PROTOTYPE SUPERCONDUCTING MAGNETS FOR THE NICA ACCELERATOR COMPLEX

H. Khodzhibagiyan#, A. Bychkov, A. Galimov, O. Kozlov, G. Kuznetsov, I. Meshkov,
V.Mikhaylov, A. Shabunov, A. Starikov, and G. Trubnikov, JINR, Dubna, Russia

Abstract

NICA is a new accelerator complex being under design and construction at the Joint Institute for Nuclear Research (JINR) in Dubna. Full-size prototype dipole and quadrupole magnets for the booster synchrotron and the NICA collider have been designed, manufactured and tested. The magnets are based on a cold window frame iron yoke and a saddle-shaped superconducting winding made from a hollow NbTi composite superconducting cable cooled with a forced two-phase helium flow at T = 4.5 K. The maximal operating magnetic field in the aperture is 1.8 T. The magnetic field ramp rate of 1.2 T/s should be achievable. The quench history, AC losses as a function of the magnetic field ramp rate and pressure drop in the cooling channels of the magnets at different pulsed operation modes are presented.

INTRODUCTION

The NICA/MPD project [1] started at the Joint Institute for Nuclear Research (JINR) in Dubna in 2007. The goal of the project is to carry out experimental studies of the hot and dense strongly interacting quantum chromodynamics matter and light polarized ions. The NICA accelerator complex will consist of two injector chains, the new 600 MeV/u superconducting booster synchrotron, the existing superconducting synchrotron – Nuclotron [2], and the new superconducting collider having two rings each of about 503 m in circumference, aimed to achieve average luminosity up to $1\cdot10^{27}$ $cm^{-2}s^{-1}$ at the collision energy of $\sqrt{s_{NN}}$ = 4÷11 GeV. The Nuclotron-type design [3-5] based on a cold iron yoke and a saddle-shaped superconducting (SC) winding has been chosen for the booster and the collider magnet. The magnet includes a cold (4.5K) window frame iron yoke and a SC winding made of a hollow NbTi composite SC cable cooled with a two-phase helium flow. Lorentz forces in the winding are supported by the yoke.

BOOSTER MAGNETS

The main goals of the intermediate heavy ion booster synchrotron are the following: accumulation of $4\cdot10^9$ ions of Au^{31+} in the booster; acceleration of heavy ions up to an energy of 600 MeV/u for the most efficient stripping ions up to bare nucleus state; simplification of the requirements to vacuum conditions in the Nuclotron, owing to higher energy and charge state of the ions injected into the Nuclotron; forming the required ion beam longitudinal emittance at an energy of 100 MeV/u with electron cooling system.

The NICA layout makes it possible to place the booster having 211 m circumference and four-fold symmetry lattice inside the existing Synchrophasotron yoke. The magnetic lattice of the booster contains four arcs. Each arc consists of five regular DFO cells with two sector dipoles each and one cell without them (see Fig. 1). The effective length of defocusing D and focusing F quadrupole magnets is 0.47 m and the dipole magnet length is 2.2 m. Main characteristics of the NICA booster magnets are given in Table 1.

Table 1: Main Parameters of the NICA Booster Magnet

Parameter	Dipole	Lens
Number of magnets	40	48
Maximum magnetic field (field gradient)	1.8 T	21.5 T/m
Magnetic field at injection (field gradient)	0.11 T	1.3 T/m
Effective magnetic length	2.2 m	0.47 m
Ramp rate	1.2 T/s	14.3. T/(m·s)
Field error at R= 30 mm	$\leq 6\cdot10^{-4}$	
Beam pipe aperture (h/v)	128 mm/65 mm	
Pole radius	-	47.5 mm
Bending angle	9	-
Radius of curvature	14.01 m	-
Yoke width	0.31	0.226
Yoke height	0.228	0.226
Overall weight	1030 kg	110 kg
Operating current	9.68 kA	
Number of turns in the coil	10	8
Inductance	630μH	96μH
Vacuum shell diameter	640 mm	
Dynamic heat releases	8.4 W	0.8 W
Static heat leak	4.4 W	4.0 W
Helium pressure drop in the cooling channel	≤ 27kPa	
Maximal temperature of helium in the coil	4.65 K	

The designs of the magnets are given in [6] and [7].

---

hamlet@jinr.ru

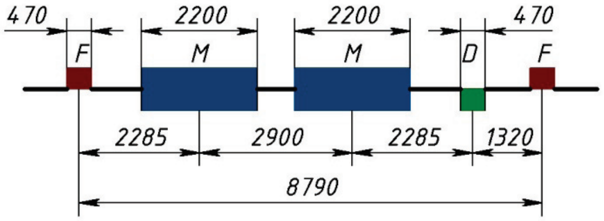

Figure 1: Layout of regular cell of the NICA booster lattice. F and D are focusing and defocusing lenses; M is bending magnet.

The iron yoke of the dipole magnet consists of two symmetric parts that are bolted together. The iron yoke of the quadrupole magnet has four symmetric parts. The half-yokes of the dipole are fabricated of laminated isotropic 0.65 mm thick electrical steel M530. The laminations are compressed by strength of 50 kN and clamped together with four steel angle-profile 8 mm thick. The steel angles are welded with laminations and end steel plates 20 mm thick. The magnet is 2.2 m long and has a radius of the curvature of about 14 m. Fig. 2 shows the two halves of the yoke of the dipole magnet before assembly of its winding.

Figure 2: Halves of the yoke of the NICA booster dipole magnet before assembly of its winding.

Doublet of the lattice lenses is a single rigid mechanical construction of about 1.8 m length. Doublet consists of a focusing lens, defocusing lens, cylinder for rigid mounting lenses with each other, as well as two beam position monitors (see Fig. 3). Doublet has a horizontal jack that allows to parsing it into two parts for assembly (disassembly) halves of the windings of the quadrupole lenses and also beam pipe with BPM. Doublet is fixed in a cryostat with 8 suspension rods and is adjusted in relation to the adjacent magnets as a unit.

A cryogenic test of the first dipole magnet for the NICA booster synchrotron had been performed in May 2011. The first quench occurred at 7705 A. After the 13th quench current reached the nominal value of 9690 A that corresponds to magnetic field induction in the gap equal to 1.8 T. Further training had been stopped because of the power supply and current leads limitation.

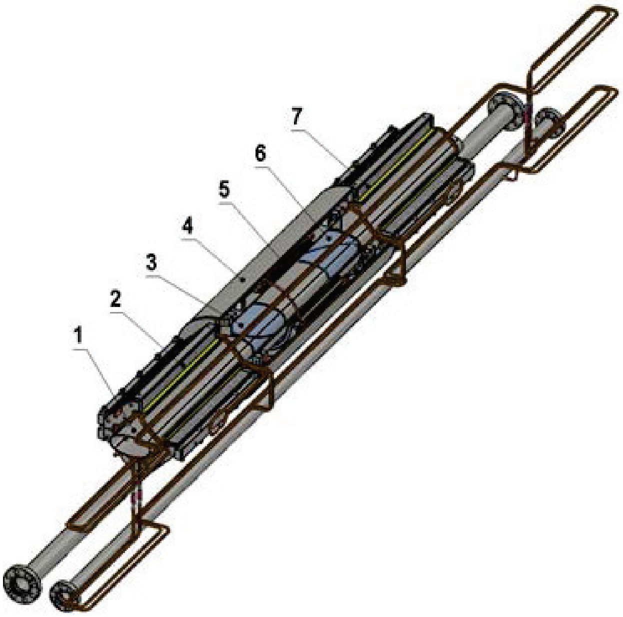

Figure 3: Doublet of quadrupole magnets: 1 – beam pipe; 2, 7 – focusing and defocusing lenses; 3, 6 – vertical and horizontal beam position monitors; 4 – support cylinder; 5 – tube for cooling the support cylinder.

The measured static (at zero current) heat flow to the magnet was 5.8 W. AC losses of 12 W were measured by the calorimetric method while the magnet was operating in the triangular cycle with the magnetic field ramp rate of 1.2 T/s without a pause. Cryogenic tests of the magnet with the new winding were performed in May 2012. Training for the new winding consisted in a single quench at 9475 A. The maximum current in the magnet of 11299 A was determined by quench in the current lead. In early 2013 the old current leads have been replaced with new HTS current leads for 12 kA. Measurements of the harmonics of the magnetic field in the aperture of dipole magnet have been performed with the equipment used for the Nuclotron magnets. Sextupole harmonic of the field in the Booster magnet was about 10 times less than in the Nuclotron magnet. Higher harmonics of the field with the specified equipment was not observed. We are currently developing methods and manufacturing new equipment for magnetic measurements in the NICA magnets with much higher requirements for the quality of the field in comparison with the Nuclotron magnets. Three pre serial dipole magnets for the NICA booster will be manufactured and tested this year.

Experimental studies of the booster quadrupole magnet were carried out in Spring 2012 after upgrade of the main power converter on the test bench. Current reached the nominal value of 9690 A after the 4th quench. The measured static heat flow to the quadrupole magnet was 3.3 W. AC losses of 4.4 W were measured by the calorimetric method while the magnet was operating in the triangular cycle with the following parameters: amplitude of the magnetic field gradient of 20.3 T/m, and ramp rate of 20.3 T/(m·s) without a pause. The pressure drop of the two-phase helium flow in the cooling channel of the lens was 7 kPa during the operation in the indicated mode.

COLLIDER MAGNETS

Two collider rings have the maximum magnetic rigidity of 45 T•m corresponding to the maximum rigidity of the Nuclotron. The rings are vertically separated and designed as “twin aperture” superconducting magnets except the common Interaction Region section. The maximum field of 1.8 T in dipoles and the maximum gradient of 23 T/m in quadrupoles are chosen to avoid the saturation effects in iron yokes. Each ring is a racetrack consisting of two bending arcs and two long straight sections with the circumference of 503 m. Collider ring lattice is based on FODO periodic cell in arc. Arc includes 12 FODO cells. There are four rectangular dipole magnets per cell, two quadrupoles, multipole correctors and BPMs. Long straight sections are matched to the arcs; they contain insertion devices, produce betatron tune variation, vertical beam separation and final focusing in IPs.

Table 2: Main Parameters of the NICA Collider Magnets

Parameter	Dipole	Lens
Number of magnets	80	86 (+ 12*)
Maximum magnetic field (field gradient)	1.8 T	23.1 T/m
Minimum magnetic field (field gradient)	0.57 T	7.3 T/m
Effective magnetic length	1.94 m	0.47 m
Ramp rate	≤0.5 T/s	≤ 6.4 T/(m·s)
Field error at R= 30 mm	$\leq 2\cdot10^{-4}$	
Beam pipe aperture (h/v)	120 mm/70 mm	
Pole radius	-	47.5 mm
Bending angle	4.5	-
Yoke width	0.302	0.300
Yoke height	0.548	0.594
Distance between beams	0.32 m	
Overall weight	1670 kg	250 kg
Operating current	10.4 kA	
Number of turns in the coil	10	8
Inductance	450μH	94μH
Total heat releases	≤13.0 W	≤5.7 W
Maximal temperature of helium in the coil	4.65 K	

* - the final focus lens

The collider magnets parameters are given in Table 2. Design of the dipole magnet is shown in Figure 4. The twin bore dipole and quadrupole magnets are manufactured and ready for test. The production technology, assembling and cooling for the dipole and quadrupole magnets are similar. Cryogenic tests of the model twin aperture dipole and quadrupole magnets are scheduled for May and June this year respectively.

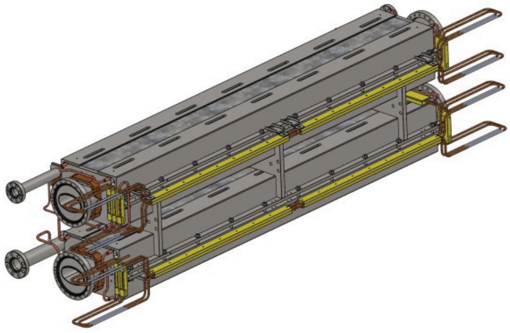

Figure 4: The dipole magnet for the NICA collider.

CONCLUSION

The full-scale Nuclotron–type superconducting model dipole and quadrupole magnets for the NICA booster and collider were manufactured at Laboratory of High Energy Physics of JINR. The first dipole and quadrupole magnets for the NICA booster have successfully passed the cryogenic test on the bench. Three pre serial dipole magnets for the NICA booster will be manufactured and tested this year. Serial production of the magnets for the booster is scheduled for 2014. Cryogenic tests of the model twin aperture dipole and quadrupole magnets for the NICA collider are scheduled for the first half of this year.

The modernization of the existing test facility is completed. Nominal current of the main power converter and current leads of the test facility increased from 6 kA to 12 kA.

REFERENCES

[1] Nuclotron - based ion collider facility. Available: http://nica.jinr.ru/

[2] A. Baldin et al., “Nuclotron status report”, IEEE Trans. Nucl. Sci., 4 (1983) 3247.

[3] H. Khodzhibagiyan, and A. Smirnov, “The concept of a superconducting magnet system for the Nuclotron”, Proc. of ICIC12, Southampton, (1988) 841.

[4] H. Khodzhibagiyan et al. “Superconducting Magnets for the NICA Accelerator Complex in Dubna”, IEEE Trans. Appl. Supercond., 3 (2011) 1795.

[5] H. Khodzhibagiyan et al., “Development of fast-cycling superconducting magnets at JINR”, Proc. of ICIC21, Prague, 1 (2006) 113.

[6] H. Khodzhibagiyan et al., “Status of the design and test of superconducting magnets for the NICA project,” Proceed. of RUPAC2012, Saint-Petersburg, Russia, pp. 149-151.

[7] H. Khodzhibagiyan et al., “Status of the development of superconducting magnets for the NICA project”, IEEE Trans. Appl. Supercond., 3 (2012) 4003004.