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FIRST EXPERIENCE OF PRODUCTION AND TESTING THE SUPERCONDUCTING QUADRUPOLE AND CORRECTOR MAGNETS FOR THE SIS100 HEAVY ION ACCELERATOR OF FAIR

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Abstract

The fast-cycling superconducting SIS100 heavy ion accelerator is the designated working horse of the international Facility for Antiproton and Ion Research (FAIR) under construction at GSI in Darmstadt, Germany [1].

The main dipoles will ramp with 4 T/s and with a repetition frequency of 1 Hz up to a maximum magnetic field of 1.9 T. The field gradient of the main quadrupole will reach 27.77 T/m. The integral magnetic field length of the horizontal/vertical steerer and of the chromaticity sextupole corrector magnets will provide 0.403/0.41 m and 0.383 m, respectively. The series production of the high current quadrupoles and of the individually ramped low current corrector magnets was started in 2020 at the JINR in Dubna and is planned to be completed in 2023. We present the technological challenges that must be solved from production of the first magnets toward a stable and high-rate series production with reliably magnet quality as well as the first test results at operation conditions.

INTRODUCTION

The international scientific center FAIR will provide high intensity beams of ions and antiprotons for experiments in nuclear, atomic and plasma physics 0. The operation modes of the FAIR facility will facilitate four experiments simultaneously. Beside the reference Uranium and proton beams, acceleration of all other ion species is foreseen. The SIS100 synchrotron has a magnetic rigidity of 100 T·m. The high repetition rate of its acceleration cycles up to 1 Hz requires fast-ramped superconducting magnets with high dynamic heat load which must be cooled steadily. The SIS100 dipole and quadrupole magnets as well as the magnets for the NICA project [2] were designed based on the fast-cycling super-ferric magnets for the Nuclotron synchrotron at JINR in Dubna [3-8]. 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 by end of 2016. For production and testing of the superconducting magnets a detailed quality assurance system was introduced, various sets of geometrical and magnetic measurement equipment were developed, methodically optimized 0, 0 and the high-resolution data analysis processing was adjusted.

THE CRYOMAGNETIC COMPONENTS

The synchrotron ring has a circumference of 1.1 km consists of six sections with cryomagnetic components, bypass lines and electrical supply systems, shown in Fig. 1. In each sector there are 9 quadrupole doubled modules (QDM) of the arc-section type, two QDM of the arc-termination type, 18 dipole modules (DPM) and 2 missing DPM. The basic ion optic cell is 12.9 m long and built of the dipole – dipole – defocusing quadrupole – focusing quadrupole structure (DP – DP – QD – QF). Besides the 108 main dipoles there are three families of quadrupoles, powered in their own electrical circuits – F1, F2, QD.

The operation modes of the accelerator are planned to vary in a wide parameter range of magnetic field amplitude, ramp rate and repetition frequency 0.

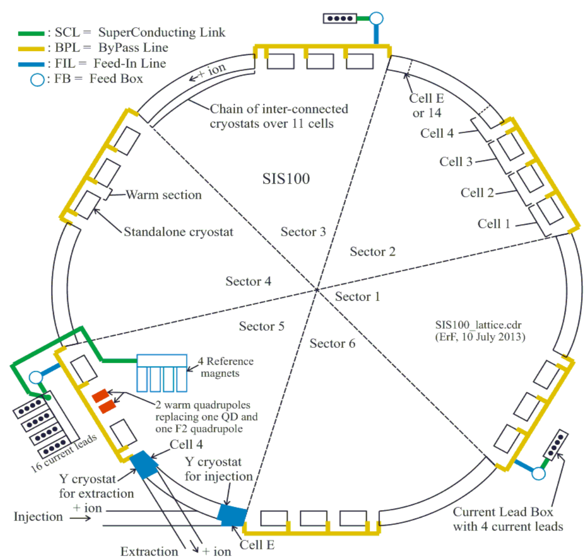

Figure 1: Scheme of the six sections of the synchrotron ring with Bypass Lines, the cryogenic and electrical supply systems.

The cryomagnetic modules have 11 different types of QDM, always containing two quadrupole units (QPU). Two QPU are mounted on a common girder system and combined with additional components of the vacuum system or a collimator. A QPU is a combination of a quadrupole magnet with different corrector magnets or also with a beam position monitor, mounted on the quadrupole as one cold mass. The detailed schema of the modules and units is given in Table 1. In this paper we present the results for the magnet parts of units VQD, SF2B and SF1B. The assembly with beam position monitors as well as their integration into a complete doublet configuration (here 2.5 or 1.7B) is not part of the working contract between JINR and the GSI/FAIR company and remains in the responsibility of the latter.

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Table 1: Quadrupole Units and Doublet Modules

Unit Configuration			Doublet Configuration		
Upstream	Centre	Downstream	Joined Name	Short Name	Quantity
QDB	-TRP-	SF2	QDB-TRP-SF2	2.123	15
QDBs	-TRP-	SF2s	QDBs-TRP-SF2s	2.13s	2
QDBb	-T-	SF2Mb	QDBb-T-SF2Mb	2.4	5
QDBx	-T-	SF2Mx	QDBx-T-SF2Mx	2.4x	1
VQD	**-CR-**	**SF2B**	**VQD-CR-SF2B**	**2.5**	**6**
BQD	-C-	SF1H	BQD-C-SF1H	1.6A	12
VQD	-CR-	SF1B	VQD-CR-SF1B	1.7B	12
BQD	-C-	SF2H	BQD-C-SF2H	2.8C	12
BQD	-CR-	SF2J	BQD-CR-SF2J	2.9D	12
MQDb	-C-	SF1Bb	MQDb-C-SF1Bb	1.E	5
MQDi	-C-	SF1Bi	MQDi-C-SF1Bi	1.Ei	1
			Total		83

The abbreviations in Table 1 are the following: QD – Defocusing quadrupole, F1 – Focusing quad. 1, F2 – Focusing quad. 2, B – Beam position monitor, V – Vertical chromaticity Sextupole, H – Horizontal chromaticity Sextupole, S – Steering magnet, M – Multipole corrector magnet, J – gamma-jump Quadrupole, C – Cryo-ion-catcher (collimator), T – Drift tube, b – modified busbars, i – injection Y cryostat, x – extraction Y cryostat, s – Star shape chamber, P – Cryo-sorption-pump, R – Roughing with cold-warm transition (CWT).

QUADRUPOLES AND CORRECTOR MAGNETS

All superconducting quadrupole and corrector magnets of SIS100 were contracted to be manufactured and tested in Dubna. The Nuclotron-type design — a cold, window-frame iron yoke with a coil made of hollow superconducting cable — was chosen for the SIS100 magnets. For the low current corrector magnets, a Nuclotron-type cable utilizing electrically insulated strands, was chosen. The main characteristics and the number of series magnets are given in Table 2. The cross sections of the sextupole (window frame design) and of the steerer (cosine-theta design) are illustrated in Fig. 2.

Table 2: Characteristics of the Magnets

Characteristic	Lattice Quadrupole	Corrector magnet		
		Multipole (Q/S/O)	Steerer	Chrom. Sextupole
Number of magnets	166	12	84	42
Max. field strength, T/m^{n-1}	27.77	0.75/25/333,3	0.37	232
Effective magnetic length, m	1.264	0.75	0.403/0.41	0.383
Aperture diameter, mm	100	150	135	120
Operation current	10512	250/246/240	245/241	252
Magnet weight, kg	850	200	120	145

Status of the Series Production

The iron yokes for all the quadrupoles, sextupoles and steerers were already produced by industry (STP, Minsk) and passed the incoming inspection at JINR. The superconducting coils are manufactured in Dubna and had passed the quality inspection for 20 %, 25 % and 50 % of the overall amount of the quadrupoles, sextupoles and steerers respectively. Using these components all magnets of the series type 2.5 (12 QPUs) and 33 % of series type 1.7B were completed, assembled to units, tested and delivered to FAIR by end of August 2021. The next 8 QPU are in preparation for shipment until end of October.

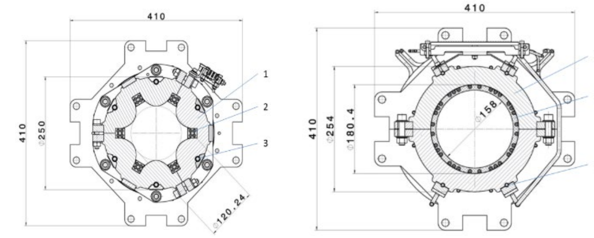

Figure 2: Cross sections of the sextupole (left) and of the steerer (right).

Test Results and Reproducibility

The details of the cryogenic procedures and the magnetic measurement systems are presented in 0-0.

The field quality of window frame magnets is dominated by the accuracy of yoke geometry to about 90 %. The geometry of the poles is checked with a dedicate gauge equipped with 20 capacitive sensors (see Fig. 3 for a typical example, yoke Nr. 142). The data are well within the tolerance limit of ±50 µm. Such a quality was found for all quadrupole apertures.

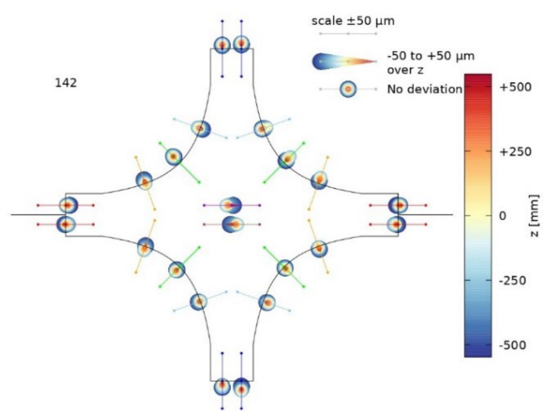

Figure 3: Geometrical measurement results for the real aperture along the yoke length compared to the designed contour.

A vibrating wire system was used for fiducialization of the quadrupoles 0. The precise knowledge of coordinates and direction of the magnetic axis with respect to the yoke symmetry and the reference points is a crucial requirement for the doublet conception: Both QPUs must be fixed finally on a common girder structure with exact mutual alignment of their magnetic axes. This alignment must hold unchanged even during an occasionally vacuum crash or other operation faults.

The horizontal y- and vertical z-position of the magnetic axis in the midplane of the quadrupole are presented in Fig. 4 for subsequent produced 22 quadrupoles. The data are showing a good reproducibility along the series production. For about 90 % the geometrical and magnetic axes do not differ more than ± 0.15 mm. Similar results were obtained for the respective pitch and yaw angles values and for their distribution along the production sequence (see Fig. 5).

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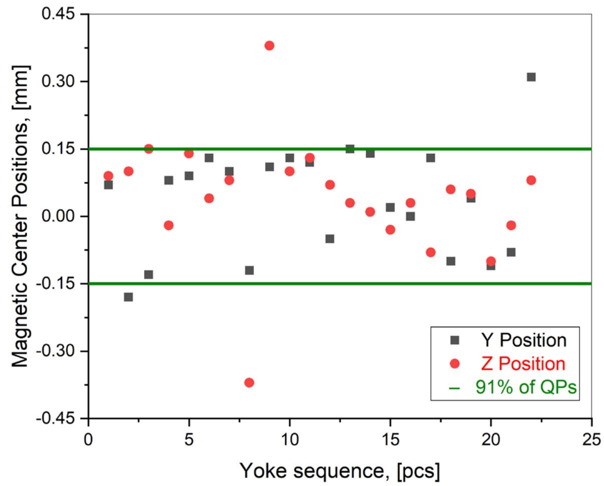

Figure 4: Positions of the magnetic axes with respect to the geometrical center of the quadrupoles for the first produces QPUs.

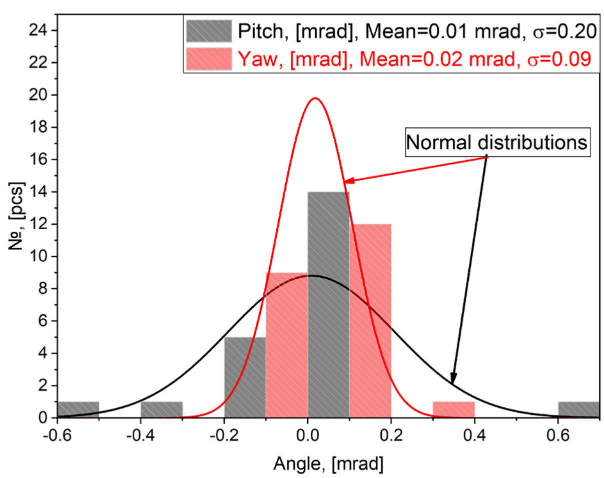

Figure 5: Distribution of the magnetic axes (pitch and yaw) for the statistics of the first 22 Quadrupoles.

The magnetic field quality of the magnets was measured by rotating coil assemblies both at ambient and at helium temperatures. Following the cooling down of the units during about 70…80 hours the preliminary magnet training had shown, that on average the magnets reach their operation current after 2…3 quenches. Their heat release during the various AC-operation modes was also reproducible within ± 10 %. The typical current dependence of integral transfer functions (ITF) of the quadrupoles and their respective statistical distribution are shown in Fig. 6. Similar good results were obtained for the ITFs of the steerers and sextupoles showing a data spread along the production sequence within ± 0.6 % and ± 0.2 % respectively. The relative variation of the magnetic length of the quadrupoles over series production is about $1{\cdot}10^{-3}$. The quadrupole series statistics for the measured multipoles is summarized in Fig. 7. It was found that b6 is the only significant multipole and reproduces for all the measured quadrupoles within ± 1 unit.

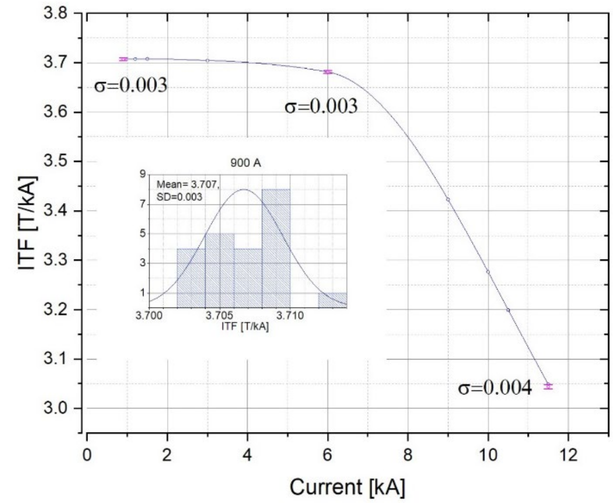

Figure 6: Current dependence of Integral transfer functions of the quadrupoles. The inset graph gives der distribution for 22 series magnets at 900 A.

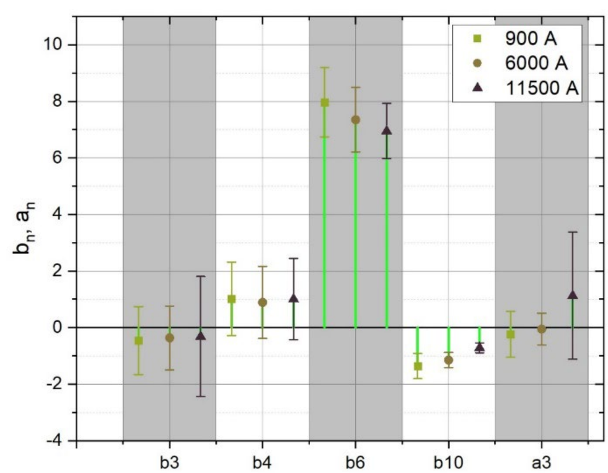

Figure 7: Integral multipoles of 22 quadrupole magnets and their variation within the series sequence.

CONCLUSION

The series production of the superconducting quadrupole and corrector units for the SIS100 of FAIR was started successful at the JINR, Dubna. Twenty quadrupole units were already assembled, tested up to 20 % above operation parameters and delivered to Darmstadt. The next eight units are under preparation for shipment in October 2021. The first unit series 2.5 was completed in March this year, the second series 1.7B will also be finished this year. JINR had established an effective and stable production and testing scenario for the Quadrupole units. The optimization of the production technology and detailed methodological adjustment of the measurement techniques resulted in the proven and continuously high quality of the series magnets.

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