NUCLOTRON AT JINR: OPERATION EXPERIENCE AND RECENT DEVELOPMENT

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Abstract

The results of 20 years of operation and development of the first superconducting synchrotron based on 2T cold iron fast cycling SC-magnets are presented. The Nuclotron technology of superconducting magnetic system for the NICA facility at JINR and for FAIR project will be used.

INTRODUCTION

The Nuclotron accelerator complex at Laboratory for High Energy Physics is the basic facility of JINR for generation of proton, polarized deuteron (also neutron/proton) and multicharged ion (nuclear) beams in energy range up to 6 GeV/amu. The Nuclotron was built during 1987-92. This accelerator based on the unique technology of superconducting magnetic system [1]. All design, tests and assembling works were carried out at the LHEP. Production of the structural cryomagnetic elements was done by the JINR workshops.

The Nuclotron accelerator complex (Fig. 1) consists of

- set of ion sources,
- Linac LU-20,
- 45 T·m SC synchrotron Nuclotron,
- 1000 m^2 experimental hall,
- beam transport lines,
- liquid He plant.

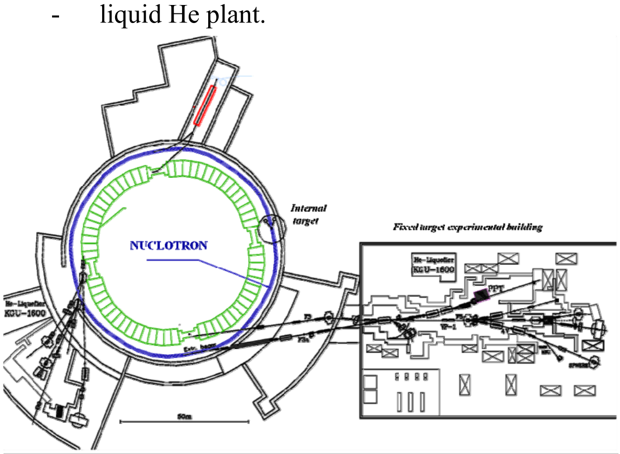

Figure 1: The Nuclotron accelerator complex.

The complex 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.

In the nearest future the Nuclotron technology of superconducting magnetic system will be used for new accelerators of the NICA facility under creation at JINR [2].

OPERATION

51 runs of the Nuclotron operation were performed since March 1993. Main result of the Nuclotron development during this period is stable and reliable operation of all the systems proving beam quality required for users. The operational time is about 2000 hours per year optimized in accordance with the JINR topical plans accounting the plan of the NICA construction. For more efficient usage of the beam time, the regime with two parallel users is realized routinely: experiment with internal target at the first plateau and beam extraction at the second one. Different types of the ion beams are delivered for the experiments (Table 1).

Table 1: Nuclotron and Beam Parameters

Nuclotron parameter	Project	Status (2015)
Max. main. field, T	2	2 (1.85 routine)
B-field ramp, T/s	1	0.8
Accelerated particles	p–U, d↑	p, d-Xe
Max. energy, GeV/u	12 (p), 5.9 (d) 4.5($^{197}Au^{79+}$)	5.9 (d, ^{12}C), 1.5 ($^{124}Xe^{42+}$, $^{40}Ar^{16+}$)
Intensity, ions/cycle	10^{11} (p,d) 10^9 (A> 100)	d $2\text{-}5\cdot10^{10}$ $^{124}Xe^{24+}$ $1\cdot10^4$ ^{12}C $2\cdot10^9$ $^{40}Ar^{18+}$ $2\cdot10^5$ $^{7}Li^{3+}$ $3\cdot10^9$

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). New powerful Nd-YAG laser was tested for the carbon beam generation during the run #48. For the first time Krion-6T

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was operated at the Nuclotron during the run #50. Test of the SPI is in progress at a test bench [3].

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 up to 20 s and for the beam intensity from 10^{11} down to 10^5 ions per cycle (Fig. 2).

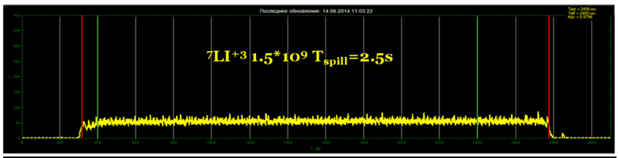

Figure 2: Example of the slow extraction beam spill.

NUCLOTRON AS TESTBENCH FOR NICA

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; 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.

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}~10^9. 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 [4].

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. In the last case the bunching factor (ratio between peak and mean current) was about 5.

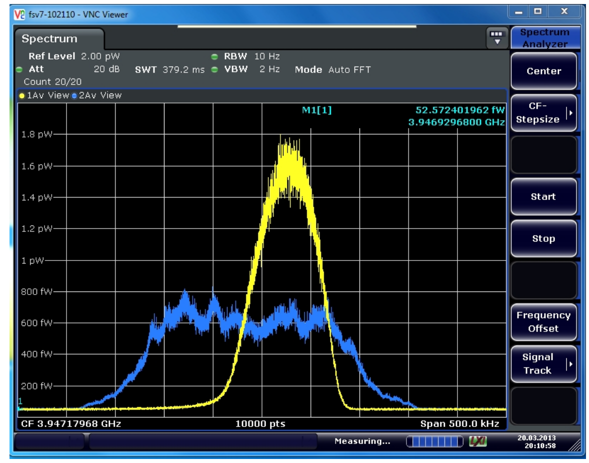

Figure 3: A longitudinal Schottky spectrum of the 3 GeV/u deuteron beam at 3500th harmonics of the revolution frequency, showing the initial spectrum (blue curve) and after 8 minutes of cooling (yellow curve). The beam intensity is $2{\cdot}10^9$ ions.

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.

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 in 2012 was developed. 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.

Minimum set of equipment was prepared to the run #46 (December 2012) and since this period the new control system is under active development. Several subsystems (beam injection control, beam slow extraction control and so on) have been converted to the Tango-based structure [5].

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.

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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.

DEVELOPMENT OF SC MAGNET TECHNOLOGY

The Nuclotron-type design based on a window frame iron yoke and a saddle-shaped superconducting winding has been chosen for the NICA booster and collider magnetic system as well as for the SIS100 synchrotron (FAIR project). Nuclotron-type magnets include a cold (4.5K) window frame iron yoke and a superconducting winding made of a hollow NbTi composite superconducting cable cooled with a two-phase helium flow.

The building construction of the new test facility for simultaneous cryogenic testing of the SC magnets on 6 benches is completed at the Laboratory of High Energy Physics [6]. More than 430 magnets will be tested at the facility during the next 4 years. Premises with an area of 2600 m^2 were prepared to install the equipment. The 15 kA, 25 V pulse power supply, three helium satellite refrigerators with capacity of 3 x 100 W were commissioned (Fig. 4).

Figure 4: First bench of the SC magnet test facility.

The equipment for cable production allows producing a Nuclotron -type hollow composite superconducting cable with the capacity of up to 50 m/h. The diameter of the cooling channel of the cable can vary from 3 to 5 mm. The number of SC wires in the cable may be up to 32. The wire diameter may be up to 1 mm. Hall for manufacturing of SC coils is equipped with a rotating table and tooling for winding of various types of SC coils as well as a furnace for heat treatment of coils with the length up to 3.5 m. The place for the assembling of the magnets is equipped with a few tables and tooling for rotating the magnet round the longitudinal axis to ease welding and brazing the cooling channels, devises for electrical insulation test, resistance and inductance measurement, hydraulic of cooling channels test and adjustment. The place for "warm" (room temperature) magnetic measurements is equipped with magnetic measurement system, pulsed linear regulated power converter with the current up to 100 A and DAQ based on National Instruments PXI measuring electronics and LabVIEW software.

The first magnets for the NICA Booster and collider have successfully passed cryogenic test on the bench. Three pre-serial dipole magnets for the NICA booster were tested in 2014 (Fig. 5). These tests include measurements of the magnetic field quality.

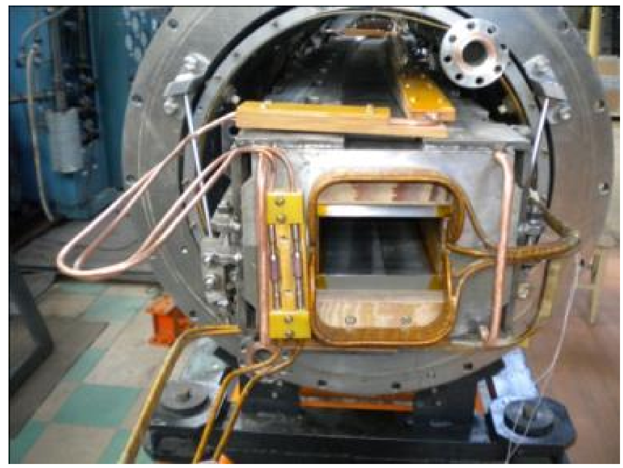

Figure 5: Pre-serial dipole magnet of the NICA Booster.

CONCLUSION

Nuclotron technology of superconducting magnetic system has been tested during more than 20 year of safety and stable operation of the ring. The results obtained can be useful under design of a modern fast cycling superconducting synchrotrons of different applications.

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