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COMMISSIONING OF NICA INJECTION COMPLEX

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Abstract

The Nuclotron-based Ion Collider fAcility (NICA) is under construction at JINR. The goal of the first stage of NICA project is to provide colliding beams for studies of collisions of heavy fully stripped ions at energies up to 4.5 GeV/u. The paper discusses results of recent commissioning run (Run IV) of NICA injection complex and plans for its further development.

INTRODUCTION

The NICA [1] injection complex has been under commissioning for more than 2 years. Its Run IV was carried from October 2022 to February of 2023. It was aimed at the injection complex preparation for the collider operations in the heavy ion mode. Additionally, the slowly extracted 3.9 GeV/u xenon beam was delivered to the BM&N experiment resulting in $2.5\cdot10^8$ events recorded by the detector. While major goals of Run IV were achieved its results revealed that an upgrade of the injection complex is required to support collider operation starting in about 2 years.

The injection complex includes:

- a new Electron String Ion Source (ESIS) (Krion-6T) generating highly charged heavy ions [2] and installed at a high voltage platform to make 16.6 keV/u ion energy for the targeted ion charge,
- 600 keV/u RFQ [3],
- 3.2 MeV/u linac (HILAC) [3],
- 600 MeV/u (A/Z=6) superconducting booster synchrotron (Booster) [4] and
- modernized main superconducting synchrotron (Nuclotron), kinetic energy up to 3.9 GeV/u (A/Z=2.5) [5].

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 in the collider mode and its main parameters are presented in Fig. 1. The reliability of the complex was low at the run beginning and was improving to its end. Overall, the complex operated 53% of time for the beam commissioning and 21% for data acquisition by BM@N [6].

ION SOURCE AND LINAC

The ion source produces highly charged heavy ions. At the Run IV 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 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].

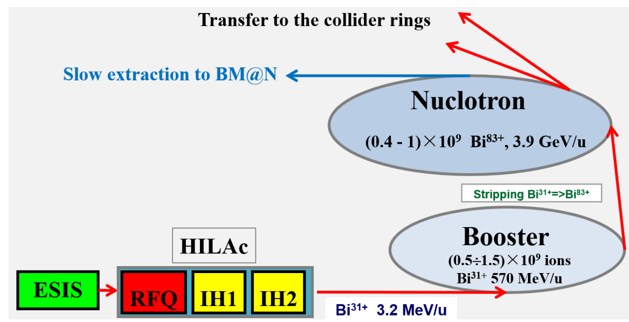

Figure 1: Schematic of the NICA injection complex.

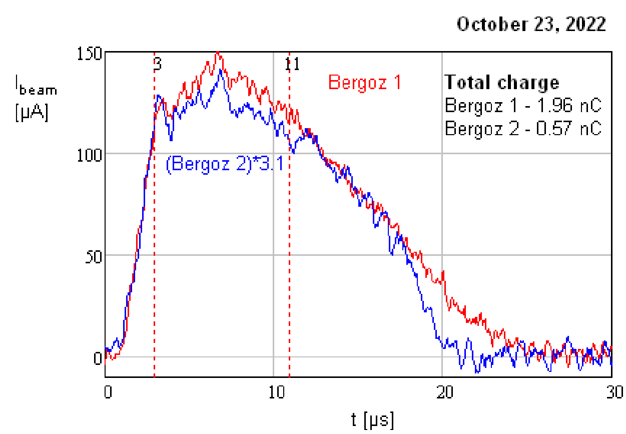

Figure 2: Typical dependencies of ion source beam current on time for ion source operation with $^{132}Xe^{28+}$ ions. Data are taken upstream (red) and downstream (blue) RFQ. The blue line was amplified by factor 3.1 to match curves. Vertical lines mark duration of one Booster revolution.

Figure 2 presents the beam current of $^{132}Xe^{28+}$ ions measured for upstream and downstream of RFQ. As one can see the RFQ accelerates about 30% of the incoming charge. We know that the RFQ accelerates few charge states simultaneously, but presently we can measure charge composition only at the very end of the linac where the first dipoles are installed. Consequently, we cannot accurately measure the beam loss distribution along the linac for the different charges of the ions.

The ion source emittance measurement has similar problem. The emittances were computed from the dependence

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of rms beam size on current of the first LEBT solenoid. The sizes were measured by the wire profile monitor. Assuming that there is only one charge state of ions we obtained the rms normalized emittances of ~100 nm with ~30% difference between horizontal and vertical planes. Emittance of ions with the targeted charge state should be somewhat smaller. Design acceptance of the RFQ should enable lossless acceleration of ions with the targeted charge but it still has to be proven by the measurements.

As one can see from Fig. 2 the duration of the pulse is much longer than the Booster revolution time at injection. Consequently, about half of the ions are lost due to excessive ion pulse duration. The pulse duration and loss were smaller for argon ions used at the run beginning [6] and, if not addressed, expected to be larger for heavier bismuth ions required for the collider.

Tedious tuning of the linac and fixing few hardware problems resulted in its stable operation. The beam energy was measured by the revolution time at the Booster injection. At time of the measurement the energy was 3.203±0.001 MeV/u which coincides well with the design value of 3.2 MeV/u.

BOOSTER AND NUCLOTRON

In addition to addressing multiple 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.

The ring optics was measured with differential orbits. Good coincidence between the measurements and the optics model were found, thus, confirming good quality of Booster magnets. The only correction required in the model is a minor adjustment (<1%) of overall quad strength to obtain correct tunes and minor quad rotations to obtain observed coupling. 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 have been driven by the same software. The differences in hardware are accounted in the configuration files. In the future 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 ion beam acceleration.

Another important part of the complex commissioning was characterization of RF systems, adiabatic 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 the run the RF voltage was equal to zero at the injection. As result, the beam debunched within few hundred turns. Then the beam was adiabatically bunched at the 5th harmonic and accelerated to ~65 MeV/u where it is debunched and rebunched at the first harmonic. This rebunching enabled 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 RF harmonic was present. The bunch-to-bunch transfer is supported by the Nuclotron Low Level RF system which phase is bound to the transfer time 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 short and only minor correction accounting dependence of synchrotron frequency on 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 process considerably improved uniformity of the spill.

ELECTRON COOLING

At the Run end the electron cooling was introduced into operation. The cooler magnetic field has considerable effect on the beam orbit and 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 turning on of the cooling.

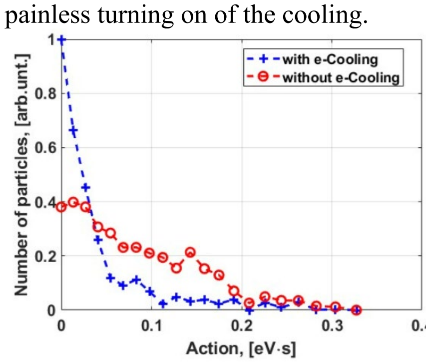

Figure 3: Longitudinal particle distribution with (blue line) and without (red line) electron cooling at the end of injection plateau. RF harmonic number is equal to 5, electron beam current is 98 mA.

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 7.4 kV just before acceleration start. The electron beam was switched on during the entire acceleration cycle. 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 the number of ions delivered to the Nuclotron top energy. With 50 mA electron beam current the longitudinal cooling time was about 70 ms. Fig. 3 shows an effect of cooling on the longitudinal distribution. Strong transverse cooling was also observed.

PREPARATIONS FOR THE NEXT RUN

To support the collider operation, we need to increase the number of ions delivered to the Nuclotron top energy by about 2 orders of magnitude. It will be achieved by the ion accumulation in the Booster with help of electron cooling and by reduction of the beam loss during beam acceleration and transfers.

Since the longitudinal cooling is much faster than transverse, we choose the beam accumulation in the longitudinal plane. In this case about half of the Booster orbit is given to the accumulated stack, and another half is assigned for the injected beam. The electron cooling has to free the injection space before next injection. Calculations, supported by the above presented results on electron cooling, determine the optimal stacking rate of about 10 Hz; and ~15 injections are required to obtain the beam population limited by its space charge at the injection energy. Thus about 1.5 s of 5.5 s acceleration cycle will be used for the beam accumulation in Booster. A 10 Hz operation of KRION-6 ion source with 10 pulses was recently demonstrated with $^{124}Xe^{28+}$ ions. Better tuning of ion source resulted in an increase of total charge from 2.4 to 3 nC.

Next step in the ion source upgrade is aimed on shortening the pulse duration to 4 µs. As one can see in Fig. 2 the measured pulse has long tail. It is associated with time required for ions to leave the ion trap electrodes (15 pipes, 4 mm diameter and 5 cm long) inside which the extraction voltage does not penetrate. Changing shape of these electrodes, so that to make uniform extraction field, should allow us to obtain the required 4 µs pulse. A special time program for powering the electrodes should additionally form rectangular pulse shape in time and decrease the energy spread of outcoming ions.

The linac was not originally built to support 10 Hz operation. Therefore, a considerable number of hardware pieces has to be upgraded to withstand higher power. This work is already proceeding and we expect the linac to be ready for 10 Hz operation by the end of 2023.

The beam accumulation in Booster will be done at the 1st RF harmonic. The RF bucket height of $(\Delta p/p)_{max} = 1\cdot10^{-3}$ was chosen to maximize the cooling rate. It requires the RF voltage of 200 V. To minimize the longitudinal emittance growth, we plan to avoid rebunching in the course of acceleration. Thus, the entire acceleration will proceed at the first harmonic. Since at the accelerator cycle beginning the RF frequency is outside nominal operation frequency band the initial RF voltage will be lower (~1.5 kV). That lengthens the accelerating cycle by 300 ms – the time which will be spent for rebunching otherwise.

Bunch-to-bunch Booster-Nuclotron transfers were tested and used through Run IV. Beam capture and acceleration in Nuclotron were done at 4th revolution harmonic. That resulted in considerable beam loss since the Nuclotron RF bucket acceptance was insufficient to capture the entire longitudinal emittance of Booster beam. During Run IV we transferred the beam at half of Booster energy due to incompletion of Nuclotron injection system. At the next Run we will do transfers at the maximum beam energy. It will reduce the beam size in the transfer line and increase the acceptance of Nuclotron RF bucket, thus minimizing the beam loss at Booster Nuclotron transfers.

Work on the orbit correction in the rings and transfer lines and optimization of beam injection together with the above-mentioned actions should increase the efficiency of beam acceleration from about 5-10% to above 50% where the major contribution to the beam loss will be efficiency of beam stripping ~70%. Note that the electron cooling will be used not only for beam accumulation but also to forming optimal beam emittances.

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