ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-WEPRI088

MAGNETIC MEASUREMENT SYSTEM FOR THE NICA BOOSTER MAGNETS

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Abstract

NICA is a new accelerator collider complex presently under construction at Joint Institute for Nuclear Research (JINR) in Dubna. More than 250 superconducting (SC) magnets need for the NICA booster and collider. These magnets will be assembled and tested at the new test facility in the Laboratory of High Energy Physics JINR. The first phase of the system for magnetic measurements was commissioned in late 2013. A method of measuring the quality of the magnetic field in the aperture of the curved dipole magnet for the booster synchrotron is described. First results of magnetic measurements are presented and discussed. Commissioning of equipment for magnetic measurements in the aperture of quadrupole magnets for the NICA booster is close to completion.

INTRODUCTION

At the Laboratory of High Energy Physics (LHEP) creation of the first stage of technical complex [1] for assembly and testing of SC magnets for the NICA and FAIR project is finished. The program of testing of magnets includes "warm" and cold magnetic measurements (MM). For carrying out MM at LHEP the measuring systems are created. The measuring system for carrying out MM of a curved dipole magnet is created and tested; the first "warm" MM of a booster dipole magnet full-scale prototype are carried out.

DIPOLE MAGNET FOR THE NICA BOOSTER

The Nuclotron-type design based on a window frame iron yoke and a saddle-shaped SC winding has been chosen for the NICA booster and collider magnetic system [2]. Nuclotron-type magnets include a cold (4.5K) window frame iron yoke and a winding made of a hollow NbTi composite SC cable cooled with a two-phase helium flow. The iron yoke of the dipole magnet consists of two symmetric parts that are bolted together. 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 stainless steel angle-profile 10 mm thick. The magnet is 2.2 m long and has a radius of the curvature of about 14 m. Main characteristics of the NICA booster dipole magnet are given in Table 1. A cross-section view of the booster dipole magnets with installed magnetic measuring system (MMS) is shown in Fig. 1. The operating cycle of a magnetic field of the booster consists of stages of linear field ramping up and down with a ramp rate of 1.2 T/s and two stages with a constant field, at stage of injection magnetic field is 0.11 T and electron cooling one is 0.56 T.

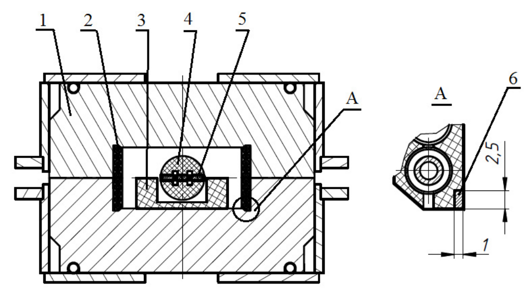

Figure 1: Cross-section view of the bent dipole magnet for the NICA booster with magnetic measurement system. 1. Yoke, 2. Main coil, 3. Base of MMS frame, 4. MMS frame, 5. PCB with harmonic coils, 6. Reference coil.

Table 1: Main Parameters of the NICA Booster Magnets

Parameter	Unit	Value
Number of magnets		40
Maximum magnetic field	T	1.8
Magnetic field at injection	T	0.11
Effective magnetic length	m	2.2
Field error at R= 30 mm		$\leq 6{\cdot}10^{-4}$
Beam pipe aperture (h/v)	mm	128 /65
Bending angle	deg	9
Radius of curvature	m	14.01
Yoke width	m	0.31
Yoke height	m	0.228
Operating current	kA	9.68
Number of turns in the coil		10
Inductance	μH	630

THE MAGNETIC MEASUREMENT SYSTEM

According to the technical specification [3] the following parameters of booster dipole magnets have to be measured: effective length of magnets; angle between the magnetic and mechanical median plane; integrated harmonics of a magnetic field up to the 10th.

The Measurement Methods

For MM of curved dipole magnets earlier a fluxmeter was used [4]. Use of the similar equipment for a SC magnet has considerable difficulties: it is necessary to use the anti-cryostat which reduces a useful aperture of a magnet and complicates exact positioning of a fluxmeter. This method provides parallel measurement on tested and

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reference magnets that doubles expenses on measurements. Due to this the system of MM for the dipole magnets of the NICA booster was developed on the basis of a well-known Fourier analysis method with a step-driwing search coils (integrated flux measured sequentially at N equally spaced azimuthal coil positions) [5]. Measurements are carried out by five rather short (43 cm) measuring sections, each of which contains radial harmonic coils. The relative value of error for use of such coils doesn't exceed tolerances of measurement [6]. In addition to the set of harmonic coils, the system includes large motionless coil located in the median plane of a magnet which measures a full flux, including face parts of a magnet.

Reference Magnetic Field

When sectioning the sensor, the solution of such problem, as orientation of the planes of measuring coils of separate sections relatively each other and magnet median plane is necessary. For the realization of this problem in measured magnets the reference magnetic field from an additional winding (see Fig.1 Pos. 6) consisting of 4 conductors located in corners of the magnet yoke was used. This winding generates a magnetic field directed parallel to the magnet poles. The direction of this magnetic field, due to small sizes of a winding, is defined by the accuracy of fabrication of the magnet yoke. In view of the high mechanical accuracy of manufacturing of a yoke, it is possible to consider that a reference magnetic field is parallel to magnet poles. We will notice that this additional reference winding can be used also, as the detector of the quench in a SC magnet.

The Systems Design

Mechanical design. The measuring system (Fig. 2) consists of five identical sections connected among themselves by the flexible couplings from Teflon. Each section consists of two glass epoxy parts, the frame and the covers. On the frame three multilayered printed-circuit measuring coils are installed. Shafts of sections rotate in ceramic bearings which by glass epoxy holders fasten to the base frame. Sections are located along a reference beam trajectory.

The edge sections are placed normally to a face surface of a yoke, the axis of section passes through the magnet aperture middle point. The base frame is fixed on the bottom pole of a magnet yoke. Precision fabrication of a yoke pole surface and base frame determines the accuracy of positioning of measuring system in a magnet aperture. In a design of a magnet yoke the precision holes for exact installation of a base frame relatively to the yoke are provided. To a shaft of the edge section the wheel for winding of the signal cable is fastened. Further the system via the coupling connects to servomotor shaft.

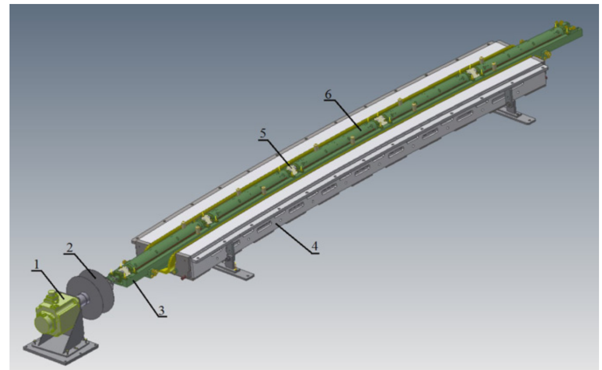

Figure 2: Layout of bottom part of magnets yoke with installed MMS: 1. Servomotor, 2. Bobbin for cable, 3. Base of frame, 4. Bottom part of yoke, 5. Flexible coupling, 6.Measuring section.

Structure of harmonic coil. Measuring coils are made as the multilayered printed-circuit board (PCB). PCB contains three identical radial coils, see Fig. 3. Coils consist of 400 turns created from 20 layers, each of which contains 20 turns. Parameters of PCB are specified in the Table 2. Production of PCB was ordered in China. The central coil is symmetric to a rotation axis, i.e. is the dipole one. The sample of PCB was tested cyclically by cooling down to the LN2 temperature. The sample wasn't destructed.

Table 2: Main Parameters of the Harmonic Coils

R1, mm	6.5
R2, mm	9.5
R3, mm	22.5
L, mm	429.1
Number of turns	400

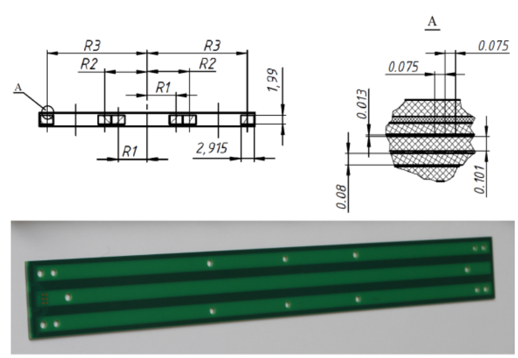

Figure 3: Cross-section view of the PCB with harmonic coils and photo of PCB.

Data Acquisition and Controls

Data acquisition and digital integration. The data acquisition system (Fig.4) is developed on the basis of the hardware NI PXI platform and the environment of LabVIEW [7] system. Measured signals from harmonic coils and the magnet current sensor are digitized in NI

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PXI 4461, 4462 blocks that are constructed on the basis of 24 bits Δ-Σ ADC with the maximum sampled rate 204,8 kS/s. For acquisition and data processing the software in the LabVIEW environment is developed. Digital offline integration with LabVIEW VI's is used.

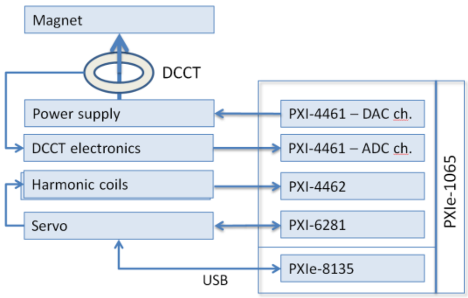

Figure 4: Data acquisition and controls schematic diagram.

Magnet Power Supply and its control. The magnet power supply during providing the warm magnetic measurements represents the linear current regulator. The power supply is controlled by the external analog signal. The operating analog signal, which is setting a shape of an impulse of current, is generated by the DAC of the NI PXI 4461 block. The triangular shape of pulses with parabolic smoothing of inflection points is used. The rate of the current ramping is up to 10 kA/s.

Current measurement. The magnet current is measured by the current sensor LEM's ITZ 600-SBPR FLEX ULTRASTAB, adjusted to the range of currents up to 200 A. The output signal is digitized by NI PXI 4461 ADC block.

Servomotor and its control. For rotation of harmonic coils the Mitsubishi HF-SP 1024B servomotor with MR-J3-100A4 amplifier is used. The servomotor is supplied by an 18-bit encoder and allows to carry out shaft positioning with high precision. Operating mode control (the step value, quantity of steps, dynamic characteristics) a servoamplifier is providing with the help of the producer MR Configurator. Control is realized by impulses generated by the NI PXI 6281 block.

MEASUREMENTS AND ANALISYS ALGORITHM

Measurements are carried out automatically under control of the program in the environment of LabVIEW. On each step of the measurements cycle the next sequence is carried out: generation of an operating signal for PS; digitization of signals of EMF induction of harmonic coils and signals from the magnet current sensor (DCCT); data recording in the TDMS format file on a hard disk of the controller; performance of the servomotor turn on the angle $\Delta\theta = 360\,\circ/N$. The round of measurements is repeated three times: in a reference magnetic field; in the main field for the noncompensated coils; in the main field for the compensated coils.

Data Analysis

The digitized signals from each coil are numerically integrated. Each value of integral for time of t is divided on the current value in this t time point. For the calculated set of values the Fourier's coefficients are estimated which are recalculated in harmonics of a magnetic field. Angular magnetic field vectors position for each of sensor sections relatively to the reference field are calculated. Angular positions of vectors for the main magnetic field are calculated. True positions of magnetic field vectors as a result of measurements of positions of vectors in a reference field are estimated. From the sections integrated harmonics the integrated ones for the magnet are calculated.

RESULTS

The first "warm" magnetic measurements of a full-scale prototype of a dipole magnet of the booster are carried out. Measurements were provided at the magnet excitation current pulses of 100 A, with a ramp rate up to 3.3 kA/s. Relative harmonics of a magnetic field are measured. In the Table 3 the measured harmonics are compared with simulated ones by 3D magnet modeling by the OPERA code [8].

ACKNOWLEDGMENT

Authors thank A. Bychkov, S. Kostromin and M. Omeljanenko for their useful suggestions and contribution.

Table 3: Measured and Calculated Integrated Fractional Field Harmonics, 10-4

	b_2	a_2	b_3	a_3	b_4	a_4	b_5	a_5	b_6	a_6
Measured	-1.30	4.34	-1.80	1.76	0.27	0.82	0.27	0.18	0.17	0.05
Calculated	-1.13	0	-7.71	0	0.04	0	3.15	0	0.14	0

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