STATUS OF THE NUCLOTRON

A. Sidorin, N. Agapov, V. Alexandrov, O. Brovko, V.Batin, A. Butenko, E.D. Donets, A. Eliseev, A.Govorov, V. Karpinsky, V. Kekelidze, H. Khodzhibagiyan, A.Kirichenko, A. Kovalenko, O. Kozlov, I. Meshkov, V. Mikhaylov, V. Monchinsky, S.Romanov, V. Shevtsov, V. Slepnev, I. Slepnev, A. Sissakian, G. Trubnikov, B.Vasilishin, V. Volkov,
JINR, Dubna, Moscow Region

Abstract

The "Nuclotron-M" project started in 2007 is considered as the key point of the first stage of the NICA/MPD project. General goal of the "Nuclotron-M" project is to prepare all the systems of the Nuclotron for its long and reliable operation as a part of the NICA collider injection chain. Additionally the project realization will increase the Nuclotron ability for realization of its current experimental program. Results of the last runs of the Nuclotron operation are presented.

INTRODUCTION

The project "Nuclotron-M" is considered as a key part of the first stage of the JINR general project NICA/MPD (**N**uclotron-based **I**on **C**ollider f**A**cility and **M**ulty **P**urpose **D**etector) [1]. The extension of JINR basic facility capabilities for generation of intense heavy ion and high intensity light polarized nuclear beams, including design and construction of heavy ion collider aimed at reaching the collision energy of $\sqrt{s_{NN}}$ = 4÷11 GeV and averaged luminosity of $1\cdot10^{27}$ cm^{-2}s^{-1} is necessary for realization of the NICA/MPD.

The first stage of the NICA/MPD realization includes the following tasks:

- upgrade the Nuclotron facility (the "Nuclotron-M" project);
- elaboration of the NICA technical design report;
- development of the laboratory infrastructure aimed for long term stable operation of the accelerator complex and preparation for construction of the NICA elements;
- R&D works for MPD elements.

The "Nuclotron-M" program includes all necessary works on the development of the existing Nuclotron accelerator complex [2] to the facility for generation of relativistic ion beams over atomic mass range from protons to gold and uranium ions at the energies corresponding to the maximum design magnetic field (2 T) in the lattice dipole magnets. Realization of the project will make it possible to reach new level of the beam parameters and to improve substantially reliability and efficiency of the accelerator operation, renovate or replace some part of the equipment that have been under operation since 1992-93 as well.

As an element of the NICA collider injection chain the Nuclotron has to accelerate single bunch of fully stripped heavy ions (U^{92+}, Pb^{82+} or Au^{79+}) from 0.6 to about 4.5 GeV/u. The required bunch intensity is about $1\div1.5\cdot10^{9}$ ions. The particle losses during acceleration have to be minimized and do not exceed 10%. The magnetic field ramp has to be ≥ 1 T/s. To demonstrate the ability of the Nuclotron complex to satisfy these requirements, the general milestones of the project are specified as an acceleration of heavy ions (at atomic number larger than 100) and stable and safety operation at 2 T of the dipole magnet field. The project has been started in 2007. During the project realization almost all the Nuclotron systems were modernized and 5 runs of the Nuclotron operation were carried out. During the last run performed from 25 of February to 25 of March 2010 the Xe ions were accelerated and the magnetic system was operated at 1.8 T. Completion of the project is scheduled for the fall of 2010.

STATUS AND MAIN PARAMETERS OF THE NUCLOTRON

The first run at the Nuclotron (the superconducting synchrotron intended to accelerate nuclei and multi charged heavy ions) was performed in March 1993. Presently the Nuclotron delivers ion beams for experiments on internal targets and for fixed target experiments using slow extraction system. Achieved energy of protons is 5.7 GeV, deuterons – 3.8 GeV/u and nucleons - 2.2 GeV/u. The maximum achieved energy is limited by the system of the energy evacuation of the Nuclotron SC magnets and power supply of the lattice magnets.

Main elements and systems of the Nuclotron facility (Fig. 1) are the following:

1. superconducting synchrotron Nuclotron, which magnetic-cryostat system of the circumference of 251,5 m is located in the tunnel surrounding the Synchrophasotron basement;
2. cryogenic supply system consisting of two helium refrigerators KGU-1600/4.5 with required infrastructure for storage and circulation of the gaseous helium, liquid helium transfer lines, tanks for the liquid nitrogen storage and nitrogen tranfer lines for thermal screens of the Nuclotron lattice magnets;
3. the injection complex consisting of HV fore-injector and Alvarez-type linac LU-20. The fore-injector voltage up to 700 kV is produced by pulsed transformer. The LU-20 accelerates the protons up to the energy of 20 MeV and ions at Z/A ≥ 0.33 up to the energy of 5 MeV/u. The wide range of the ion species is provided by the heavy ion source "KRION-2", duoplasmatron ion source, polarized deuteron source

POLARIS and laser ion source.
4. beam transport line from LU-20 to the Nuclotron ring including equipment for the beam injection onto the orbit;
5. system of the resonant slow extraction of the accelerated beam in the direction to main experimental hall (bld. 205);
6. transport lines for the extracted beam;
7. power supply units for the Nuclotron lattice magnets and the transport lines to the experimental facilities located in the separated building 1A (it does not shown in the Fig. 1);
8. control system, diagnostics of the beam and the accelerator complex parameters;
9. RF system for the beam acceleration in the Nuclotron;
10. radiation shielding and automatic system for the radiation measurements.

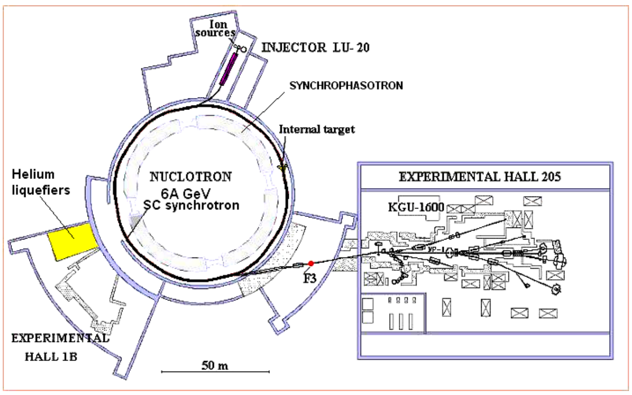

Figure 1. Schematics of the Nuclotron facility.

NUCLOTRON-M PROJECT

General goal of the project is to prepare all the existing systems of the Nuclotron for its long and reliable operation as a part of the NICA facility. Additionally the project realization will increase the Nuclotron ability for realization of its current experimental program. The project working program includes the next main tasks:
1. Development of the heavy ion source.
2. Development of the polarized deuteron source.
3. Sufficient improvement of the vacuum conditions in the Nuclotron beam pipe and linear accelerator-injector.
4. Development of the power supply system and energy evacuation system in order to reach magnetic field in dipole magnets of 1.8 - 2 T.
5. Upgrade of the Nuclotron RF system, realization of the adiabatic trapping into acceleration.
6. Development of the slow extraction system.
7. Development of the beam transfer lines and radiation shielding.
8. Beam dynamics investigations, minimizations of the particle loss at all stages of the acceleration.
9. Preparation of the KRION-2 ion source for generation of the ion beam at A > 100 and q/A > 0.33.
10. Design of new heavy ion linear injector.

Sufficient part of the first run performed after beginning of the project - #37 (November of 2007) - was devoted to the test of the status of the Nuclotron systems and machine development experiments. During this run experimental estimate of average vacuum in the Nuclotron was made based on the studies of $^2H^+$ and deuteron beam circulation at the injection energy (5 MeV/u). It was shown, the beam pipe pressure scaled to equivalent concentration of N_2 molecules at T = 300 K is measured to about $p \approx 2\cdot10^{-8}$ Torr, that is not sufficient for heavy ion acceleration. To start modernization of the system for orbit position measurements and the orbit correction the existing PU stations and correctors were tested and calibrated. Preliminary test of new scheme of the structural magnet supply based on the consequent magnet connection was performed. It was demonstrated that the large inductivity sufficiently suppresses the magnetic field ripple. It leads to stable acceleration process and improve the quality of slow extracted beam.

RESULTS OF LAST RUNS

During the “Nuclotron-M” project realization four runs of the Nuclotron operation were carried out - #38 (June of 2008), #39 (June of 2009), #40 (November 2009) and #41 (March 2010). Sufficient part of them was devoted to the test of new equipment installed at the Nuclotron accelerator complex. Within this period two stages of the ring vacuum system upgrade were completed. Deep reconstruction of the cryogenic system was performed. New supply system for electrostatic septum of the slow extraction system was constructed and tested at a test bench and at the ring. New power supplies for the closed orbit corrector magnets were designed and first 4 units were tested at the ring. Partial upgrade of the ring RF system aiming to increase RF voltage and realize the adiabatic trapping into acceleration was performed. A set of works at LU-20 accelerator was performed to improve the vacuum conditions and to increase the acceleration efficiency.

In parallel with the Nuclotron modernization a good progress was achieved in design and construction of the new heavy ion and polarized light ion sources.

Upgrade of the Nuclotron ring vacuum system

The Nuclotron vacuum system consists of two sub-systems: insulation vacuum system of the cryostat and high vacuum system for the beam pipe. Insulation vacuum system satisfied to all the requirements of the accelerator operation and its serious upgrade is not necessary. Before beginning of the “Nuclotron-M” project the Nuclotron beam pipe had no effective pumping of gaseous hydrogen and helium, while gaseous helium can to penetrate into the pipe due to diffusion from insulation vacuum volume of the cryostat through non welded connection between beam extraction channel and circulating beam chamber.

Upgrade of the vacuum system was performed in two stages:

- reconstruction of a few sections of the ring and installation of new vacuum pumps and diagnostic equipment;
- creation of automatic control system for the vacuum equipment.

The first stage was realized in a general between the runs #37 and #38. Installed vacuum equipment was tested and put into operation during the run #38 and its application was resulted in improvement of the vacuum conditions by about one order of magnitude.

The automatic control system was put into operation during the runs #40 and #41 that permitted to provide experimental study of evolution of the residual gas pressure and composition during long period of the ring operation. At the moment the vacuum conditions in the beam pipe satisfies to requirements of the NICA project that was additionnaly demonstrated during the #41 run in acceleration of Xe ions.

Upgrade of the cryogenic system

Starting from August of 2008 the Nuclotron cryogenic system was deeply reconstructed. Almost all the equipment was dismounted, transferred to specialized factories, repaired and transferred back into JINR. From the February of 2009 the equipment was tested and step by step put into operation.

Heavy ion acceleration

During the run #41 the ions of $_{124}Xe^{42+}$ were accelerated up to about 1.5 GeV/u. At 1 GeV/u the slow extraction of the accelerated beam was used for a few methodical and physics experiments. To reach this goal the following works were performed during 2009 and first month of 2010:

- four stand runs (five weeks each) at multi charged heavy ion source Krion-2 have been done in order to optimize operational parameters;
- modernization of power supply system of the beam transfer line from LU-20 to the Nuclotron;
- readjustment of the LU-20 accelerating-focusing system in order to improve the acceleration efficiency;
- three runs at LU-20 dedicated to test all the systems at acceleration of deuteron, C^{+4} and heavy ion beams.

During LU-20 run performed in January – February of 2010 the following ions were obtained with Krion-2 source in the pulse of 6.7 μs of duration:

- a) $_{84}Kr^{28+}$ $3.5\cdot10^7$ ions per pulse,
- b) $_{84}Kr^{29+}$ $3.2\cdot10^7$ ions per pulse,
- c) $_{84}Kr^{30+}$ $3.0\cdot10^7$ ions per pulse,
- d) $_{124}Xe^{41+}$ $3.0\cdot10^7$ ions per pulse,
- e) $_{124}Xe^{42+}$ $3.0\cdot10^7$ ions per pulse,
- f) $_{124}Xe^{43+}$ $2.7\cdot10^7$ ions per pulse,
- g) $_{124}Xe^{44+}$ $1.5\cdot10^7$ ions per pulse.

The beams of $_{84}Kr^{29+}$ and $_{124}Xe^{42+}$ ions were accelerated with LU-20 up to 5 MeV/u.

The Nuclotron run #41 was started with laser ion source. All the ring systems were tested and tuned with deuteron beam initially. Thereafter initial part of the beam acceleration was optimized for acceleration of ions at charge to mass ration closed to 1/3 with C^{+4} beam. The C^{+4} beam life-time due to stripping on residual gas is not long enough to accelerate them to energy of the range of 1 GeV/u. The slow extraction system was tuned with Xe ions after change of the ion source. The Xe beam intensity during the acceleration was measured with the ionization monitor and even relative change of the intensity is complicated to estimate due to variation of the ionization cross-section. Intensity of the accelerated beam was at the sensitivity threshold therefore accurate tuning of the slow extraction was not provided. Even at these conditions the beam intensity at the exit of the ring was about a few thousands ions per pulse. Most likely the source of the ion loss during the acceleration was interaction with the residual gas. As a part of the NICA injection chain the Nuclotron will be operated for acceleration of fully striped gold ions from 600 MeV/u up to 4.5 GeV/u. During Xe ion acceleration it was demonstrated that the vacuum conditions in the Nuclotron beam pipe is sufficient for this goal.

FURTHER DEVELOPMENT

During # 41 run the magnetic system was operated at 1.8 T of the dipole magnetic field for a few hundred of cycles. It was demonstrated that after more than 15 years of the operation a degradation of the magnet properties is practically absent. The long and safe operation of the accelerator magnetic system at maximum design level of the magnetic field (2 T) is related to the following modifications of the power supply system:

- manufacturing, assembling and put into operation seven units of the new switches for energy damp from the magnets in a case of quench for both the dipoles and the quadrupoles power supply circuits;
- upgrade of the quench detection system;
- development of scheme of the Nuclotron magnet power supply.

The works are in the final stage, and beginning of the commissioning of the new power supply and quench protection systems is scheduled for the Autumn Nuclotron run in 2010. After that the Nuclotron upgrade project will be completed. The next stage of the development is connected with construction of the NICA facility elements.

REFERENCES

[1] NICA Conceptual Design Report, JINR, January 2008. http://www.jinr.ru/

[2] A.A.Smirnov, A.D.Kovalenko, “Nuclotron-superconducting accelerator of nuclei at LHE JINR (Creation, Operation, Development)” Particles and Nuclei, Letters, 2004, v.1, №6 (123), p.11-40