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SUPERCONDUCTING DIPOLE MAGNETS FOR THE SIS100 SYNCHROTRON

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Abstract

The Facility for Antiproton and Ion Research (FAIR) is currently under construction at GSI Darmstadt, Germany. For its main accelerator, the SIS100 synchrotron, 110 superconducting dipole magnets have been produced and extensively tested. The fast-ramped Nuclotron-type superferric dipoles were manufactured with high effort regarding a precise magnetic field which could be proven by magnetic field measurements with high accuracy. Stable operation conditions at 4.5 K were achieved including an excellent quench behaviour and precise geometrical and electrical properties. An overview on design, production, operation, tests and measurement results is given.

INTRODUCTION

The FAIR project [1] is an international accelerator facility and one of the largest research complexes worldwide. Its scientific goals aim to a broad physics spectrum and gain among others new insights into the structure of matter and the evolution of the universe. The main accelerator for FAIR is the SIS100 [2] (from the german word "Schwerionensynchrotron"), a heavy ion synchrotron with a designed rigidity of $B\rho = 100\,\mathrm{Tm}$. With a circumference of approximately 1.1 km it will create particle beams of unique intensity and quality, including ions from all natural elements in the periodic table as well as antiprotons. The SIS100 design contains more than 400 superconducting magnets, among these are 108 main dipole magnets [3]. The production, delivery and test of in total 110 dipole magnets (including 2 additional spares) was successfully completed in early 2021, which is a major milestone for the SIS100 project and is described in this paper and the accompanying poster [4].

PRODUCTION

The SIS100 main dipoles (see Fig. 1) are iron dominated superconducting (superferric) magnets with a nominal magnetic field of 1.9 T with an applied current of 13.2 kA. The magnetic field generating coil is made of a Nuclotron-type cable [5] with its superconducting strands out of niob-titanium (NbTi). The cooling is provided by forced flow of two-phase helium with a temperature of 4.5 K. The magnets are fast ramped with cycle frequencies of 1 Hz and ramp rates of 4 T/s (corresponding to current ramp rates of 28 kA/s). The iron yoke with a length of 3.002 m is bended with 3.33° and a total curvature radius of 52.632 m. From beam dynamics a field homogeneity of $\Delta B/B \leq 6 \times 10^{-4}$ is required inside an elliptical cross section of 115 mm × 60 mm, as well as a sufficient suppression of higher order multipole field components [6].

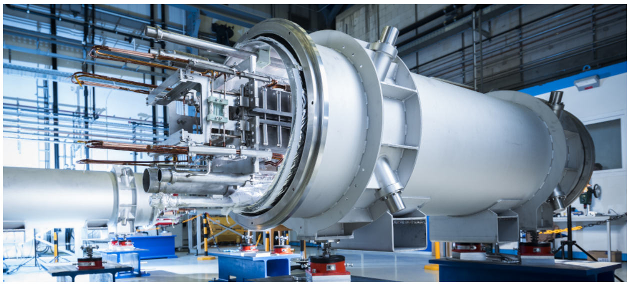

Figure 1: One of 110 dipole magnets for the SIS100 accelerator of FAIR.

After the final design was defined in 2010 the contract with the manufacturing company Bilfinger Noell GmbH (BNG, Würzburg, Germany) was fixed in 2012. In 2013 a pre-series dipole magnet was delivered to GSI. In the following years certain steps of the mechanical design and the production of the yoke were revised to improve the magnets performance, mainly regarding the magnetic field properties. The process of fabrication of the iron lamination was changed to a precise stamping. The permeability μ_r of each charge of the used iron was measured and the lamination was sorted to equalize the magnetic properties of all yokes as good as possible. The distortion of the magnetic end fields at both sides of the yoke was optimized by a so-called Rogowski profile which was designed by simulations regarding a suppression of undesirable multipole terms [7]. The outer shell welding was established with a laser technique which is lowering the heat input and the tension on the yoke.

The series production started in 2016 yielding to the delivery of the first series dipole magnets end of 2017. At the same time the extensive test programm in the Serial Test Facility (STF) [8] at GSI Darmstadt started. The full rate of production, delivery and test of one magnet per week was reached in 2018 and could be continued only with minor interruptions until mid of 2020. Finally, the two special dipole magnets for the ring positions at beam-injection and -extraction were manufactured and delivered end of 2020. After they passed the test program the complete series of 110 dipoles was successfully finished in spring 2021.

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TESTING

Overview

The STF at GSI provides four test benches for parallel operations including a strong cryoplant for helium-cooling and high precision power supplies for high currents and fast ramping. With the help of the quench detection system the magnets were protected from damage in case of a quench. The extensive testing program for each dipole magnet included a verification of a large number of parameters which are crucial for precision, functionality and operational stability. The yoke dimensions and the positions of the cold mass and the helium lines with respect to the cryostat were determined. The leak tightness of the process lines and the cryostat with its instrumentation flange was verified. The functionalities of installed instrumentation such as temperature sensors, cryo-heaters and voltage taps were checked under full operational conditions when electrical parameters like insulation integrity, quench performance, inductance, static heat load and AC losses were monitored and the magnetic field was measured. Some of these subjects will be further illuminated in the following sections.

Quench Training and Behaviour

Each magnet was subjected to a quench training process in order to mechanically stabilize the superconducting coil. In all cases the nominal current of $I = 13.2$ kA was reached at least during the second cycle. After that no significant degradation concerning the quenching current was observed, neither at subsequent quench cycles, nor during additional thermal cycles. In Fig. 2 the training curves for all magnets are shown. After four to six quenches most of the magnets did not quench up to 16.9 kA which is the safety limit of the used power converter.

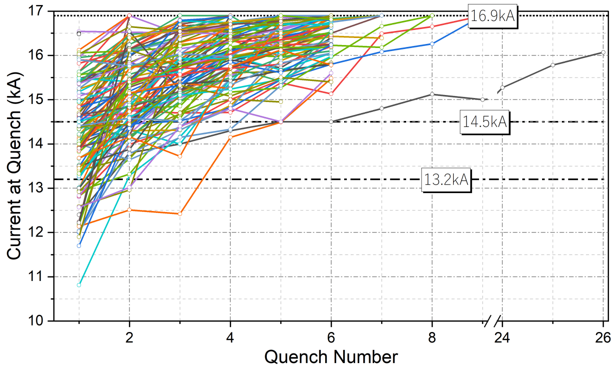

Figure 2: Quench training curves of all dipole magnets.

Yoke Geometry

For iron dominated magnets the magnetic field quality strongly depends on geometrical properties of the yoke. The magnetic field strength B of the dipoles depends on the aperture height h as

$$B \approx \frac{IN\mu_0}{h} \qquad \text{(approximation for } \mu_r \gg 1\text{)},$$

where I is the applied current, μ_0 the magnetic constant and N the number of windings of the coil. Therefore the production was accompanied by regular quality checks of the main yoke parameters. A carrier with capacitive sensors was moved inside the aperture along the complete magnet's length and measured height deviations Δh inside the aperture with a resolution of a few micrometer. It could be proved that the specification of $\Delta h \leq 100$ m was fulfilled in all magnets apart from a few small and narrow-located outliers which can be neglected. Mounted reflectors on the carrier enabled the observation of the path of the carrier through the yoke with a laser tracker with the goal to determine a possible sag or torsion of the yoke.

Magnetic Field Measurements

The magnetic field measurements with rotating coils were realized under full operational conditions inside the magnets yokes at a temperature of 4.5 K. It was a remarkable development by engineers at GSI and CERN to realize this system to be functional close to absolute zero. A 3.4 m long shaft consists of 5 segments built out of glass-fibre carriers for the coil windings. Special ceramic bearings enable a smooth rotation even at cold. The motor unit was placed outside of the cryostat connected via a feedthrough where also the signal cables were included. The signals were recorded by voltage integrators and were analyzed by fourier analysis, leading to a magnetic field parametrization in multipole expansion

$$\mathbf{B}(\mathbf{z}) = B_y + iB_x = \sum_{n=1}^{\infty} \mathbf{C}_n \left(\frac{\mathbf{z}}{R_{\mathrm{Ref}}}\right)^{n-1},$$

where the reference radius $R_{\mathrm{Ref}} = 30$ mm is given by the radius of the rotating coils. A dedicated compensation scheme based on a combination of two different rotating coils allows to disentangle both the strength and orientation of the main dipole field as well as the multipole parts of the signal spectrum which are suppressed by a factor 10^4 and more with respect to the main field. The absolute field strength was carefully cross calibrated with a stretched wire system and a NMR probe applied to a warm-operating calibration magnet. Figure 3 shows the distribution of integrated magnetic dipole fields $B_1L = \int_L B_1(l)\,dl$ as measured with rotating coils for all 110 dipole magnets. The relative variance of the sample is only $\sigma/\mu = 2.8 \times 10^{-4}$ which is a factor 10 better then specified. This outstanding result proves a high qualitiy and reproducibility of the whole manufacturing process and the precision and stability of the measurement system. In Fig. 4 the transfer function is shown with measurements at several applied currents between 1 kA and 13.5 kA. One observes a linear behaviour in the range of 1.5 – 10 kA, disturbed by hysteresis and saturation effects at lower and higher currents, respectively.

Figure 5 shows the measured multipole spectra for two different applied currents which agree very well to the expectation from simulation. The quadrupole term b_2 is created at the ends of the yoke where the measurement coil enters with an angle due to the bending of the dipole. Sextupole

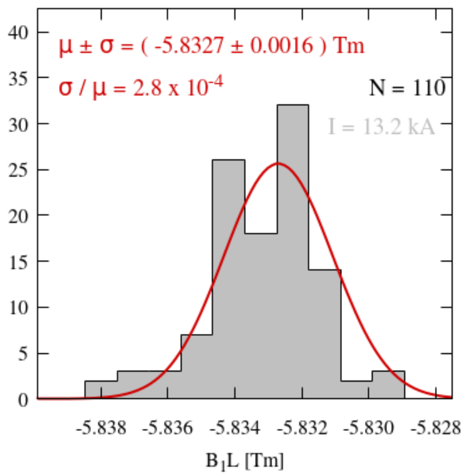

Figure 3: Distribution of the measured magnetic length at a current of $I = 13.2$ kA of 110 dipole magnets.

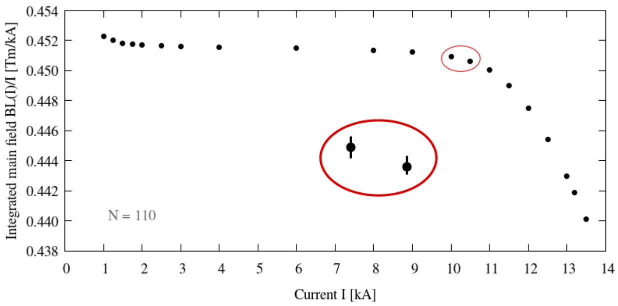

Figure 4: Current dependency of the integrated magnetic field (transfer function). The statistical errorbars are too small for visualization (compare Fig. 3 for quantification).

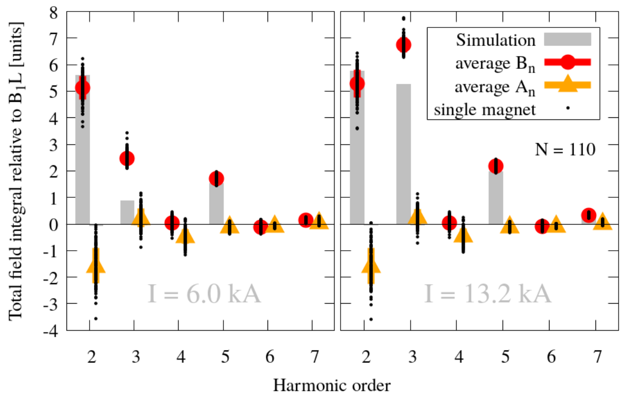

Figure 5: The multipole spectra are shown as measured for each single dipole (black dots), averaged over all dipoles (red and orange) and as expected by simulations (grey bars).

b_3 and decapole b_5 are allowed harmonics underlying the same symmetry as the main field. However, the presence of small skew quadrupoles (a_2) weren't foreseen. Since a_2 never exceeds a few units it is uncritical regarding beam dynamical restrictions because uncertainties in the alignment of quadrupole magnets will create much bigger values of a_2. Nevertheless, it could be shown by simulations with Roxie2D that a horizontal shift of the magnetic coil compared to the yoke would cause an a_2 component, and in addition the latter should be linearly correlated with an a_4 term. In fact the measured data perfectly confirm this prediction even quantitatively which is shown in Fig. 6. The amount of the coil's shift could be estimated to be between 0 and 100 μm, depending on the magnet.

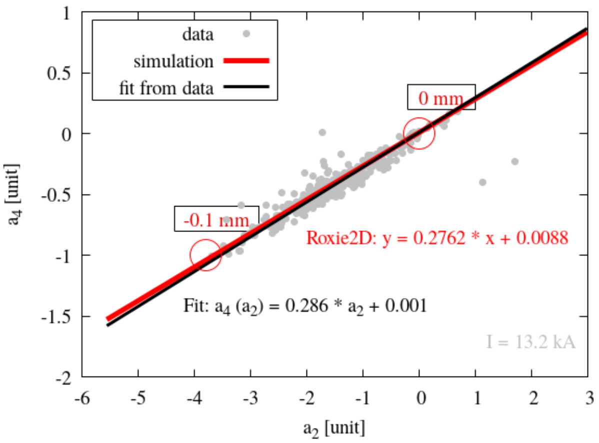

Figure 6: Correlation of a_2 with a_4. The prediction from simulation is perfectly confirmed.

SUMMARY

The production, delivery and testing of all SIS100 dipole magnets was successfully completed in spring 2021. The final step towards the readiness for an installation in the accelerator tunnel is the beam chamber integration which is currently ongoing at GSI and will be presumably finished by the end of 2021.

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