STATUS OF THE NUCLOTRON

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Abstract

Since last RuPAC five runs of the Nuclotron operation were performed. Diagnostic and control systems were improved. Commissioning of new quench detection system was completed. Deuteron beam was accelerated up to maximum design energy corresponding to 2 T of the dipole magnetic field. Stochastic cooling of coasting deuteron, coasting and bunched carbon beams was obtained. First run with new heavy ion source was performed. Results of these and other works are presented.

INTRODUCTION

The Nuclotron is used presently for fixed target experiments on extracted beams and experiments with internal target. The program includes experimental studies on relativistic nuclear physics, spin physics in few body nuclear systems (with polarized deuterons) and physics of flavours. At the same time, the Nuclotron beams are used for research in radiobiology and applied research.

Five Nuclotron runs (#46 ÷ #50) at total duration of about 4000 h were performed in the period from November 2012 till June 2014. About 70% of the runs were spending for experiments with accelerated beams (cooling down and preparation of the machine required about 25%). For more efficient usage of the beam time, during the run #49 the regime with two parallel users was realized routinely: experiment with internal target at the first plateau and beam extraction at the second one.

Improvement of the cryogenic complex performance, better cooling conditions of the magnetic system, modernization of quench detection system permitted gradual increase of the beam energy. As result during the run #48 (December 2013) the carbon beam was accelerated and extracted at maximum design energy corresponding to dipole magnetic field of 2 T.

Deuteron, lithium, carbon and argon beams were delivered for the experiments. Increase of the beam intensity and widening of the ion species are related with construction of three new ion sources: SPI (Source of Polarized Ions), LIS (Laser Ion Source), Krion-6T (ESIS type heavy ion source) [1]. New powerful laser was tested for the carbon beam generation during the run #48. For the first time Krion-6T was operated at the Nuclotron during the run #50.

Development of slow extraction system resulted in realization of acceptable quality of the extracted beam in the interval of the spill duration from 60 ms to 20 s.

In addition to the implementation of the current physics program the Nuclotron having the same magnetic rigidity as the future NICA collider [2] and based on the same type of the magnetic system is the best facility for testing of the collider equipment and operational regimes. Development works for NICA performed during recent Nuclotron runs include the testing of elements and prototypes for the MPD (Multy Purpose Detector which will be operated at the collider) using extracted deuteron beams; operational tests of the automatic control system based on the Tango platform, which has been chosen for the NICA facility; tests of diagnostic equipment for the Booster – small superconducting synchrotron constructing in the frames of the NICA project to improve the Nuclotron performance.

Simulation of the collider magnetic system operational conditions was performed at the Nuclotron during runs #45-47 (in years 2012-2013). This presumed test of the Nuclotron systems in the operational mode with long plateau of the magnetic field. In the run #45 the circulation of accelerated up to 3.5 GeV/u deuteron beam during 1000 seconds was demonstrated. During the runs #46 and #47 such a regime was used for test of stochastic cooling at the Nuclotron, which is an important phase of the NICA collider cooling system design.

In this report we are concentrated on the most important results of these works.

DEVELOPMENT OF THE ION SOURCES

The new LIS is based on commercially available Nd-YAG laser LPY 7864-2 providing output energy of 2.8 J at wave length of 1064 nm [3]. The new laser was investigated at test bench (Fig. 1) during outman 2013 and thereafter it was used at the Nuclotron run.

During the run the source and the LU-20 (linac using for injection into the Nuclotron) operation was optimized at acceleration of C^{5+} and C^{6+} ions. The current of C^{6+} beam reach to about 1.5 mA at the linac output. The pulse duration was of about 3 μs. Routinely the injector was operated in C^{5+} mode because of larger output beam current (up to 3 mA) and slightly longer the pulse duration - about 4 μs (the beam revolution period in the Nuclotron is about 8 s at injection energy). The carbon

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beams were delivered to both the Nuclotron users and stochastic cooling experiments during about two weeks.

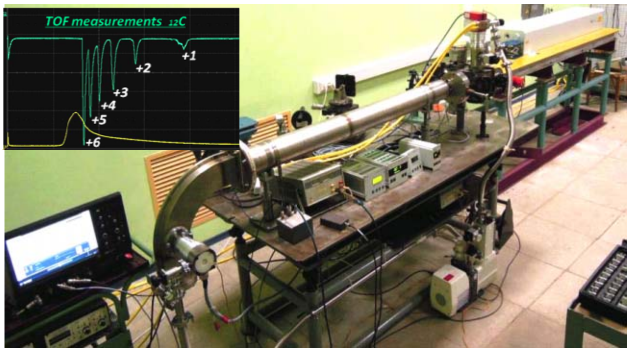

Figure 1: Nd-YAG laser at the test bench.

Krion-6T is a prototype of the heavy ion source which will be used for operation at new heavy ion linear accelerator – the HILac. Construction and assembly of Krion-6T were completed in spring 2013 and full-scale tests in reflex mode of operation had been started at a test bench. After reaching of 5.4 T of the solenoid magnetic field in a robust operation (the design value is 6 T) the $Au^{30+} \div Au^{32+}$ ion beams have been produced at intensity of about $6 \cdot 10^8$ particles per pulse. The required ionization time is 20 ms. The obtained parameters are close to the HILac requirements.

In difference with the heavy ion source used at the Nuclotron before the magnetic field and electron beam energy are sufficiently increased. Design of a few elements is changed also. Therefore, after investigations at the test bench, the source was optimized for production of ions with charge to mass ratio of $q/A \geq 1/3$ in order to provide complex test of all its systems at existing injection facility. In May 2014 the source was installed at high-voltage platform of the LU-20 fore-injector (Fig. 2).

Figure 2: Krion-6T at high-voltage platform of LU-20 fore-injector [3].

During about 250 h of operational time the source systems and linac were optimized for generation of different ion species. As result the Ar beams were accelerated and delivered for experiments.

NUCLOTRON TESTS STOCHASTIC COOLING FOR NICA

Application of the beam cooling methods (electron and stochastic) in the NICA collider rings has the purposes of beam accumulation using cooling-stacking procedure and luminosity preservation during experiments. During 2011-2013 the elements of the stochastic cooling chain for test at the Nuclotron were designed, constructed and installed at the ring. Main parameters of the system are the following: bandwidth 2-4 GHz, optimal beam kinetic energy 3.5 GeV/u, system (and notch filter) delay accuracy 1 ps, N_{ion}~1e9. This work performed in close collaboration with the Forschungszentrum Jülich (FZJ) is also important to FZJ for testing elements of the stochastic cooling system designed for the High-Energy Storage Ring (HESR, FAIR) [4]. In March 2013 (run #47) the effect of the longitudinal stochastic cooling using notch-filter method had been demonstrated at the Nuclotron for the first time (Fig.3). Experimentally obtained characteristic cooling time is in good agreement with simulation results. The beam cooling system includes ring-slot couplers as pick-up and kicker (designed at FZJ), unique optical notch-filter and a full remote-controlled automation of measurements and adjustments [5].

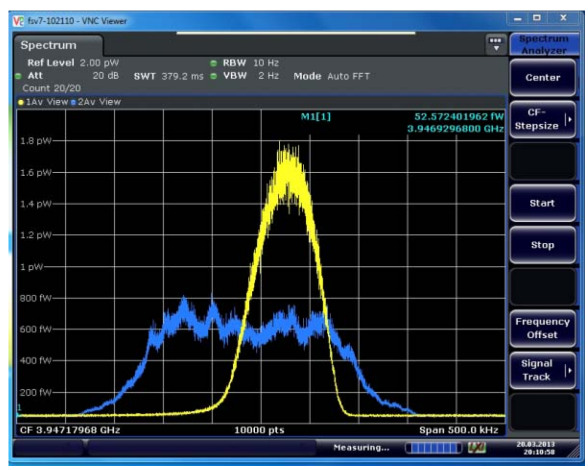

Figure 3: A longitudinal Schottky spectrum of the 3 GeV/u deuteron beam at 3500th harmonics of the revolution frequency, showing the initial spectrum (blue curve) and after 8 minutes of cooling (yellow curve). The beam intensity is $2x10^9$ ions.

The experimental investigation of stochastic cooling was a complex test of machine performance. During the experiment, the cryogenic and magnetic systems, power supply, cycle control and diagnostic equipment were operated stably in a mode in which the circulation time of the accelerated beam at the flat-top of the magnetic field was gradually increased from a few tens of seconds up to eight minutes.

The safe operation of the magnetic system was guaranteed by a new quench-detection system commissioned during the runs #46-47. It permits a prompt

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change in the number of detectors, uniform work with the group and individual detectors and implementation of the total reservation of the line controlling the energy evacuation system. The system provides monitoring of the status of all of its components, as well as signal-testing of external systems, and also indicates malfunctions [6].

The next step of the stochastic cooling experiments was dedicated to test of a bunched beam cooling (such a regime corresponds to luminosity preservation during collider experiment). Partial modernization of the Nuclotron RF accelerating system permitted to prolong the RF pulse duration up to about 25 s. Thereafter during the run #48 (December 2013) the stochastic cooling effect had been successfully demonstrated in both for coasting and bunched carbon beams (Fig.4) [7]. In the last case the bunching factor (ratio between peak and mean current) was about 5.

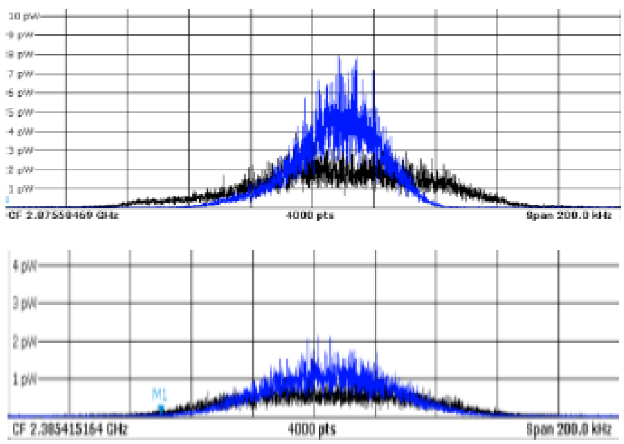

Figure 4: Experimental results of beam stochastic cooling of coasting $^{12}C^{6+}$ and bunched $^{12}C^{6+}$. Schottky beam spectra: black – initial beam, blue – cooled beam.
Upper: coasting beam, I~2e9 ions, E=2.5 Gev/u, $dP/P_{initial}$=0.15e-3, dP/P_{final}=0.07e-3, τ_{cool} ~ 27 sec.
Below: bunched beam, I~2e9 ions, E=2.5 Gev/u, $dP/P_{initial}$=0.2e-3, dP/P_{final}=0.13e-3, τ_{cool} ~ 64 sec.

CONTROL SYSTEM DEVELOPMENT

NICA facility will consists of two linacs, two synchrotrons, collider rings equipped with two detectors and a few beam transport lines. To operate this equipment a modern automatic control system is necessary. The concept of the NICA control system based on Tango platform was presented for international machine advisory committee (MAC) in October 2012. MAC approved the choice of the designer team and recommended to test a fragment of the system as soon as possible. Minimum set of equipment was prepared to the run #46 (December 2012) and since this period the new control system is under active development.

The Tango control system is a free open source device oriented controls toolkit for controlling any kind of hardware or software and building SCADA systems. It is used for controlling synchrotrons, lasers and physics experiments in over 20 sites. It is being actively developed by a consortium of research institutes. Addition argument for the Tango usage is that this system has been chosen as a basis for the control system of the FAIR facility, which is developed in very close co-operation with NICA.

Tango introduction to NICA has started with Nuclotron. Several subsystems (beam injection control [8], beam slow extraction control) have been converted to the Tango-based structure. For instance, the upgraded Nuclotron injection control and diagnostics system was put into operation during the run #47of in March 2013. It has demonstrated high reliability, operation convenience and fulfilled the injected beam quality requirements. Both hardware and software parts of the system were fully redeveloped. As example the client application for the injection system control is presented in the Fig. 5.

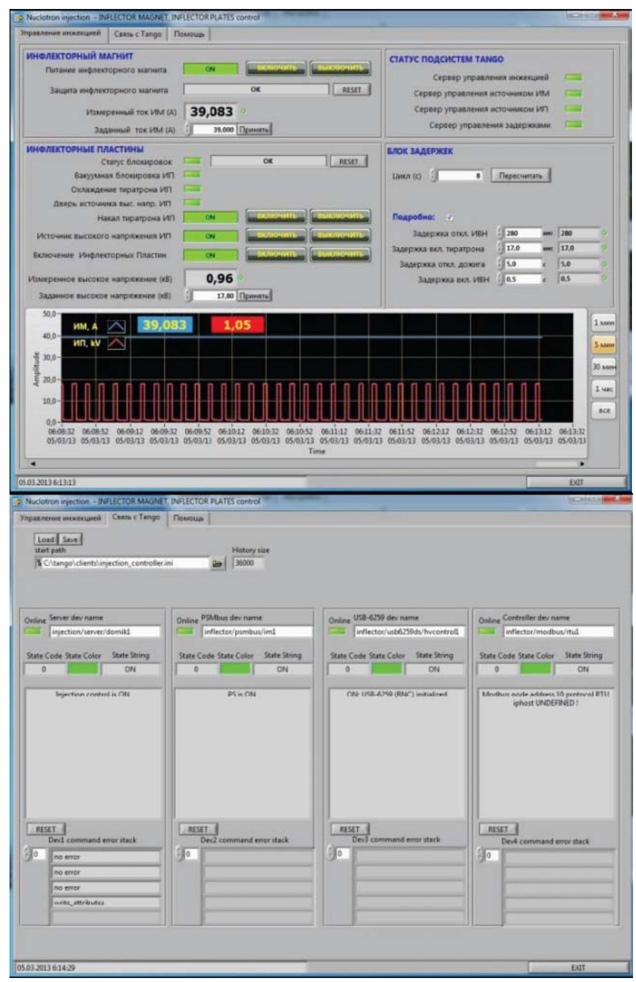

Figure 5: Injection control client application.

Several Tango-based subsystems are being developed now [9]. The software implementation using Tango framework allowed to reduce the development time significantly and confirmed the usage of Tango concept as a basis for the future NICA control system.

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To implement the Tango control system as a control system of the NICA accelerator complex the 4 main tasks there were performed:
1) The control equipment database was designed and created.
2) The web-tool for using and managing of the control equipment database was developed.
3) Servers were purchased and configured.
4) The necessary toolbox for development, storing, documenting and using of Tango-based software was set up.

NEAREST PLANS

Nearest Nuclotron run is scheduled for February – March 2015. It will be dedicated to experiments with light ions in accordance with the JINR topical plans. In the frame of stochastic cooling development we plan to test time of flight method for longitudinal cooling. Test of the new source of polarized ions (SPI) is in progress at a test bench. The first run of the SPI operation at the Nuclotron dedicated to polarized deuteron beam production and acceleration is scheduled for the end of 2015 after commissioning of the new RFQ pre-accelerator for LU-20 [3]. The beginning of the HILac commissioning will be started in this year. The systems of the Nuclotron Booster are under construction in cooperation with Budker institute of nuclear research (Novosibirsk) and scientific centers from member states of JINR [10-14]. Serial production of the Booster magnets will be started this year [15].

CONCLUSION

Main result of the Nuclotron development during last years is stable and reliable operation of all the systems proving beam quality required for users. The operational time is optimized in accordance with the JINR topical plans with account the plan of the NICA construction. For more efficient usage of the beam time, the regime with two parallel users was realized routinely: experiment with internal target at the first plateau and beam extraction at the second one.

The beam time dedicated to the machine development is used for enhancement of the Nuclotron performance for current physics program realization and for tests of the equipment, diagnostics and operational regimes of the new NICA accelerators.

One of the key processes required for the NICA collider operation – the stochastic cooling – is under active experimental investigation at the Nuclotron.

Two new ion sources of the NICA injection facility - the LIS and Krion-6T - was tested at existing accelerator complex. As result in nearest runs we expect an increase of the beam intensity and widening of the ion species.

The segment of the NICA control system based on Tango platform was successfully tested at the Nuclotron, and presently the system is under active development.

REFERENCES

[1] A.V.Butenko et al, “Development of the NICA injection facility”, Proceedings of IPAC2013, Shanghai, China.
[2] G. Trubnikov et al., “Heavy ion collider facility NICA at JINR (Dubna): status and development”, Proc. ICHEP'12, Melbourne, Australia.
[3] A.V.Butenko et al, “Development of NICA injection complex”, Proceedings of IPAC2014, Dresden, Germany.
[4] R. Stassen, et al., “The stochastic cooling system of HESR”, COOL’11, Alushta, Ukraine.
[5] N.Shurkhno et al, Study for stochastic cooling at Nuclotron, JINR, Proceedings of COOL13, Murren, Switzerland.
[6] E.Ivanov et. al. Quench Detector for Superconducting Elements of the NICA Accelerator Complex, These proceedings.
[7] G.Trubnikov et al., Status of the NICA project at JINR, Proceedings of IPAC2014, Dresden, Germany
[8] E.Gorbachev et.al., Upgrade of the Nuclotron injection control and diagnostic system, Proceedings of ICALEPCS2013, San Francisco, CA, USA.
[9] G.Sedykh, E.Gorbachev, The equipment database for the control system of the NICA accelerator complex, Proceedings of ICALEPCS2013, San Francisco, CA, USA.
[10] A. Fateev, The Power Supply System of Electrostatic Deflecting Plates for Accelerating Complex NICA Booster, These proceedings.
[11] G.Kurkin et. al., RF System of the Booster of NICA Facility, These proceedings.
[12] A. Styuf, Fast Digital Phase meter for Booster of NICA Project, These proceedings.
[13] G. Fatkin, Controller for RF Stations for Booster of NICA Project, These proceedings.
[14] V. Parkhomchuk, Low Energy Cooler for NICA Booster, These proceedings.
[15] S. Kostromin, Facility for Assembling and Testing of SC Magnets for NICA and FAIR projects, These proceedings.

ISBN 978-3-95450-170-0