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NUCLOTRON DEVELOPMENT FOR NICA ACCELERATION COMPLEX

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Abstract

The Nuclotron is the basic facility of JINR used to generate beams of protons, polarized deuterons and protons, and multi charged ions in the energy range of up to 5.6 GeV/n. Polarized deuteron and proton beams were obtained at the intensity of 2×10^9 ppp and 10^8 ppp, respectively. The injection with RF adiabatic capture was used in two last Nuclotron runs where C^{6+}, Xe^{42+}, Kr^{26+} and Ar^{16+} ion beams were accelerated. The resonant stochastic extraction (RF knockout technique) was realized. The complex is now used for fixed target experiments with extracted beams and experiments with an internal target. In the near future, the Nuclotron will be the main synchrotron of the NICA collider facility being constructed at JINR. The installation in the Nuclotron of beam injection system from the Booster and of the fast extraction system in the Collider are required for its operation in the NICA complex. In the frame of the Nuclotron injection chain upgrade, a new light ion linac (LILac) for protons and ions will be built.

INTRODUCTION

NICA (Nuclotron-based Ion Collider fAcility) is a new accelerator complex being developed and constructed at JINR [1] to search for the mixed phase of baryonic matter and to investigate the nature of nucleon/particle spin. Ion beams from p to Au ions with energies from a few hundred MeV/u to a few GeV/u will be provided for the NICA collider by two injection LINACs and two superconducting synchrotrons, the currently assembled Booster and the operating Nuclotron (Fig. 1).

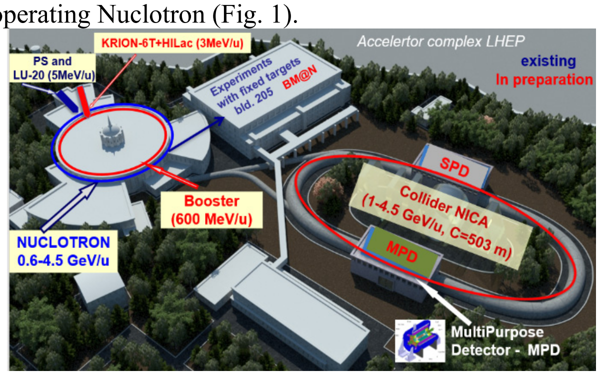

Figure 1: The NICA complex.

The Nuclotron based on the unique technology of the superconducting magnetic system [2]. All design, tests and assembling works were carried out at JINR. Fifty-five Nuclotron runs have beam performed since March 1993. The Nuclotron is currently used for fixed target experiments. During the last few years, all the systems of the ring were completely modernized and prepared for long and stable operation in the NICA complex. The Booster superconducting ring is now under assembling. The Booster ring commissioning is planned for 2019. The main goals of the Booster and Nuclotron rings in the heavy ion program are the following: formation of Au^{79+} ion beams with the intensity of 10^9 ppp; acceleration of heavy ions to the energy required for injection in the collider rings. Installation in the Nuclotron of the beam injection system from the Booster and of the fast extraction system in the Collider [1] are required for the Nuclotron to operate as the main synchrotron of the NICA complex. The kickers and Lamberson magnets should be constructed for the injection and extraction sections. The Nuclotron is the JINR basic facility for high-energy physics. The Nuclotron accelerator complex consists of the Alvarez-type linac LU-20, superconducting synchrotron Nuclotron equipped with an internal target, slow extraction system, and facilities for fixed target experiments. The beams are generated by three new ion sources: SPI (Source of Polarized Ions), LIS (Laser Ion Source), and Krion (ESIS type heavy ion source). The Nuclotron program includes experimental studies on relativistic nuclear physics, spin physics, and physics of flavors. At the same time, Nuclotron beams are used for applied researches in radiobiology and relativistic nuclear power. The last Nuclotron runs were dedicated to spin physics experiments with polarized deuteron and proton beams and formation of the heavy ion beams for the fixed target BM&N experiments.

FORMATION AND ACCELERATION OF POLARIZED DEUTERON AND PROTON BEAMS

Upgrade of many Nuclotron systems was oriented to formation and acceleration of polarized deuteron and proton beams for the polarized collider mode of the NICA project.

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A new source of polarized ions (SPI) - protons and deuterons - was constructed by the JINR-INR collaboration. The present beam current of polarized deuterons corresponds to 3 mA.

The injector of polarized protons, deuterons, and light ion beams is based on the existing conventional Alvarez-type DTL LU-20 at the frequency of 145.2 MHz.

The upgrade of this injector includes replacement of the 700-kV DC acceleration tube for the drift-tube linac with an RFQ. The RFQ provides 156 keV/u ion beams for subsequent acceleration by the DTL at 2βλ-mode to the energy of 5 MeV/u and was successfully commissioned in 2016.

Designing of the 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 for acceleration of light ions and protons to the energy of 7 MeV/u, a warm medium energy section for proton acceleration to the energy of 13 MeV, and superconducting HWR sections, which provides proton acceleration to the energy of 20 MeV. LILAc should provide the beam current of 5 emA.

The last Nuclotron runs were carried out using the source of polarized ions SPI. Optimization of the SPI regimes and polarimetry were methodological tasks of the runs. Initially, intensity of polarized deuteron beams was obtained at the level of (2-5) $\times 10^8$ particles per cycle.

Development of the diagnostics, investigations of dynamic behaviors of the Booster power supply prototypes with the beam acceleration, tests of a new current source for optic elements in the extracted beam lines, and investigations of stochastic cooling were the main goals of the machine development. Polarized deuterons were accelerated to the energy of 4.6 GeV/u. (Fig. 2).

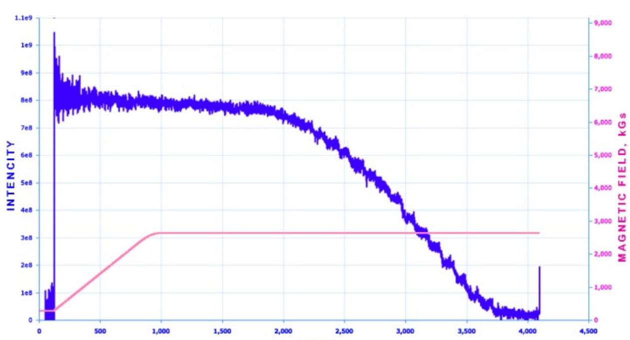

Figure 2: Intensity of the polarized deuteron beam (blue curve) and magnetic field (pink curve) during an acceleration cycle.

Further optimization of the SPI and routine operation with adiabatic capture at injection permitted increasing the polarized deuteron beam intensity to 2×10^9 particles per cycle. The maximum achieved extracted beam energy was 5.2 GeV/u (which corresponds to 1.85 T of the dipole magnetic field). An acceptable quality of the slow extraction was achieved in the total energy range.

Further machine development was concentrated on demonstration of polarized proton beam acceleration. The LU-20 was designed for the proton acceleration to 20 MeV. Now protons can be accelerated in the LU-20 only at the second harmonic and the output proton energy is 5 MeV. At this energy, the Nuclotron dipole magnetic field at injection has to be about 150 G (instead of about 290 G for other ions). Decrease of the field at injection leads to stronger influence of residual fields on the closed orbit and requires stabilization of the magnet power supply at a small current. In future, this problem will be solved by replacing the LU-20 with the new LILAc; however, during the nearest few years the facility will be operated at the current conditions. Because of high importance of the polarized proton program the following was consequently done: tuning of the LU-20 and the injection channel for the proton acceleration, orbit correction at injection at a low dipole magnetic field, working point adjustment and stabilization at a low current of the power supply, and tuning of acceleration regime.

As a result, a polarized proton beam with the intensity of 10^8 ppp was successfully accelerated (Fig.3) and polarization was measured at the internal target and the extracted beam.

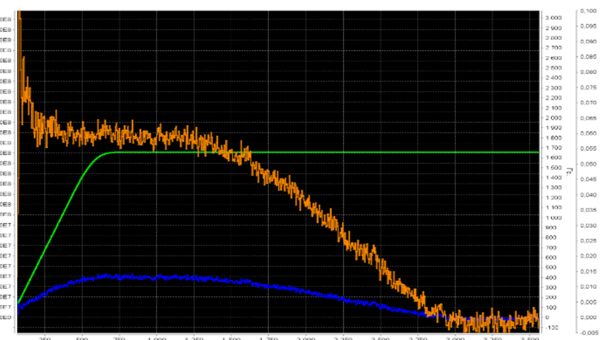

Figure 3: Intensity of the polarized proton beam (orange curve) and magnetic field (green curve) during an acceleration cycle. Measurements of the polarization at the Nuclotron internal target.

During acceleration, the proton beam crosses two spin resonances, and the decrease in the degree of polarization was used as a benchmark of the Nuclotron mathematical model. Special measures to keep the proton polarization in the Nuclotron are under development now. In the future, a spin-rotator in the LU-20 - Nuclotron transfer channel will be necessary for acceleration of a polarized proton beam (alternatively, the spin orientation can be adjusted in the SPI).

HEAVY ION BEAM FORMATION, ACCELERATION, AND EXTRACTION

The last Nuclotron runs were used to test the BM@N detector elements. BM@N (Baryonic Matter at Nuclotron) is the fixed target experiment with heavy ions supposed to be the first stage of the NICA experimental program. During last run #55, experiments for relativistic nuclear physics at BM@N and radiobiology researches were performed with carbon, argon, and krypton beams. For realization of the NICA scientific program, heavy ion

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beams at intensities of 10^9 ions per cycle will be accelerated in the Nuclotron using a new injection chain including a new heavy ion linear accelerator and the Booster. Last Nuclotron run #55 was performed with the existing injection chain that can provide beam intensity for Ar or Kr ions about 2 - 4 orders of magnitude lower than this ultimate goal. Therefore, accurate tuning of all elements of the facility was necessary to minimize particle loss at all acceleration and extraction stages.

To adjust bunch parameters after RFQ with the LU-20 RF bucket, the buncher cavity was installed in the Medium Energy Beam Transfer and tuned for the beam acceleration using a laser ion source in 2018. In parallel, the KRION-6T was tuned for generation of carbon, argon, and krypton beams at the test bench, and then it was transported to the Nuclotron accelerator facility. The beam intensity was obtained at the level of about $4{\cdot}10^7$ ppp for Ar^{16+}, and for of $1{\cdot}10^7$ ppp Kr^{26+}at the entrance of the Nuclotron. For instance, for the argon beam the switch on the buncher and accurate tuning of the phase and amplitude of its RF field permitted the intensity of the accelerated beam to be increased by about a factor of five.

For a few Nuclotron runs the beam extraction efficiency at the energy larger than about 3 GeV/n was limited by the Electro-Static Septum (ESS). Achievement of high voltage was restricted by discharges at the level of about 120 kV. Intensive training of the ESS during the last runs (for a total of about 3000 h) permitted an increase in voltage to 150 kV, which corresponds to well control beam extraction in the total required energy range.

All these measures and usage of the adiabatic capture for acceleration in the Nuclotron permitted the intensity of the extracted argon beam to be increased by more than a factor of ten in comparison with the previous heavy ion run in 2014.

Long-term stability of the beam parameters at the BM@N detector target is determined by the quality of the power supply of the extracted beam optics. The beam transport line from the exit of the Nuclotron to the target of the BM@N detector, which is about 160 m long, includes 8 dipole and 18 quadrupole magnets. In run #55 their power supply system was partially modernized. A few new supply units were put into operation, including a 2.5 MW source at the current stabilization of 10^{-4} for the large-aperture BM@N dipole magnet. A precise measurement system based on LEM sensors and a remote control system were created.

Stability of the beam intensity during the spill at the extraction from the Nuclotron is provided by controllable displacement of the working point into the nonlinear third-order resonance of the horizontal oscillations. Two families of sextupole lenses adjust the phase and the amplitude of the nonlinearity. The family of extraction quadrupoles determines the choice of the working point. The feedback based on the PID regulator controls the gradient of the extraction quadrupoles and stabilizes the extracting beam intensity. A special fast current source is used for the quadrupole supply. This scheme provided the required spill quality at the beam intensity from a few 10^{10} ions down to about 10^7 particles per cycle. However, at intensity of the order of 10^5 the output current has relatively large ripple with intensity notches of a few tens of microseconds. One of the ways to improve the slow extraction quality at low intensity is to use stochastic extraction that was used for instance at LEAR for antiproton extraction at the spill duration of 2 h. The uncontrolled stochastic extraction was tested at the Nuclotron during run #54 when the amplitude of the horizontal oscillations was excited by wide-band noise applied to the diagnostic kicker of the Q-meter system. During run #55, a hybrid method of the beam extraction was tested and used in the routine regime. The working point was moved by the extraction quadrupole that operated with feedback simultaneously with noise influence on the horizontal oscillations. The direct current coefficient obtained in this way was larger than 90% at intensities down to 10^5 particles per spill (Fig. 4).

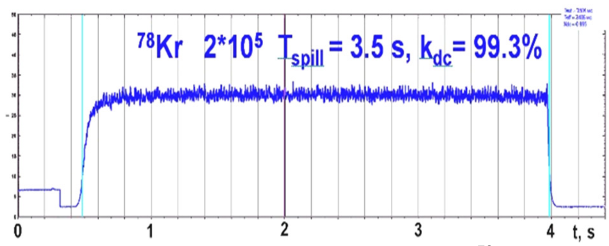

Figure 4: Time dependence of the extracted ^{78}Kr beam intensity at energy of 2.8 GeV/u.

Injection with RF adiabatic capture at the efficiency of 80% was used in the last two Nuclotron runs. During run #55, beam injection adjustment, adiabatic capture regime, closed orbit correction, and beam acceleration were provided using carbon beams with intensity sufficient for standard Nuclotron diagnostics (beam position monitors, current transformers) and mass-to-charge ratio close to the accelerated argon and krypton ions. Fine-tuning of the acceleration at low intensities was performed with specially developed diagnostic equipment. This equipment includes an ionization profile monitor on the basis of the MCP, a scintillation hodoscope providing dynamic profiles installed at the beginning of the extracted beam line, and scintillation counters installed in the transport line that were used for the tuning of the extraction and measurement of the nuclear fragment spectrum.

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[2] N. Agapov et al, "Nuclotron at JINR: Operation Experience and Recent Development", HIAT'2015, Japan, MOPA19, p.86.