slowly extracted beam to the BM@N experiment [2]. The injection complex includes:

- a new Electron String Ion Source (ESIS) (Krion-6T) generating highly charged heavy ions [3] and installed at a high voltage platform to make 16.6 keV/u ion energy for the targeted ion charge,
- 600 keV/u RFQ [4],
- 3.2 MeV/u linac (HILAC) [4],
- 600 MeV/u (A/Z=6) superconducting booster synchrotron (Booster) [5] and
- modernized main superconducting synchrotron (Nuclotron), kinetic energy up to 3.9 GeV/u (A/Z=2.5) [6].

Complete stripping of the ions is produced at the beam extraction from Booster at the very beginning of the Booster-Nuclotron transfer line. The schematic of the injection complex for the heavy ion operations and its main parameters are presented in Fig. 1. Figure 2 presents statistics of the complex operations for the entire Run. Note that the reliability of the machine was greatly improved to the Run end. The major contribution to lost time and repairs of ~45% came from the cryogenic system since the power of cryogenic system, designed and build for Nuclotron, was barely sufficient for cooling both rings. At the end of this year an extension of the cryogenic system will increase its cooling power from 4 kW to 10 kW. Together with other improvements it shall greatly improve reliability of the cryogenics. Note also that the "Electric power loss" shown in Fig. 2 corresponds to the planned power outage.

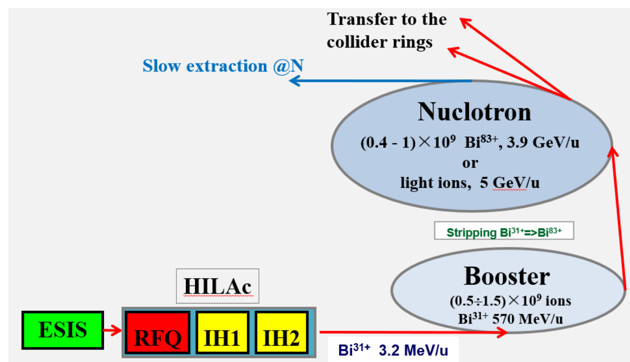

Figure 1: Schematic of the NICA injection complex.

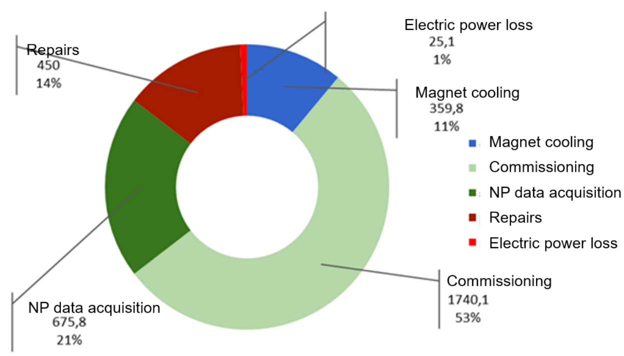

Figure 2: Statistics of the Run 4 Operations.

ION SOURCE

The ion source, shown in Fig. 3, produces highly charged heavy ions. At the Run beginning, for the ion source commissioning, we used $^{40}Ar^{13+}$ ions, which then were replaced by $^{124}Xe^{28+}$. The magnetic field of source solenoid is equal to 5 T while its value at the cathode is 0.25 T. That results in a reduction of the primary electron beam diameter from 1.2 mm to 0.27 mm. The electron beam energy is 6 keV. The reflex mode of operation requires the electron string being formed [7]. That yields the cathode current in the range of 4-6 mA. For operation with xenon the targeted ion charge was chosen to be 28. That required 18 ms ionization

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time and resulted in the total ion charge of 2.4 nC. About 20-25% of these ions had the targeted charge. That coincides well with CBSIM code predictions yielding 23% [8].

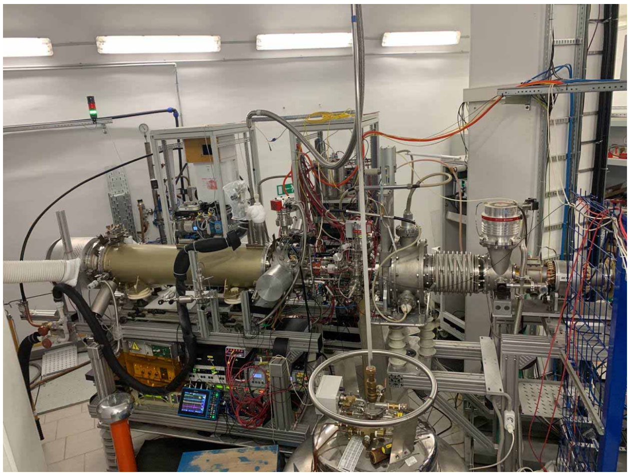

Figure 3: View of Krion-6T ion source.

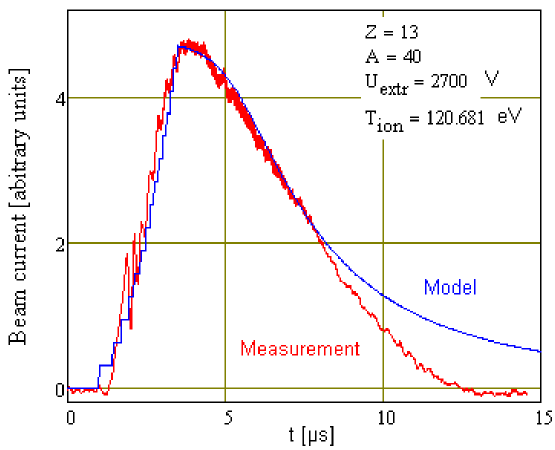

Figure 4: A dependence of beam current on time for ion source operation with $^{40}Ar^{13+}$ ions.

Figure 4 presents the beam current measured for Ar^{13+} ions at the linac end where the ions of targeted charge present main constituent. The measured shape of the pulse has long tail associated with time required for ions to leave the ion trap electrodes (15 pipes, 4 mm diameter and 5 cm long) to which the extraction voltage does hardly penetrate. Changing shape of these electrodes, so that to make uniform extraction field, should allow us significantly decrease pulse duration and make it shorter than the 8.2 µs revolution time at the Booster injection. Note that in this Run, for ion source operation with xenon, the pulse duration is almost twice longer and, if not addressed, expected to be even longer for operation with heavier bismuth ions planned to be used for the NICA collider.

To support the collider operation, we need an increase in the number of ions injected into Booster by an order of magnitude. It will be achieved by mentioned above shortening the ion pulse, an increase of total ion charge with further optimization of ion source operation and the ion accumulation in the Booster at the injection. Since the longitudinal electron cooling is faster than the transverse one, we plan to do accumulation in the longitudinal phase space. That requires shortening of the beam pulse to about 4 µs, so that to leave other 4 µs of revolution time to already cooled particles.

BOOSTER AND NUCLOTRON

In addition to addressing hardware and software problems, significant efforts in commissioning of Booster and Nuclotron were directed into their optics measurements, orbit correction, and measurements of the longitudinal beam dynamics.

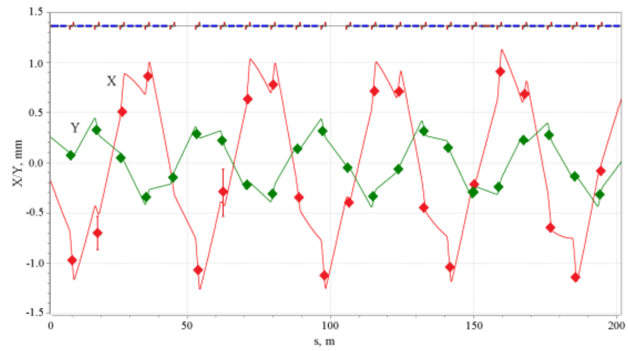

Figure 5: Orbit response to one horizontal (red dots) and one vertical (green dots) corrector. Solid lines show corresponding model predictions. Measurement accuracy is shown only for two BPMs which had problems with electronics.

Figure 5 shows measured and predicted differential orbits for two Booster correctors. One can see very good coincidence between the measurements and the optics model. Thus, the performed measurements confirm good quality of Booster magnets; and the only correction required in the model is a minor adjustment (<1%) of overall quad strength to obtain correct tunes. The response matrix was measured for each corrector. This work enabled to find and fix all miswirings in correctors and BPMs. Good coincidence between the measurements and the model allowed us to use the computed response matrix for orbit correction. The orbit correction and measurements in both rings and transfer lines are driven by the same software. The differences in hardware are accounted in the configuration files. The same software will be used for optics measurements and orbit correction in the collider rings. Both Booster and Nuclotron have reasonably small *x-y* coupling which does not require correction. At the Booster injection energy, the tune split is ~0.02 with switched off electron cooling solenoid. Introduction of nominal 0.7 kGs solenoid field increases the tune split at the injection energy to 0.07. Effect of solenoid disappears fast with the ion beam acceleration.

Another important part of the complex commissioning was characterization of RF systems, beam bunching and acceleration. The nominal frequency of Booster RF is in the range of 0.5-5 MHz. In this range the system can make up to 7.4 kV/turn accelerating voltage. During injection from the linac the RF voltage is switched off, and the beam debunches within few hundred turns. Then the beam is adiabatically bunched at the 5th harmonic and accelerated to

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~65 MeV/u where it is debunched and rebunched at the first harmonic. This rebunching enables to keep RF frequency within RF system operating range. The rest of the acceleration occurs at the 1st harmonic. After acceleration to 205 MeV/u the beam was extracted and transferred to Nuclotron where 4th harmonic RF voltage is on. The bunch-to-bunch transfer is supported by the Nuclotron LLRF (Low Level RF) system which phase is bound to the transfer since the ratio of circumferences for Booster and Nuclotron is not a rational number. Entire acceleration in Nuclotron was carried out at the 4th harmonic. Calibration of the RF voltage in Booster was carried out with measurements of synchrotron frequency at the maximum energy where the bunch is sufficiently short and only minor correction accounting non-linearity of synchrotron motion with amplitude is required. The calibration of the voltage showed that the actual Booster RF voltage is 26% lower than the measured with the cavity capacitive divider.

After acceleration in Nuclotron the beam was resonantly (slowly) extracted to the BM@N experiment during 2 s. The extraction was done at 3rd harmonic of betatron frequency. Measurements of betatron frequency were helpful for the extraction optimization. Minor excitation of horizontal beam motion by noise during extraction considerably improved uniformity of the spill.

ELECTRON COOLING

At the Run end the electron cooling was introduced into operation. The magnetic field of the electron cooler has considerable effect on the betatron motion in the Booster. Therefore, to simplify the electron cooling commissioning, its solenoid was switched on at the beginning of the Run; and most beam operations, optics measurements and orbit correction were performed with the solenoid being on. That enabled painless commissioning of the cooling itself which was carried out at the Run end.

The electron cooling of $^{124}Xe^{28}$ ions was performed at the Booster injection plateau of 200 ms. The 5th harmonic RF voltage was adiabatically increased from zero to about 2 kV shortly after injection and adiabatically increased to its maximum of 7.5 kV just before acceleration start. The electron beam was permanently switched on. Its effect on the beam was negligible at other parts of acceleration cycle due to large velocity difference between electrons and ions. Other operations of the injection complex were the same as for regular beam delivery to the BM@N experiment.

A usage of electron cooling greatly improved acceleration efficiency resulting in doubling in number of ions delivered to the Nuclotron top energy. With 50 mA electron beam current the longitudinal cooling time was about 100 ms. Figure 6 shows an effect of cooling on the longitudinal plane. Strong transverse cooling was also observed. The observed cooling rates open a possibility of ion accumulation in the longitudinal plane at the 10 Hz rate.

ASSEMBLY OF THE COLLIDER

An installation of the collider started at the end of 2021. The tempo was accelerated at the end of 2022 and presently proceeds well (Fig. 7). Now about half of the installation work is done for the collider arcs. An installation of RF1 and RF2 cavities, high-voltage electron cooler and other systems is scheduled for the second half of the year. Tests of the cryo-magnetic system are scheduled for the end of 2023.

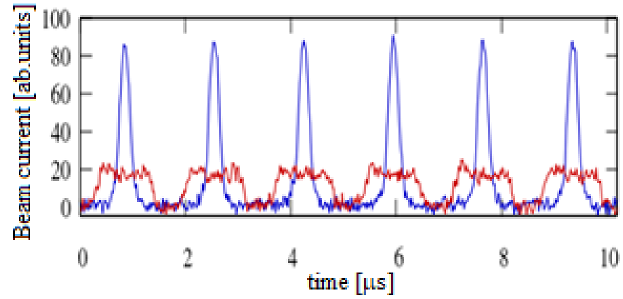

Figure 6: Dependence of ion beam current on time with (blue line) and without (red line) electron cooling at the end of injection plateau. RF harmonic number is equal to 5, electron beam current is 50 mA, cathode voltage is 1.83 kV.

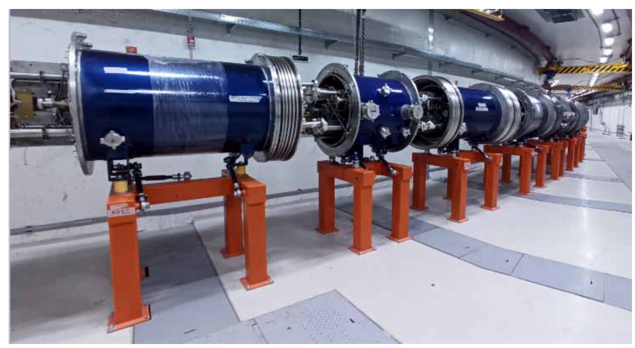

Figure 7: View of collider tunnel in April of 2023.

ACKNOWLEDGEMENTS

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