ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB383

# MAGNETIC FIELD PERFORMANCE OF THE FIRST SERIAL QUADRUPOLE UNITS FOR THE SIS100 SYNCHROTRON OF FAIR

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*Abstract*

The FAIR project is a new international accelerator complex, currently under construction in Darmstadt, Germany. The heavy ion synchrotron SIS100 is the main accelerator of the whole complex. It will provide high intensity primary beams with the magnetic rigidity of 100 Tm and a maximum repetition rate up to 4 Hz. The series production and testing of superconducting quadrupole units began in 2020 at JINR, Dubna. The first batch of units were delivered to Germany in September 2020. Each unit is subjected to a comprehensive testing program both at ambient temperature and under cryogenic conditions. We present the performance characteristics of the first quadrupole units (consisting of a lattice quadrupole magnet and correcting magnet mechanically and hydraulically coupled to a quadrupole). The main attention is paid to the field quality of the series of 6 quadrupoles measured by the same probe.

## INTRODUCTION

The FAIR accelerator complex [1] will include the heavy ion synchrotron SIS100 as the main accelerator of the complex, which uses superconducting (SC) magnets: 108 dipoles, 168 quadrupoles, and various corrector SC magnets.

The production and test facility [2] of SC magnets for the NICA and FAIR project at the Laboratory of High Energy Physics of JINR was commissioned at the end of 2016. To prepare the production of the NICA magnets a set of magnetic measurement equipment was developed and manufactured [3, 4]. For the magnetic measurements of the SIS100 units, a new specialized probe was developed and manufactured.

The serial production of SIS100 quadrupole units started in 2020. Currently 16 quadrupole units of SIS100 have been manufactured and fully tested, 12 units have been delivered to the customer in Germany.

## THE SIS100 QUADRUPOLE UNITS

The SIS100 quadrupole units (Fig. 1) are iron dominated superconducting (super-ferric) magnets cooled by forced flow two phase helium provided by Nuclotron-type cables [5, 6]. The designs of the SIS100 units are given in [7, 8].

### *Main Characteristics of the Magnets*

The magnets are ramped with rates of up to 58 (T/m)/s. The design quadrupole gradient is 27.77 T/m at the centre of the magnet for an applied current of 10.512 kA. In order to meet the beam dynamics requirements, the field quality has to be <±6·10$^{-4}$ within a reference radius of 40 mm. The

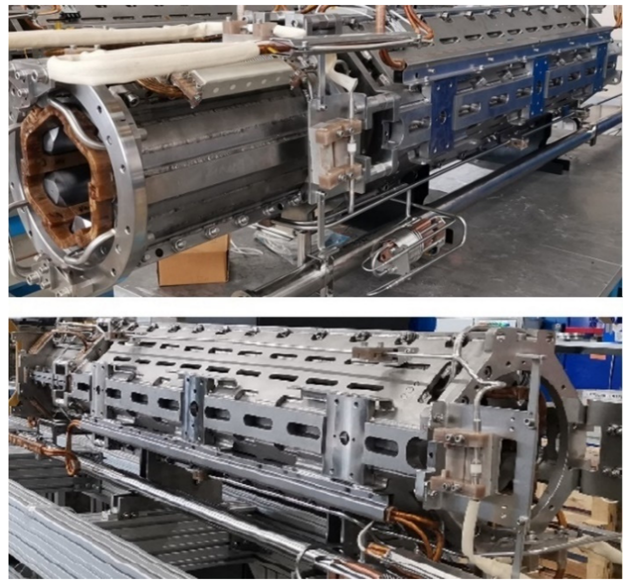

Figure 1: Photos of the serial units of first batch, SF2B (top) and VQD (bottom).

Table 1: Main Characteristics of the SIS100 Quadrupole Magnets

| Parameter | Units | Value |
|---|---|---|
| Number of turns | | 3 turns per pole |
| Minimum quadrupole magnetic field $B_2^{min}$ at magnet centre | T/m | 2.06 |
| Maximum quadrupole magnetic field $B_2^{max}$ at magnet centre | T/m | 27.77 |
| Effective magnetic length $L_{eff}$ | m | 1.264 |
| Ramp rate dB/dt | (T/m)/s | 58 |
| Multipole field at reference radius 40 mm | | <±6·10$^{-4}$ |
| Random variation of integral quadrupole field | | < ±1·10$^{-3}$ |
| Maximum current | A | 10512 |
| Inductance | mH | 0.41 |
| Magnet aperture, pole tip radius | mm | 50 |
| Magnet length z | m | 1.4 |
| Magnet height y | m | 0.41 |
| Magnet width x | m | 0.39 |
| Magnet weight | kg | 850 |

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random variation of the integral quadrupole field has to be $< \pm 1 \cdot 10^{-3}$. The main characteristics of the SIS100 quadrupole magnets are presented in the Table 1.

## MAGNETIC MEASUREMENTS

Magnetic measurements are performed at both ambient and cryogenic conditions for 100% of the magnets. The cryogenic measurement is performed after the training of the unit magnets. A new specialized probe was developed and manufactured. The magnetic measurement probe was developed based on our experience gained in the development and operation of probes for magnets of the NICA project [6] and also for the "first of series" SIS100 unit [9]. The probe operates under vacuum and cryogenic temperatures. Magnetic measurements are performed in step-wised mode with a linearly increasing magnetic field with ramp-rate 5.75 kA/s. The remanent field is measured at zero current in rotation mode with constant speed. The other measurement equipment is the same as for the NICA magnets.

### *The Rotating Coil Probe*

The probe (see Fig. 2) consists of five radial coil arrays, manufactured as multilayer PCB. Each of them has 400 turns; distributed over 20 layers and 20 turns. The coils form the well-known 5-coil radial array [10] for quadrupole compensation (1 spare coil). The probe has five PCBs, 3 of the same length in the center of the probe, they overlap the quadrupole field area and two larger boards at the edges of the probe overlap the corrector areas. The boards are assembled into an assembly, fastened by two plates of fiberglass. This assembly is placed inside a fiberglass pipe, in which they are aligned in radial position on the probe rotation axis. All PCBs are equipped with temperature sensors, which are required to do correct for the temperature dependence of the coils sensitivities. The mechanical accuracy of the assembly of the probe was verified using a portable coordinate machine (ROMER Arm). The length of the probe is 3 m.

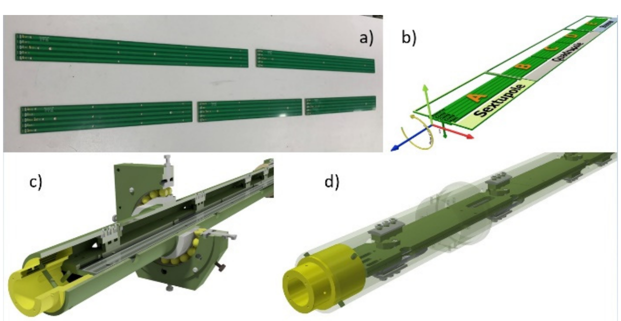


Figure 2: Measuring probe design: a) PCB coils arrays; b) boards arrangement inside unit; c) and d) internal design pf the probe.

Figure 3 shows the view of the probe installed inside the quadrupole magnet (1). Inside the magnet the axial position of the probe (2) is determined by precision ceramic bearings with small clearance and tolerances (4). The outer diameter of the bearings is nearly equal to the bore of the quadrupole magnet so that the bearing rests directly on the lower yoke poles. External self-aligning ceramic bearings (3) are used to align the whole probe to the axis of rotation. Adjustable bearing supports are attached to a stainless steel frame (5).

Figure 4 shows the probe inside the cryostat (cryostat not shown). The rotation of the motor is transmitted from the servomotor (1) to the probe by a magnetic fluid rotary feedthrough and then a tubular shaft made of stainless steel with two compensating bellows. On the other side of the probe, the signals are output to the outside on the other side of the cryostat also through a tubular shaft also with two bellows, followed by slip-rings. An angular encoder is installed at the end of this shaft.

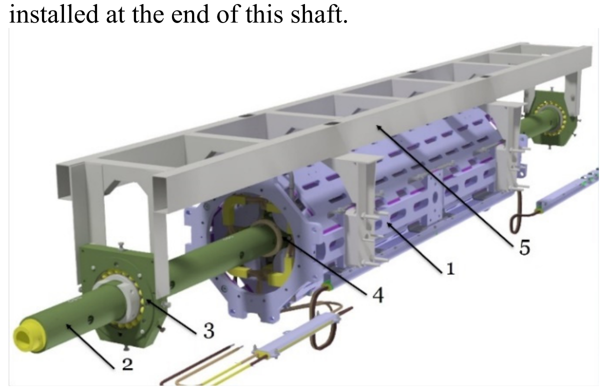


Figure 3: Measuring probe inside the quadrupole magnet: 1 - quadrupole magnet; 2 – probe; 3 – outside self-aligning ceramic ball bearings and adjustable housings; 4 – inside precision ceramic ball bearing with small clearance and tolerances; 5 – frame.

The standard procedure of step-wise magnetic measurements for warm and cold is used. The measurement is performed in 64 angular positions. After the end of the AC program the measurement is performed with constant rotation for the measurement of the residual field at zero magnet current. The signals from the coils and the signal from the current probe are digitized with the NI PXIe-4464 modules and written to disk. Integration and all subsequent data processing are performed offline.

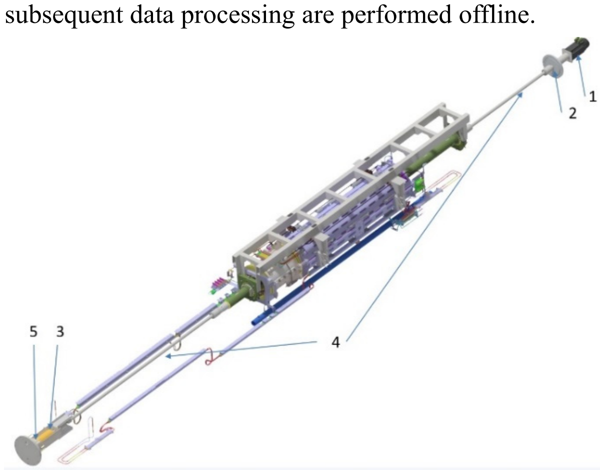


Figure 4: Measuring probe inside cryostat (not shown)1 – servo-motor; 2 – magnetic fluid rotary feedthrough; 3 – slip-rings; 4 – stainless steel tubular shafts with two bellows compensators; 5 – angular encoder.

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# MAGNETIC MEASUREMENTS RESULTS

## *Relative Deviation of Quadrupoles Field Integrals*

The current dependence of the integrated transfer functions for a series of 6 units of the first batch are shown in Fig. 5. The random variation of the integral quadrupole field $\sigma_{GL}/GL$ is below $1{\cdot}10^{-3}$ for all currents, which is in accordance with the design parameters of the quadrupole magnets.

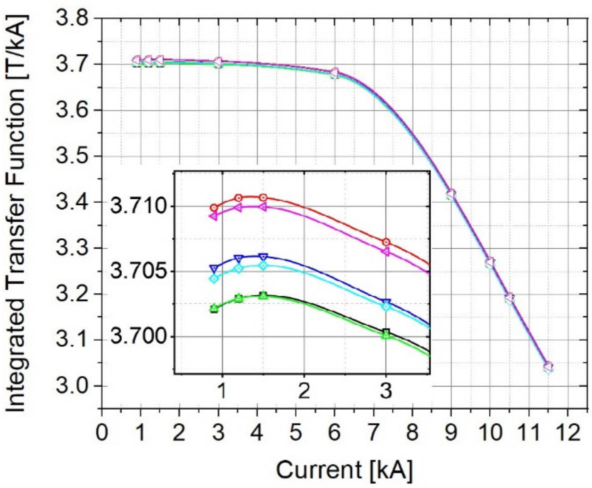


Figure 5: Current dependence of the integrated transfer function for series of 6 units.

## *Relative Integrated Multipoles*

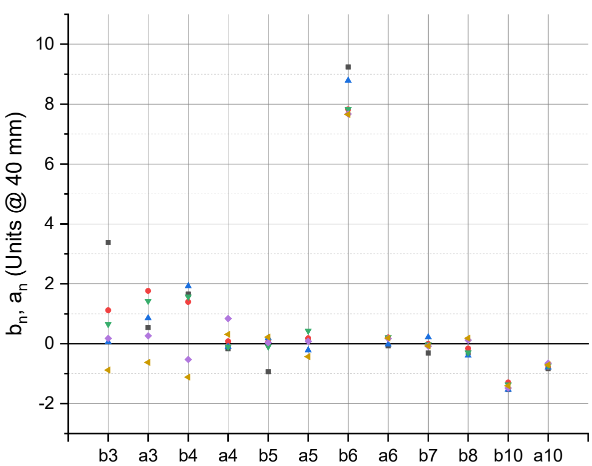


Figure 6: Field quality at 900 A for 6 serial magnets.

For these 6 units, the multipole components are given for 900 A and 10.5 kA in Fig. 6 and 7. The multipoles at reference radius 40 mm are integrated over the all-unit length, i.e. calculated by data from all 5 sections of the probe. The multipoles were measured while the correctors were switched off. Multipoles are normalized to the main quadrupole field integral. Most integrated multipoles are within the design limit for both the low and the high current. Some discrepancy was found for the components a3 (skew sextupole) of one unit at high current and b6 (dodekapole) for both current levels.

# CONCLUSION

A new magnetometer has been developed, manufactured, and put into operation for measuring the magnetic field of SIS100 superconducting quadrupole units of the FAIR project. These operate at cryogenic and at room temperature. The measurement performance was demonstrated by the test results of the first series quadrupole units for the SIS100 accelerator of the FAIR project. The measurement results were presented for the first six quadrupole magnets for the entire field range for operating conditions. A technology has been developed that allows serial measurements of the magnetic field of SIS100 units. Serial production and testing of SIS100 units has been started and is progressing successfully. Figure 8 shows current dependence of the b6 harmonic.

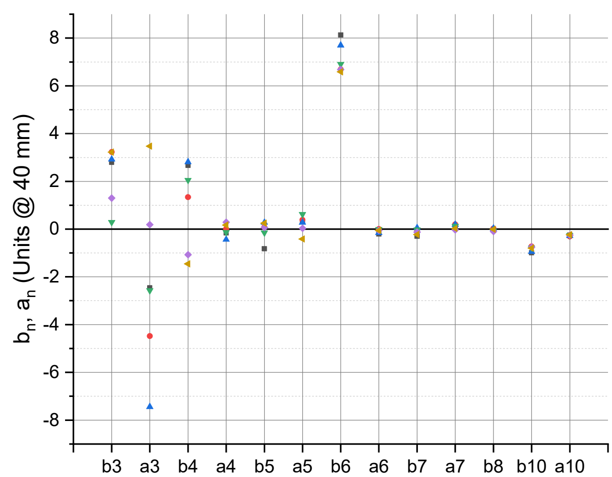


Figure 7: Field quality at 10500 A for 6 serial magnets.

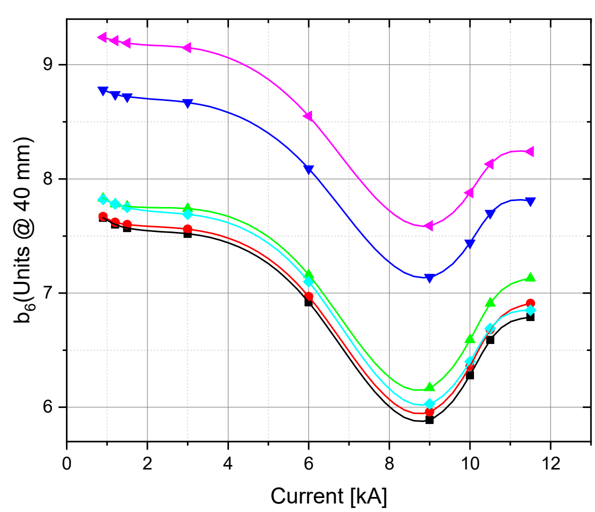


Figure 8: Current dependence of the b6 for series of 6 units (lines are splines).

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## REFERENCES


[1] P. J. Spiller *et al.,* "Status of the FAIR Project", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 63-68. doi:10.18429/JACoW-IPAC2018-MOZGBF2

[2] D. Nikiforov, N. Agapov, H. Khodzhibagiyan, N. Emelianov, and V. Korolev, "Cryogenic test facility of superconducting magnets for the accelerator complex NICA*," Journal of Physics: Conference Series*, vol. 507, no. 3, p. 032034, May 2014. doi:10.1088/1742-6596/507/3/032034

[3] V. V. Borisov *et al.*, "Magnetic Measurement System for the NICA Booster Magnets", in *Proc. 5th Int. Particle Accelerator Conf. (IPAC'14)*, Dresden, Germany, Jun. 2014, pp. 2696-2699. doi:10.18429/JACoW-IPAC2014-WEPRI088

[4] A. V. Shemchuk *et al.*, "Serial Magnetic Measurements of Quadrupole Magnets of the NICA Booster Synchrotron," *Physics of Particles and Nuclei Letters*, vol. 15, no. 7, pp. 873–877, Dec. 2018. doi:10.1134/S1547477118070658

[5] H. G. Khodzhibagiyan, A. Kovalenko, and E. Fischer, "Some aspects of cable design for fast cycling superconducting synchrotronmagnets," *IEEE Trans. Appl. Supercond.*, vol. 14, no. 2, pp. 1031–1034, Jun. 2004. doi:10.1109/TASC.2004.830386

[6] H. G. Khodzhibagiyan, "Design of new hollow superconducting NbTi cables for fast cycling synchrotron magnets", *IEEE Trans. Appl. Supercond.*, vol. 13, no. 2, pp. 3370–3373, Jun. 2003. doi:10.1109/TASC.2003.812323

[7] E. S. Fischer *et al.*, "Superconducting Quadrupole Module System for the SIS100 Synchrotron", in *Proc. 23rd Russian Particle Accelerator Conf. (RuPAC'12)*, Saint Petersburg, Russia, Sep. 2012, paper THAOR01, pp. 143-145. https://accelconf.web.cern.ch/rupac2012/papers/thaor01.pdf

[8] J. P. Meier *et al.*, "Cryo-technical design aspects of the superconducting SIS100 quadrupole doublet modules", *Amer. Inst. Phys.*, vol. 1573, pp. 1529-1526, 2014. doi:10.1063/1.4860887

[9] E. S. Fischer *et al.*, "First Tests of the Main Quadrupole and Corrector Magnets for the SIS100 Synchrotron of FAIR", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 2751-2754. doi:10.18429/JACoW-IPAC2018-WEPML030

[10] J. Billan *et al.*, "Magnetic measurements of the LHC quadrupoles and dipole magnets at room temperature", LHC-PROJECT-NOTE-283, Jan. 2002. https://cds.cern.ch/record/691928