VB LHEP accelerator complex development

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Abstract

Current development of the VB LHEP accelerator facility is aimed to creation of new modern accelerator-collider facility NICA. The first stage of the NICA creation – upgrade of the existing facility (so called Nuclotron-M project) was fulfilled during 2007 – 2010. After completion of the Nuclotron-M project three runs of the Nuclotron operation were carried out. The machine development shifts were dedicated to the performance increase for current physical program realization and to test equipment and operational modes of the NICA collider.

Introduction

Starting from 2007 the works on development of VB LHEP accelerator complex are carried out at JINR with the aim of creation a modern accelerator-collider facility NICA (Nuclotron-based Ion Collider fAcility) with wide program of fundamental and applied researches [1]. In the field of fundamental researches this program prolongs at qualitatively new level the investigations in relativistic nuclear and spin physics, traditional for LHEP. The new accelerator complex will include existing accelerator facilities as well as new linear accelerator, new synchrotron – booster and two rings of the collider. The facility will have to provide:

- experiments on extracted ion beams (from protons up to gold or uranium nuclei) at the kinetic energy up to 13,8 GeV (for protons), 6 GeV/u (for deuterons) and up to 4,5 GeV/u for heavy nuclei (like Lead, Gold or Uranium);

- experiments on colliding heavy ion beam at kinetic energy in the range from 1 to 4,5 GeV/u at the luminosity of 10^{27} $cm^{-2}s^{-1}$;

- experiments on colliding heavy and light ions with the same energy range and luminosity;

- experiments on colliding polarized beams of light ions at the kinetic energy range from 5 to 12,5 GeV/u for protons, and from 2 to 5,8 GeV/u for deuterons, at the luminosity level not less than 10^{31} $cm^{-2}s^{-1}$.

For users of the NICA beams the following experimental areas and facilities will be available:

- building #205 for fixed target experiments (presently full-scale reconstruction of the building is being carried out);

- building #1B – here one plans to realize beam slow extraction from the booster for applied researches;

- the collider for heavy and light polarized ions equipped with MPD (MultiPurpose Detector) and SPD (Spin Physics Detector) is aimed for fundamental study of hot and dense state of the nuclear matter;

- the Nuclotron, that will be used as a basic facility for research in the field of accelerator physics and techniques, for development of modern diagnostics and test of prototypes of the collider systems;

- internal target set-up at the Nuclotron.

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"Nuclotron-M" project completed during 2007-2010 considered as a first stage of the NICA construction. The goal of the project was preparation of all the Nuclotron systems for reliable operation as a part of the new accelerator complex. Presently the Nuclotron development is aimed to the performance increase for current physical program realization and for testing equipment and operational modes of the NICA collider.

Results of the Nuclotron upgrade program

Necessity of deep modernization of the VB LHEP accelerator facility explained by two main reasons. From the one hand, Nuclotron main systems were created in the beginning of 1990-th, when the economical situation did not permit to realize the project in the total volume: the modernization of LU-20 accelerator was not completed, booster synchrotron was not constructed, RF acceleration system of the Nuclotron was realized at the level of full-scale prototype for commissioning period, diagnostic of the circulating beam was realized partially only, system for vacuum diagnostics in the beam pipe was absent practically, the power supply and protection systems for main magnetic elements did not satisfy completely to reliability requirements. From the other hand, main technological systems of the Nuclotron worked out their resources for many times, part of them has morally also physically become outdated.

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 losses 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.

Demonstration of acceleration of heavy ions at atomic number larger than 100 (before beginning of the modernization the heaviest ions accelerated at the Nuclotron were the iron ones - $^{28+}Fe^{56}$) with stable and safe operation of the magnetic system at the field of the dipole magnets of 2 T (before the maximum achieved value was 1.2 T) were chosen as indicators of successive completion of the project. 6 runs of the Nuclotron operation at total duration of about 3200 hours were carried out during the "Nuclotron-M" realization course. Commissioning of modernized and newly installed equipment, investigation and optimization of the operational conditions were the first priority tasks.

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

The run (#37) performed after beginning of the project 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 using equivalent concentration of N_2 molecules at T = 300 K was measured to approximately $2 \cdot 10^{-8}$ 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 lattice magnet supply based on the electrical 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).

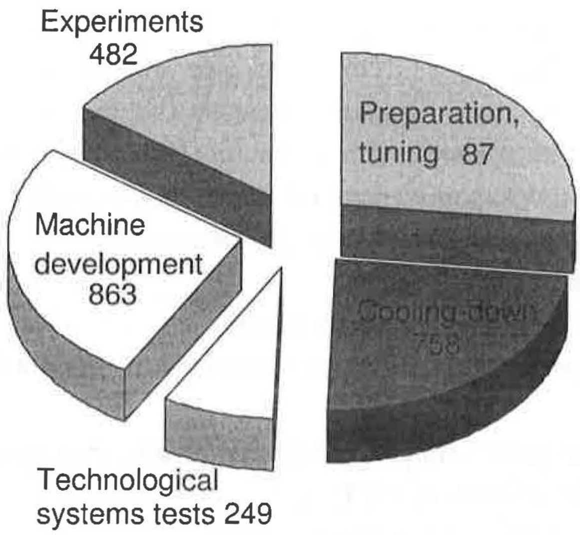

Figure 1: Statistics of the Nuclotron operation in hours.

Within this period two stages of the ring vacuum system upgrade were completed. Deep reconstruction of the cryogenic system was performed. New power supply system for electrostatic septum of the slow extraction system was constructed and tested at the test bench first and after installed 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 [2].

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 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 allowed to provide experimental study of evolution of the residual gas pressure and composition during long period of the ring operation [3]. At the moment the vacuum conditions in the beam pipe satisfies to requirements of the NICA project that was additionally demonstrated by 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 made it possible to realize heavy ion acceleration at the Nuclotron facility. During the run #41 the ions of $_{124}Xe^{42+}$ were accelerated up to 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) (experiment "Becquerel").

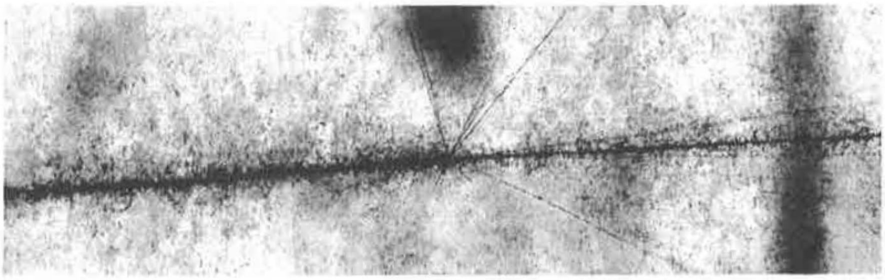

Figure 2: Extracted Xe (1 Gev/u) ion trace on photoemulsion (experiment "Becquerel").

As a part of the NICA injection chain the Nuclotron will be operated for acceleration of fully striped gold ions from 600 MeV/u. One has to mention that injection energy of Xe ions to 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 requirements.

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 systems

Stable and safe operation of the power supply and energy evacuation system was obtained at the magnetic field magnitude of 2 T during the run #42 performed in December 2010. The new power supply and quench protection system, based on the structural magnet connection in series, consists of the following general elements and subsystems [5]:

- New main power supply unit;
- New power supply unit for current adjustment in the quadrupole lenses;

- New 6 kA "warm" cable lines of about 5 km of the length;
- Energy evacuation system consisting of new 6 thyristor energy evacuation keys with dump resistors.

First 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. Finally 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 (Fig. 3). 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.

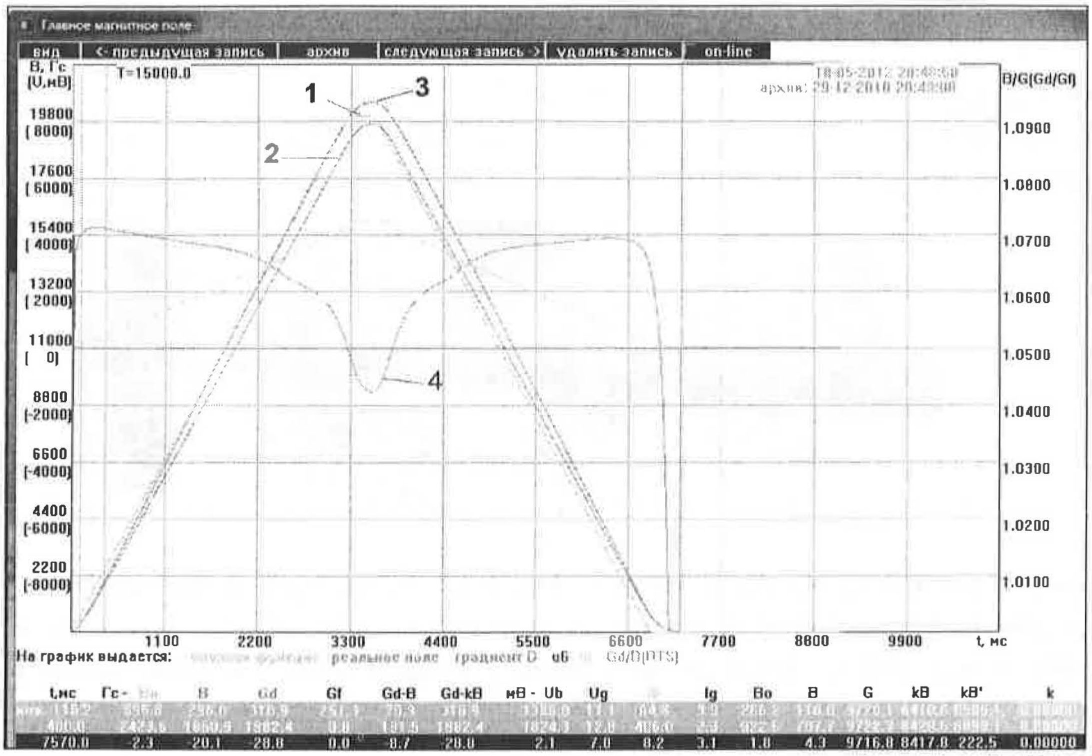

Figure 3: Cycle diagram at dipole magnetic field of 2 T. 1 – basic function, 2 & 3 – field of the magnets and gradient of the lenses correspondingly. December 2010.

In 2010 the Nuclotron-M project was successfully completed. Presently the creation of the NICA general elements is realizing in the frame of three officially approved JINR projects: "Nuclotron-NICA" (accelerator part), MPD (the project oriented to creation of one of the collider detectors) and BM@N (Baryonic Matter at Nuclotron – the new fixed target experiment with heavy ions, the detector is under construction in the building #205 in cooperation with GSI (Germany). The Nuclotron is the key element of all three projects: as the ion source for MPD element testing and for experimental program BM@N realization, as the main synchrotron in the injection chain of the future collider and as the basic facility for testing of new equipment of the booster and collider rings. After completion of the Nuclotron upgrade three runs (#43- #45) at total duration of about 2900 hours were performed. About 1400 hours were spent for physical experiments including the shifts dedicated to machine development.

Machine development

The machine development aimed to increase the Nuclotron ability for the current physical program realization is provided in the following main directions:

- step by step increase the beam energy up to maximum design value (6 GeV/u for deuterons);
- optimization of the beam dynamics in order to minimize the particle losses during acceleration;
- further development of power supply system in order to provide required quality of slow extraction;
- development of the beam diagnostics;
- development of ion sources and fore-injector modernization.

Before modernization the Nuclotron provided the beam energy up to 3 GeV/u maximum (for the ions with A/Z = 2). During the run #44 (December 2012) carbon beam was accelerated up to about 3.5 GeV/u and after slow extraction transported along the transport line to the point of the future location of the BM@N detector. During the same run the slow extraction of deuteron beam-had been realized at 4 GeV/u. In the run #45 (March 2012) the slow extracted 4 GeV/u deuteron beam was routinely used for physical experiments. At the end of the run #45 the possibility of the slow extraction was demonstrated at the deuteron beam energy of 4.5 GeV/u. Further increase of the extracted beam energy is related to development of the slow extraction system (increase of the electrostatic septum voltage and current of the slow extraction quadrupoles) and optimization of operational conditions of the power supply system.

Decrease of the ion losses during acceleration is related with further development of the accelerating RF system, optimization of the closed orbit (including the orbit bump in the slow extraction region), development of the beam diagnostics. Sufficient part of these works was performed during runs #43 – #45.

Fast current transformer (FCT) installed at the Nuclotron before the run #44 was optimized for work in required dynamic range. Now the analogous device is installed in the beam injection line. In future one plans to use such FCTs at the Booster and collider.

New ionization beam profile monitor based on MCP was installed in the «warm» section of the Nuclotron. During run#45 it was optimized for work with heavy ion beams at relatively low intensity.

During the runs #44 and #45 experimental fragment (two octants of the ring) of new system of superconducting element thermometry were tested. Full scale implementation of the new system is scheduled to the end of this year.

In the frame of the Nuclotron upgrade program a new quench detection system was designed. Prototypes of the quench detector were consequently tested during two runs of the accelerator. On the basis of the test results the serial production of the quench detectors was started in 2010. During two runs of the accelerator the fragment of the new quench detection system including 20 quench detectors was operated during more than 1500 hours. Stable and reliable work of all elements was demonstrated. The system performs scheduled self-test diagnostics in real time and controls power elements of energy evacuation. Full-scale implementation of the new quench detection system is scheduled for the Nuclotron run #46 (at the fall of 2012).

The works oriented to creation of new sources of high intensive heavy ions and light polarized nuclei are in the final stage. In 2011 the 6 T solenoid for the heavy ion source (of electron string type – ESIS) was constructed, assembly of the source was completed this year. Experimental investigations of the source parameters have been started. The atomic beam source for the source of polarized particles was assembled and tested at INR (Troitsk), the plasma ionizer and test bench for the final assembly and test of the source is under construction at JINR. Completion of these works is scheduled for 2012.

The LINAC LU-20 fore-injector upgrade is required for operation of the new ion sources. Replacement the electrostatic accelerating tube by RFQ will allow to reduce HV potential of the Ion Source platform from 400-700 kV down to 50-150 kV. The compact isolation transformer (160kV-35kWA) will fine solution as power supply of the ion sources up to 35 kW. The production of RFQ in cooperation with ITEP is in progress, the isolation transformers produced by STL Stewart Transformers Ltd.

Nuclotron as a test facility for NICA

The Nuclotron having the same magnetic rigidity as the future NICA collider and based on the same type of the magnetic system is the best facility for testing of the collider equipment and operational regimes. Simulation of the collider magnetic system operational conditions was performed at the Nuclotron during runs #44 and #45. This presumed test of the Nuclotron magnetic system, power supply and quench protection systems, cycle control and diagnostic equipment in the operational mode with long plateau of the magnetic field. In the run #44 the magnetic field cycle duration was prolonged up to 500 s without beam acceleration, in the run #45 the circulation of accelerated deuteron beam during 1000 s was demonstrated (Fig. 4).

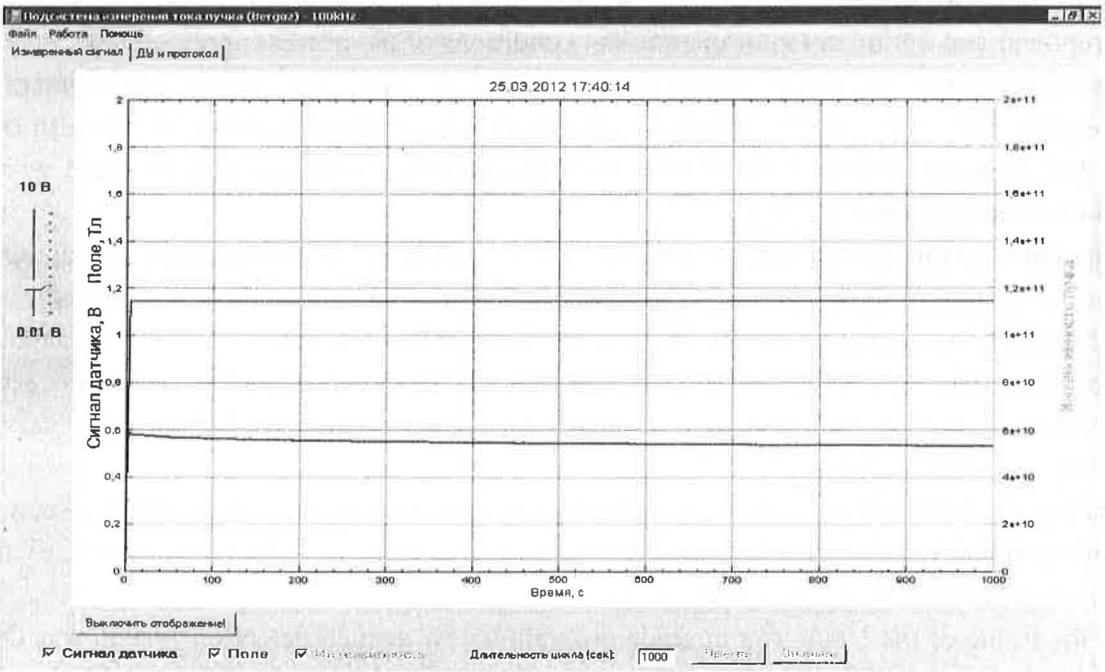

Figure 4: Circulation of the deuteron beam at the field plateau during 1000 s. Dipole field is 1.2 T (upper curve), the beam intensity is $5 \cdot 10^9$ particles (lower curve), middle curve – beam current transformer signal. March 2012.

Application of beam cooling methods (electron and stochastic) in the collider ring has the goals of beam accumulation using cooling + stacking procedure and luminosity preservation during experiments. Experimental test of the stochastic cooling at the Nuclotron is considered as important phase of the collider beam cooling system design. This work is developed in very close collaboration with FZ Juelich (Germany). During 2010-2011 the elements of the stochastic cooling chain for test at the Nuclotron were designed, constructed and after vacuum and cryogenic tests installed at the ring (Fig. 3). Experiments started in December 2011 were continued in 2012. We plan step by step investigate longitudinal and transverse cooling of coasting and bunched beams [6].

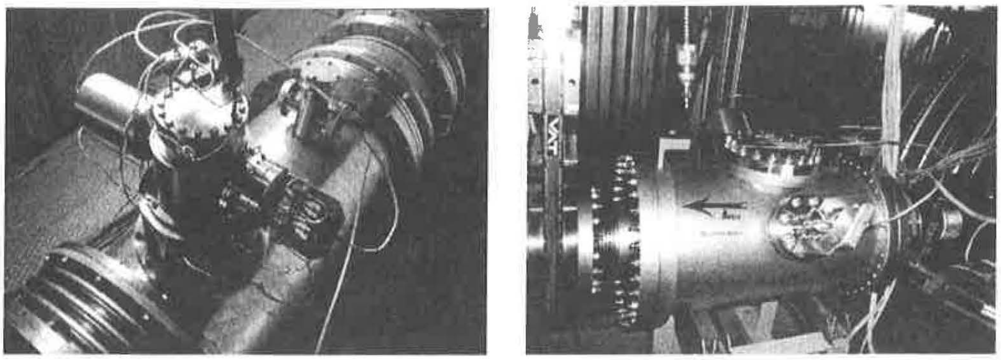

Figure 5: Pick-up (left) and kicker (right) of the Nuclotron stochastic cooling chain.

Conclusions and outlook

The works on design and construction of the new accelerator facilities of the NICA complex are carried out in parallel with development and operation of the Nuclotron. Technical design of the booster is completed: construction of the booster RF accelerating stations is in the final stage at BINP (Novosibirsk), the prototype of the sector dipole magnet was constructed and tested, first measurements of its magnetic field were performed, the prototype of the booster quadrupole lens was constructed and prepared for the test and successfully tested, the power supply, control and diagnostic system, the elements of vacuum system are under development. The design of the collider optic structure is in the final stage. Experts from FNAL and BNL (USA), FZJ and GSI (Germany), CERN, ITEP, BINP actively participate in the design works, the results are analyzed by international machine advisory committee on the regular base. Technical project of the required civil construction works for the collider and beam transport lines location is developed by specialized designer company and prepared for state expertise.

The full-scale Nuclotron–type superconducting model dipole and quadrupole magnets for the NICA booster and collider were manufactured during 2010 – 2012. First dipole and quadrupole magnets for the NICA booster have successfully passed the cryogenic test on the bench. To construct the Booster and collider rings, it is necessary to fabricate more than two and half hundreds of the dipole magnets and lenses during a short period of time. Special area for the magnets assembly and comprehensive tests required for the magnets commissioning are currently being prepared.

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