ISBN: 978-3-95450-197-7 doi:10.18429/JACoW-RUPAC2018-TUZMH04

STATUS OF THE NUCLOTRON

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Abstract

Since last RuPAC two runs of the Nuclotron operation were performed. The run #54 performed in February – March of 2017 was dedicated to polarized beam acceleration. One of the achievements was the acceleration of polarized proton beam performed at the Nuclotron for the first time. During the run #55 in February- April of 2018 the Nuclotron provided heavy ion beams for first fixed target experiments in the frame of the NICA scientific program. These and other results of the facility operation and development are presented.

INTRODUCTION

The Nuclotron is the basic facility of the Veksler and Baldin laboratory for high energy physics (VBLHEP). The accelerator complex consists of Alvarez-type linac LU-20, superconducting synchrotron Nuclotron equipped with an internal target station, slow extraction system and facilities for fixed target experiments. The program includes experimental studies on relativistic nuclear physics, spin physics and physics of flavours. At the same time, the Nuclotron beams are used for research in radiobiology and applied research. In future the Nuclotron will be main synchrotron of the NICA facility being constructed at JINR [1].

The Nuclotron operational time is optimizing in accordance with the JINR topical plans with account the plan of the NICA construction. The Nuclotron run #53 started 26 of October 2016 was successfully completed 25 of December. It was longest (about 1400 h) run in the Nuclotron history. This and the next run (#54, provided at the beginning of 2017) were dedicated to spin physics experiments with polarized deuteron beams and test of the BM@N detector elements with deuteron and light ion beams. BM@N (Baryonic Matter at Nuclotron) is the fixed target experiment with heavy ions realizing as a first stage of the NICA experimental program. In the frame of machine development works during the run #54 the acceleration of polarized proton beam was performed at the Nuclotron for the first time. Preparation for the heavy ion run #55, started just after completion of the run #54, included development and tuning of the Nuclotron injection complex [see in details in 2], development of low intensive beam diagnostics, improvement of power supply of optic elements in the extracted beam lines. During the run #55 provided in February – April of 2018 the experiments for relativistic nuclear physics at BM@N and radiobiology researches were performed with carbon, argon and krypton beams.

In September 2018 assembly of the Nuclotron Booster was started.

STATISTICS OF OPERATION

Main task of the run #53 (26.10-25.12.2016) was experimental investigations in spin physics in few body nuclear systems (with polarized deuterons). Unpolarized deuteron beams were used for test of BM@N and MPD elements. Development of the diagnostics, investigations of dynamic behaviors of the Booster power supply prototypes with the beam acceleration, test of new current source for optic elements in the extracted beam lines, investigations of stochastic cooling were the main goals of the machine development. The run was provided using the source of polarized ions (SPI). Optimization of the SPI regimes and polarimetry were methodical tasks of the run. 77.6% from 1400 hours of the run duration were spending for experiments with the beams at energy up to 4.6 GeV/u. Intensity of polarizes beams was obtained at the level of $2 \div 5 \cdot 10^8$ particles per cycle (Fig. 1).

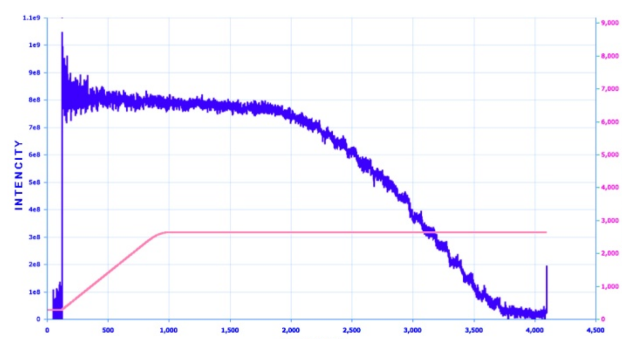

Figure 1: Intensity of polarized deuteron beam (blue curve) and magnetic field (pink curve) during acceleration cycle. Deuteron Spin Structure experiment provided at the Nuclotron internal target

Run #54 provided from 10.02 till 24.03.2017 was dedicated to acceleration of polarized and unpolarized deuterons and protons from the SPI, carbon and lithium ions from the laser source. Maximum achieved extracted beam energy was 5.2 GeV/u (that corresponds to 1.85 T of the dipole magnetic field). In the total energy range an acceptable quality of the slow extraction was achieved. Further optimization of the SPI and routine operation with

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adiabatic capture at injection permitted to increase the polarized deuteron beam intensity up to 2*10^9 particles per cycle. Machine development works were concentrated on demonstration of polarized proton beam acceleration.

Main task of the run #55 (provided in the period from 22.02 till 05.04.2018) was to start experimental program at BM@N and to provide radiobiology research with heavy ions. The run was performed with KRION-6T ion source (ESIS type) optimized for generation of carbon, argon and krypton beams. 60% of the run duration was spending to fulfillment of the experimental program. Combination of resonant and stochastic slow extraction was used to provide acceptable beam quality at low intensity in the total energy range.

ACCELERATION OF POLARIZED PROTON BEAM

LU-20 was designed for the proton acceleration to 20 MeV. The injection energy of about 625 keV was provided by High Voltage (HV) transformer. The deuterons and light ions were accelerated at second harmonics for output energy of 5 MeV/u. This regime requires the injection energy of 156 keV, which was provided by the same HV transformer. After modernization of the injection facility the HV transformer was replaced by new RFQ fore-injector that provides output energy of 156 keV for all types of ions. Presently the protons can be accelerated in LU-20 at the second harmonics only 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 more strong influence of residual fields on the closed orbit and requires stabilization of the magnet power supply at small current value. In future this problem will be solved by replace of LU-20 by new modern Linac [3], however during nearest few years the facility will be operated at the current conditions.

Because of high importance of the proton program (including acceleration of the polarized proton beams) 4 shifts of the run #54 were spent to test a possibility of the proton acceleration. To perform the tuning of the accelerator complex in this new regime the following works were consequently done:

- tuning of LU-20 and injection channel for the proton acceleration,
- orbit correction at injection at low value of the dipole magnetic field,
- working point adjustment and stabilization at low current of the power supply,
- tuning of acceleration regime.

As result the polarized proton beam was successfully accelerated (Fig. 2) and measurements of polarization were provided at internal target and extracted beam. During acceleration the proton beam crosses two spin resonances and decrease of the polarization degree was used for benchmark of the Nuclotron mathematic model. Special measures to keep the proton polarization in the Nuclotron are under development now. In future for acceleration of polarized proton beam a spin-rotator in the LU-20 - Nuclotron transfer channel is necessary (alternatively the spin orientation can be adjusted in SPI).

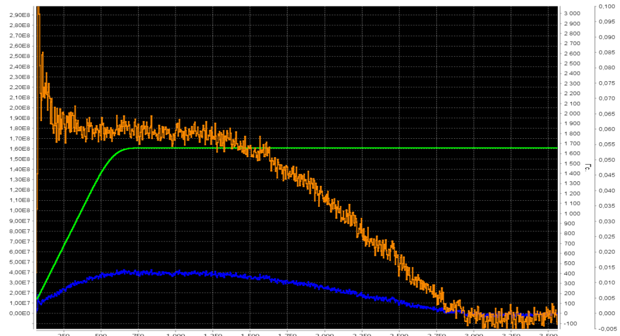

Figure 2: Intensity of polarized proton beam (orange curve) and magnetic field (green curve) during acceleration cycle. Measurements of the polarization at the Nuclotron internal target

HEAVY ION BEAM ACCELERATION AND EXTRACTION

Main goal of the run #55 was to provide heavy ion beams at intensities required for the first experiments in the frame of the NICA scientific program. In future the heavy ion beams at intensities up to 10^9 ions per cycle will be accelerated in the Nuclotron using new injection chain including new heavy ion linear accelerator and the Booster. The run #55 was performed with existing injection chain that can provide beam intensity for Ar or Kr ions of about 2 - 4 orders of magnitude less than this ultimate goal. Therefore an accurate tuning of all elements of the facility was necessary to minimize particle loss at all stages of the acceleration and extraction.

To provide adjustment of the bunch parameters after RFQ with the LU-20 RF bucket the buncher cavity in the Medium Energy Beam Transfer [2] was installed in June 2018 and preliminary tuned for the beam acceleration using a laser ion source. In parallel the KRION-6T was tuned for generation of carbon, argon and krypton beams at test bench. In October the ion source was transported to the accelerator facility. To the beginning of February 2018 the intensity for Ar^{16+} beam was obtained at the level of about $4 \cdot 10^7$ ions per injection an for Kr^{26+} of about $1 \cdot 10^7$ at the entrance of the Nuclotron. For instance, for argon beam the switch on the buncher and accurate tuning of the phase and amplitude of its RF field permitted to increase the intensity of the accelerated beam by about 5 times.

For a few Nuclotron runs the beam extraction efficiency at the energy larger than about 3 GeV/n was limited by Electro-Static Septum (ESS) performance. The achieving High Voltage was restricts by discharges at the level of about 120 kV. Intensive training of the ESS during the runs #52 - #54 (at total duration of about 3000 h) permitted to increase the Voltage up to 150 kV

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that corresponds to well control beam extraction in the total required energy range.

All these measures and usage of the adiabatic capture to acceleration in the Nuclotron permitted to increase intensity of the extracted argon beam by more than 10 times in comparison with previous run with the same ion source performed in June 2014.

Optimum operation of the BM@N detector demands long term stability of the beam profiles at the target and stability of the beam intensity during the spill.

Long term stability of the beam parameters at the target is determined by 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 of the length of about 160 m includes 8 dipole and 18 quadrupole magnets. During preparation to the run #55 their power supply system was partially modernized. A few new supply units were put into operation including 2.5 MW source at the current stabilization of 10^{-4} for large aperture BM@N dipole magnet (tested during the run #54). Precise measurement system on the basis of LEM sensors and 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 non-linear 3-d order resonance of the horizontal oscillations. Phase and amplitude of the non-linearity are determined by two families of sextupole lenses. The working point is determined by family of extraction quadrupoles. Feedback realized on the basis of PID regulator controls the gradient of the extraction quadrupoles and stabilizes the extracting beam intensity. For the quadrupole supply a special fast current source is applied. This scheme realized in 2002 provided required spill quality at beam intensity from a few 10^{10} 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 msec. One of the ways to improve the slow extraction quality at low intensity is to use stochastic extraction [4] that was used for instance at LEAR for antiproton extraction at the spill duration up to 2 hours. The uncontrolled stochastic extraction was tested at the Nuclotron during run #54 when for the amplitude of the horizontal oscillations was exited by wide-band noise applied to diagnostic kicker of Q-meter system. During the run #55 a hybrid method of the beam extraction was tested and used in routine regime. The working point was moved by the extraction quadrupole operated with feedback simultaneously with noise influence on the horizontal oscillations. By this way the direct current coefficient was obtained at the level larger than 90% at intensities down to 10^5 particles per spill (Fig. 3). The notches of intensity and 50 Hz harmonics were absent.

During the run #55 preliminary adjustment of the beam injection, regime of the adiabatic capture, the closed orbit correction and the beam acceleration was provided using carbon beams which intensity was sufficient for standard Nuclotron diagnostics (beam position monitors, current transformers) and mass to charge ratio is close to the accelerated argon and krypton ions.

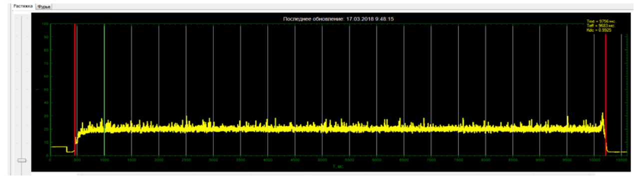

Figure 3: Time dependence of the extracted ^{78}Kr beam at energy of 2.8 GeV/u. The number of extracted particles is $2*10^5$, the spill duration is 10s, k_{dc}= 99,3%.

Fine tuning of the acceleration at low intensities was performed with especially developed diagnostics including ionization profile monitor on the base of MCP located in the Nuclotron “hot” section, scintillation horoscope providing dynamic profiles installed 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 measurements of nuclear fragment spectrum. The diagnostics were used during total run duration in parallel with the first user.

CONCLUSION

Main results of the VBLHEP accelerator complex development during last two years are the following.

Adiabatic capture of the beams at injection into the Nuclotron at efficiency of about 70% was used in routine operation. Possibility of the polarized proton acceleration was demonstrated. Presently the slow extraction system provides required beam quality at dipole magnetic field up to 1.85 T and at the beam intensity in the range from 10^4 to 10^{10} particles/sec. NICA experimental program with heavy ion was started.

The Booster assembly has been started in September of 2018. The Booster technological run is scheduled for the end of 2018.

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