RESULTS OF THE NUCLOTRON UPGRADE PROGRAM

A. Eliseev, N. Agapov, A. Alfeev, V. Andreev, V. Batin, O. Brovko, A. Butenko, D.E. Donets, E.E. Donets, E.D. Donets, A. Govorov, E. Gorbachev, V. Karpinsky, V. Kekelidze, H. Khodzhibagiyan, A. Kirichenko, A. Kovalenko, O. Kozlov, N. Lebedev, I. Meshkov, V. Mikhaylov, V. Monchinsky, S. Romanov, T. Rukoyatkina, A. Sidorin, V. Slepnev, I. Slepnev, A. Sorin, G. Trubnikov, B.Vasilishin, V. Volkov
JINR, Dubna, Moscow Region

Abstract

The Nuclotron upgrade – the Nuclotron-M project, which had been started in 2007, involved the modernization of almost all of the accelerator systems, using beam time during seven runs devoted to testing newly installed equipment. Following the project goals, Xe ions were accelerated to about 1.5 GeV/u in March 2010. In December 2010, the stable and safe operation of the power supply and energy evacuation system was achieved with a field in the lattice magnets of 2 T. The successful completion of the project paves the way for further development of the Nuclotron-based Ion Collider fAcility (NICA).

INTRODUCTION

The first run at the Nuclotron (the superconducting synchrotron intended to accelerate nuclei and multi charged heavy ions [1]) 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 other light nucleus - 2.2 GeV/u.

The project "Nuclotron-M" was 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) [2]. 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 "Nuclotron-M" program was oriented to the development of the existing Nuclotron accelerator complex to the facility for generation of relativistic ion beams over atomic mass range from protons to gold ions at the energies corresponding to the maximum design magnetic field (2 T) in the lattice dipole magnets. Another important goal of the project was 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 an element of the NICA collider injection chain the Nuclotron has to accelerate single bunch of fully stripped heavy ions (as a reference Au^{79+} is considered) 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 rate has to be 1 T/s and more. To demonstrate the ability of the Nuclotron complex to satisfy these requirements, the general milestones of the Nuclotron-M project were 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 working program included 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 T - 2 T.
5. Modernization of the cryogenic system.
6. Upgrade of the Nuclotron RF system, preparation to the adiabatic trapping into acceleration.
7. Development of the slow extraction system.
8. Development of the beam transfer lines and radiation shielding.
9. Beam dynamics investigations, minimizations of the particle loss at all stages of the acceleration.
10. Preparation of the KRION-2 ion source for generation of the ion beam at A > 100 and q/A > 0.33.
11. Design of new heavy ion linear injector.

The project has been started in 2007. During the project realization almost all the Nuclotron systems were modernized and 6 runs of the Nuclotron operation were carried out. To the end of 2010 all general goals of the project were reached. The project realization course was described in [3-6]. In this report the statistics of the Nuclotron operation and general results of the Nuclotron-M project are briefly reviewed.

THE NUCLOTRON OPERATION

During the "Nuclotron-M" project development six runs of the Nuclotron operation were carried out - #37 (November 2007), #38 (June of 2008), #39 (June of 2009), #40 (November 2009), #41 (March 2010) and #42 (December 2010) of the total duration of about 3200 hours.

The first run performed after beginning of the project - #37 - 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 $2{\cdot}10^{-8}$ Torr, that was not sufficient for heavy ion acceleration. To start modernization of the system for orbit position measurements and the orbit correction the existing beam pick-up stations and correctors were re-tested and calibrated. Preliminary test of new scheme of the structural magnet supply based on the connection of all magnets in series was performed.

Sufficient part of further runs was devoted to the test of new equipment installed at the Nuclotron accelerator complex (Fig. 1).

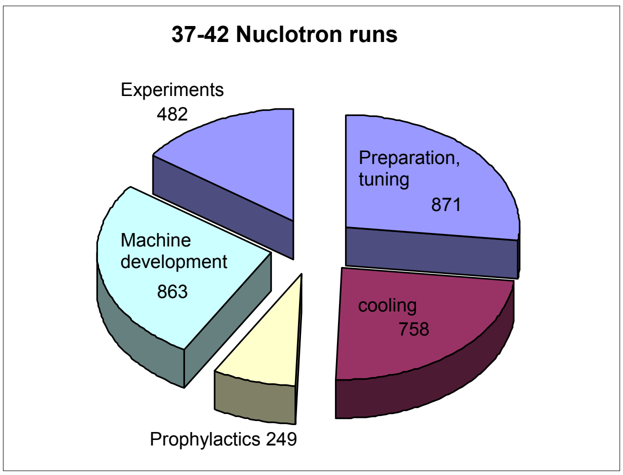

Figure 1: Statistics of the Nuclotron operation in hours.

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. Partial upgrade of the ring RF system aimed to increase RF voltage and realize the adiabatic particle capture 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. New power supplies for the closed orbit corrector magnets were designed, constructed and put into operation. Electronics for the field cycle control, new power supply and quench protection system for structural magnets and lenses were created and tested at maximum design magnetic field.

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.

BASIC RESULTS OF THE PROJECT

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.

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 two orders 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 additionally demonstrated in successful acceleration of Xe ions.

Heavy Ion Acceleration

Sufficient improvement of the vacuum conditions, as well as partial modernization of LU-20 linear accelerator and optimization of the ion source KRION-2 madr it possible to reach the new level of heavy ion acceleration at the Nuclotron facility. 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 (Fig. 2). This result have shown real possibility to obtain ion beams with atomic mass of A > 100 of GeV region in Dubna.

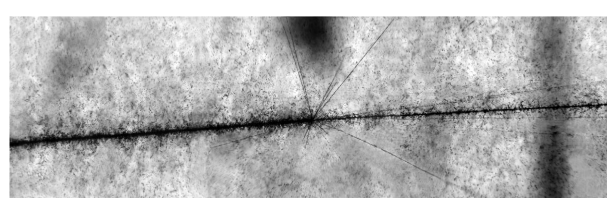

Figure 2: Extracted Xe (1 Gev/u) ion trace on photo emulsion (experiment "Becquerel").

As a part of the NICA injection chain the Nuclotron will be operated for acceleration of fully striped gold ions from 600 MeV/u. Remind, Xe ion injection energy in the Nuclotron was 5 MeV/u. Acceleration of partially stripped heavy ion beam starting from such low energy is demonstrated that the vacuum conditions in the Nuclotron beam pipe is sufficient for the NICA goal.

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 February of 2009 the equipment was tested and step by step put into operation. As a result, presently the cooling capacity of each of the two refrigerators increased from 1.6 kW to 2 kW.

New Power Supply and Energy Evacuation System

During the run #42 performed from 10 to 30 of December 2010 stable and safe operation of the power supply and energy evacuation system was obtained at the bending field of 2 T. The new power supply and quench protection system, based on the structural magnet connection in series, consists of the following general elements and subsystems:

- New main power supply unit;
- New power supply unit for current adjustment in the quadrupole lenses;
- New 6 kA "warm" cable lines of about 10 km of the length;
- Energy evacuation system consisting of new 6 thyristor energy evacuation keys with dump resistors.

Before the run the main power supply unit and energy evacuation system were tested at equivalent load. At the beginning of the run the main power supply, power supply for current adjustment in the lenses and the energy evacuation system were tested in the cycle at low level of the field. On the basis of obtained results the main power supply unit was adjusted for stable operation at maximum field. During 29 of December the power supply and quench protection system was consequently tested in cycles with the bending field of 1.4, 1.6 and 1.8 T at the plateau. After that during a few hundreds of cycles the magnetic system was successfully operated at 2 T field at the plateau. The field ramp rate was 0.6 T/s, the duration of the cycle active part was about 7 s. A few tens of the energy evacuation events acquired – in all of them the process was in the nominal regime.

CONCLUSIONS

In 2010 the Nuclotron-M project was successfully completed. The last Nuclotron run - #43 (February-March 2011) was performed in the frame of new JINR project, so called "Nuclotron-NICA", dedicated to construction of the NICA facility main elements. During this project the Nuclotron will be used for prolongation and development of its current experimental program, test of the MPD elements. About of 40% of duration of the run #43 was used for physics experiments. To the end of this year one plans to perform one additional run of duration of 1.5 – 2 months. In the nearest future the strategy of the Nuclotron operation presumes an increase the operational time up to about 3000 hours per year with gradual increase of the extracted beam energy and intensity.

In parallel with the accelerator modernization the technical design of the collider injection chain elements (new heavy ion linear accelerator, small booster synchrotron, LU-20 upgrade program) was prepared. Technical design of the collider is at the final stage.

The structural dipole and quadrupole magnets for the collider, as well as for the booster, will be based on the Nuclotron-type design. The Nuclotron superconducting magnets are based on a cold-iron window frame type yoke and low inductance winding made of a hollow composite superconductor. The magnetic field distribution is formed by the iron yoke. The Nuclotron magnet manufacturing has brought a great experience to the JINR in the field of SC magnet design and serial production. Such type of magnets one plans to use for construction of SIS-100 synchrotron of the FAIR project. The booster dipole magnet prototype was constructed in 2010 and tested at the stand in spring 2011. The collider magnet model, based on the preliminary design, was also constructed in 2011. To construct the Booster and collider rings, it is necessary to fabricate more than two hundreds of the dipole magnets and lenses during a short period of time. Special area for the magnet assembly and full-scaled tests required for the magnet commissioning [7] are currently being prepared.

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