IOP Conference Series: Materials Science and Engineering

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To cite this article: H Khodzhibagiyan *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **502** 012096

IOP Conf. Series: Materials Science and Engineering **502** (2019) 012096 doi:10.1088/1757-899X/502/1/012096

Cryogenic test results of the superconducting magnets for the NICA complex and the SIS100 synchrotron of FAIR

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Abstract. NICA is an international accelerator complex under construction at the Joint Institute for Nuclear Research in Dubna. At GSI Darmstadt the planned heavy ion synchrotron SIS100 has to deliver high intensity ion beams for the FAIR project. The NICA booster and collider as well as the FAIR accelerator use superconducting magnets of the Nuclotron type. The magnet design and cryogenic test results presented in this work focus on quench history, static heat leak and dynamic heat releases under pulsed operation mode, cooling down and warming up histories, pressure drop in cooling channels with two-phase helium flow.

1. Introduction

NICA is an international accelerator complex [1] under construction at the Joint Institute for Nuclear Research in Dubna. The main goal of the project is to study hot and dense strongly interacting matter in heavy-ion (up to Au) collisions at center-of-mass energies from 4 to 11 GeV. A study of spin physics is also foreseen with extracted and colliding beams of polarized deuterons and protons at energies of up to 27 GeV for protons. The NICA accelerator complex will consist of two injector chains, the new 600 MeV/u superconducting (SC) booster synchrotron, the upgraded SC synchrotron Nuclotron [2], and the new SC collider built of two storage rings each about 503 m in circumference with luminosity up to $1 \cdot 10^{27}$ cm^{-2} s^{-1} for Au^{79+} and two interaction points. The Nuclotron-type magnet design [3], [4], which is based on a cold iron yoke and a saddle-shaped SC coil has been chosen for the booster and the collider magnets as well as for the SIS100 magnets. The SIS100 synchrotron is the main accelerator of the international Facility for Antiproton and Ion Research – FAIR in Darmstadt [5]. SIS100 will provide high intensity, high-energy proton and ion beams. Beside the reference Uranium and proton beams, acceleration of all other ion species is foreseen.

2. Magnet design

The design of the NICA and the SIS100 magnets is based on the magnet of the Nuclotron, a SC synchrotron operated at VBLHEP, JINR since 1993. This design is based on a window frame yoke at 4.5 K and a SC coil made of a hollow NbTi composite SC cable cooled with a forced two-phase helium flow. The yoke supports the Lorentz forces in the coil. Nuclotron-type cable of coil consist of Cu-Ni tube wrapped with multifilament SC wires. The SC wires are pressed to the cooling tube by means of a binding wire to ensure a good thermal contact. The cable is insulated with two layers of Kapton tape and two layers of fiberglass tape, impregnated with an epoxy compound of hot curing.

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2.1. Magnets for the NICA booster

The detailed designs of the magnets for the NICA booster are given in [6] – [8]. The iron yoke of the magnet is fabricated from laminated isotropic 0.65 mm thick M530 silicon steel. The side plates are welded to the laminations and the stainless steel end plates, forming half of the yoke. Two symmetric half-yokes are bolted together.

2.1.1. Dipole magnet. The magnet is 2.2 m long and has a curvature radius of about 14 m. Figure 1 shows the dipole magnet for the NICA booster.

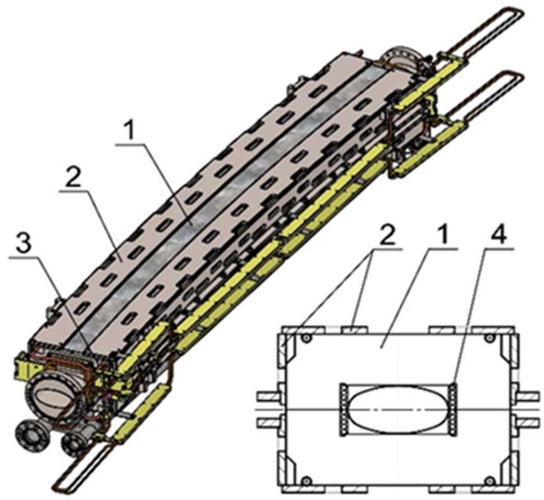

Figure 1. The dipole magnet for the NICA booster. 1 - lamination, 2 – side plate, 3 – end plate, SC coil.

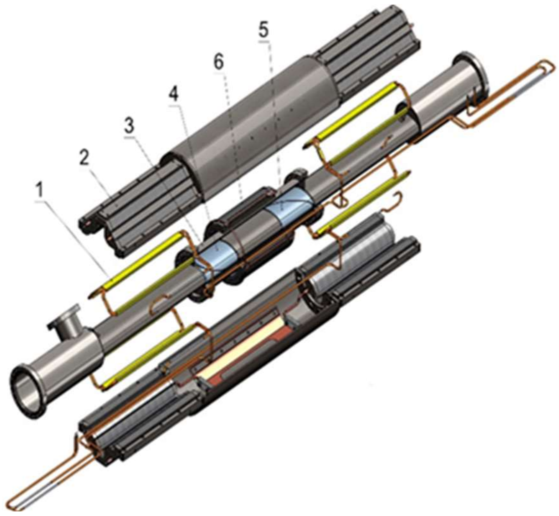

Figure 2. The doublet of the NICA booster lenses. 1 – half-coil, 2 – half-yoke, 3 – beam pipe, 4, 5 – beam position monitors, 6 – corrector magnet.

2.1.2. Doublet of the lenses. Two lattice lenses are connected together using an intermediate cylinder and form a doublet (see figure 2). This doublet is about 1.8 m long and has a rigid mechanical design. It has a demountable construction that allows splitting the doublet into two horizontal parts.

2.1.3. Corrector magnet. 32 corrector magnets, each 0.32 m long, will be installed in the booster synchrotron. 24 steering magnets will have two coils each (horizontal and vertical dipole SC coils) other 8 corrector magnets will contain four SC coils each: normal and screw sextupole, screw quadrupole and octupole coils. Flat coils of SC wire (see figure 3) are glued to the cooling cylinder and have indirect cooling. Figure 4 shows a photo of the corrector magnet yoke.

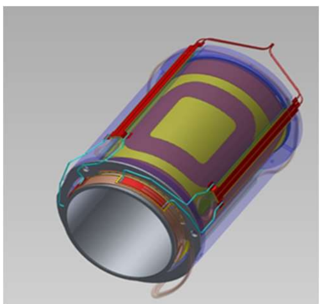

Figure 3. View of the corrector magnet coil.

Figure 4. Photograph of the corrector yoke.

2.2. Magnets for the NICA collider

The two collider rings are placed one above each other. The design of the twin bore dipole and quadrupole magnets is shown in figure 5. The distance between the ring median planes (beam axes) is chosen to 320 mm. That is achieved with the magnet having two apertures in one yoke ("twin aperture" SC magnets). The distance between the ring median planes (beam axes) is chosen to be 320 mm. That is achieved with the magnet having two apertures in one yoke ("twin aperture" SC magnets). The design of the correcting magnet of the collider is similar to the booster corrector magnet design.

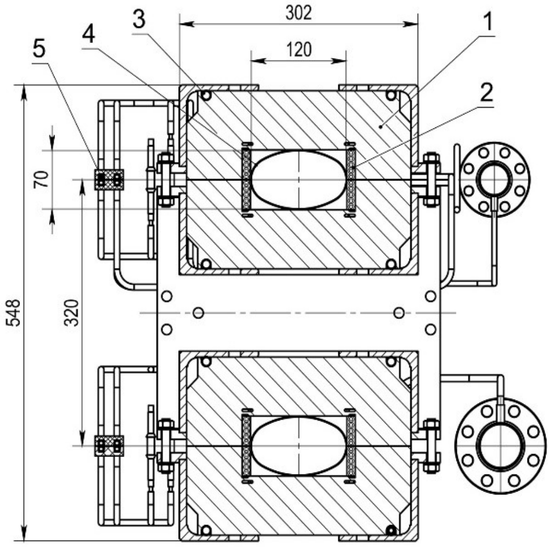

Figure 5. Cross-section of the collider dipole magnet. 1 – lamination, 2 – SC coil, 3 – tube for cooling the yoke, 4 – beam pipe, 5 – bus bars.

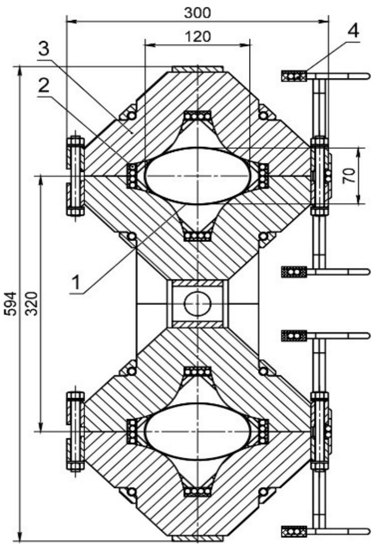

Figure 6. Cross-section of the collider quadrupole lens. 1 – beam pipe, 2 – half-yoke, 3 – lamination, 4 – bus bars.

2.3. Magnets for the SIS100 synchrotron

The Nuclotron type design was chosen for the SIS100 lattice dipole and quadrupole magnets [9], [10]. A single-layer dipole magnet (see figure 5) has a radius of curvature of about 52 m. A quadrupole magnet with hyperbolic poles is shown in figure 6. The iron yokes of the magnets are fabricated of laminated isotropic 1.0 mm thick M600-100A silicon steel.

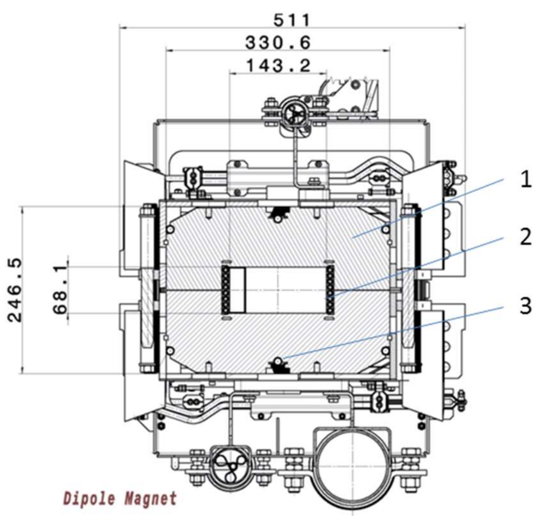

Figure 7. Cross-section of the SIS100 dipole.

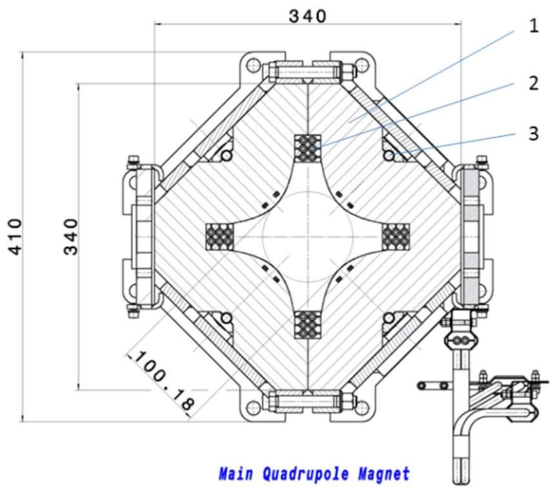

Figure 8. Cross-section of the SIS100 quadrupole magnet.

2.3.1. Corrector magnets. The multipole corrector and the steerer were designed as a nested magnet, namely, a quadrupole, a sextupole and an octupole in the multipole corrector and horizontal and vertical dipoles in the steerer (see figure 9). These magnets are of the Cosine-theta type. The chromaticity sextupole was designed as a superferric magnet (see figure 10). The corrector coils are wound with the Nuclotron type cable of electrically-insulated wires.

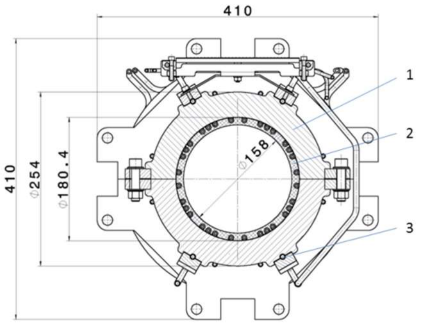

Figure 9. View of the steerer magnet.

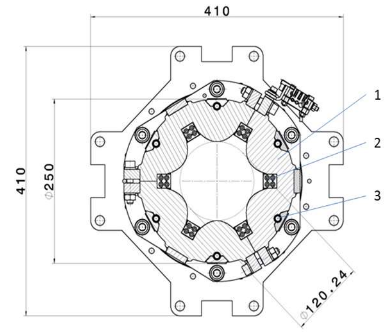

Figure 10. View of the chromaticity sextupole magnet.

3. Cryogenic test results

All magnets for the NICA and the FAIR projects must successfully withstand cryogenic tests before they are installed in the tunnel of the accelerator. Cryogenic tests include: training of the magnet, measuring the static heat input and dynamic heat dissipation, measuring the hydraulic resistance of the cooling channel during operation in a reference cycle, measuring the quality of the magnetic field in the aperture and the effective magnetic length of the magnet, checking the tightness of the helium cooling channels and the electrical insulation strength in the operating conditions, etc.

Cooling-down and warm-up history of the NICA dipole magnet are shown in figure 11 and figure 12, respectively. The time spent for cooling-down the dipole magnet of the NICA collider, dipole magnet, and quadrupole unit of the SIS100 was 69, 82 and 80 hours, respectively. Typical quench history for the booster magnets are shown in figure 11 and figure 12. Magnets for the NICA collider and the

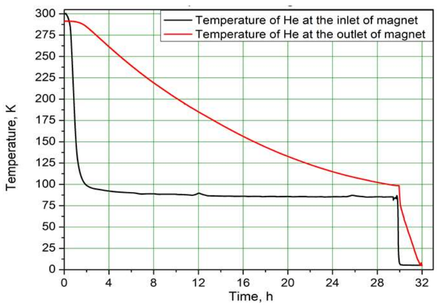

Figure 11. Cooling-down history for the NICA booster magnet.

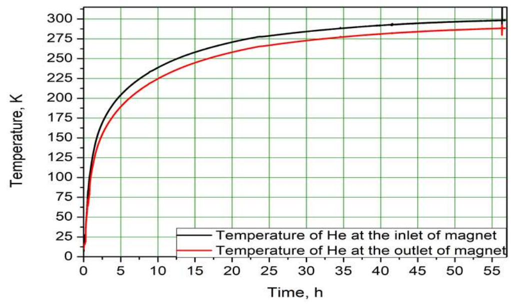

Figure 12. Warm-up history for the NICA booster magnet.

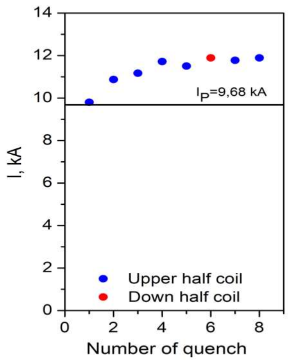

Figure 13. Quench history for the booster dipole.

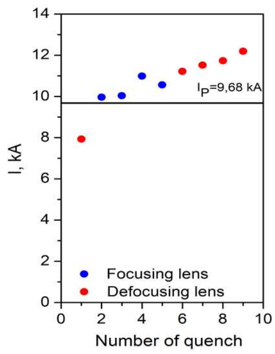

Figure 14. Quench history for the booster doublet.

SIS100 synchrotron also have a short training of several quenches. The recovery time of the operating conditions after the quench is about 3 minutes. Magnetic measurements have good repeatability and

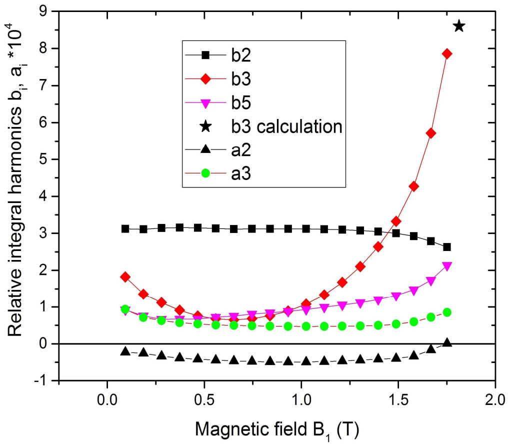

Figure 15. Relative integral harmonics of the magnetic field in the aperture of the booster dipole at the radius of 30 mm as a function of the magnetic field in the magnet center.

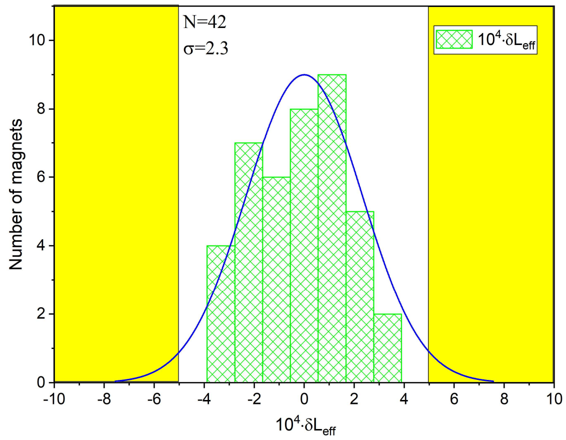

Figure 16. Distribution of effective lengths of the booster dipole magnets relative variations for maximum RSD.

their magnitude is within the permissible values (see figure 15 and figure 16). The static heat leak to the NICA booster dipole magnet and doublet, the dipole magnet of the NICA collider, the dipole magnet, and the quadrupole unit for the SIS100 was 4.6 and 8.1, 7.8, 7, and 4.6 W, respectively. The dynamic heat release during operation in the reference cycle for the NICA booster dipole magnet and doublet, the dipole magnet of the NICA collider, the dipole magnet, and the quadrupole unit for the SIS100 was 9.1 and 2.9, 2.1, 42 and 31 W, respectively. The pressure difference between the supply and return helium headers under operating conditions will be 0.35, 0.25 and 0.5 bars respectively for the booster NICA, collider NICA and SIS100 synchrotron.

4. Conclusion

- The serial production of the NICA booster magnets has been completed. Installation of magnets in the accelerator tunnel will begin in September 2018.
- The serial production of the NICA collider magnets began in March 2018. Completion of the magnets manufacture is planned for 2020.
- There is a serial production of the magnets for the SIS100 synchrotron. Completion of the magnets manufacture is planned for 2020.

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