The optimised sc dipole of SIS100 for series production

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Abstract. At the international facility for antiproton and ion research (FAIR) in Darmstadt, Germany, an accelerator complex is developed for fundamental research in various fields of modern physics. In the SIS100 heavy-ion synchrotron, the main accelerator of FAIR, superconducting dipoles are used to bend the particle beam. The fast ramped dipoles are 3 m long super-ferric curved magnets operated at 4.5 K. The demands on field homogeneity required for sufficient beam stability are given by $\Delta B/B \leq \pm 6 \cdot 10^{-4}$. An intense measurement program of the First of Series (FoS) dipole showed excellent quench behavior and lower than expected AC losses yielding the main load on the SIS100 cryoplant. The FoS is capable to provide a field strength of 1.9 T. However, with sophisticated measurement systems slight distortions of the dipole field were detected. Those effects were tracked down to mechanical inaccuracies of the yoke proven by appropriate geometrical measurements and simulations. After a survey on alternative fabrication techniques a magnet with a new yoke was built with substantial changes to improve the mechanical accuracy. Its characteristics concerning cryogenic losses, cold geometry and the resulting magnetic-field quality are presented and an outlook on the series production of superconducting dipoles for SIS100 is given.

1. Introduction
SIS100, the core machine of the FAIR project, is now in the procurement phase. The first objects to be procured are the main dipoles. These dipole magnets are following a superferric magnet design pioneered for the Nuclotron [1, 2, 3]: these magnets are iron dominated but with a superconducting coil. The coil is based on the Nuclotron cable, which is a hollow tube with superconducting wires wrapped around it. This tube is cooled by a forced two phase helium flow which provides large continuous cooling capacity [4, 5]. The fast ramped Nuclotron magnets were the basis for the SIS100 dipole magnets. A common R&D program of JINR and GSI then led to significant AC losses reduction and field quality improvements [6, 7, 8]. Based on these achievements different model magnets were manufactured and tested [9, 10, 11, 12]. These tests, however, showed that the cooling capacity of the magnet had to be increased [13] by reducing the cooling tube length. This was achieved by reducing the number of coil turns, increasing the current of the cable and widening the cable diameter. Further the magnet design was changed from a straight to a curved magnet, which allows reducing the width of the magnet gap and thus its losses.
Based on all this R&D the series of SIS100 dipole magnets was ordered to Babcock Noell GmbH in 2012. The First of Series magnet thus demonstrated the first time:

- the new high current cable
- a single layer coil of only 8 turns
- and curved yoke with a reduced apperture of 125 mm × 68 mm.

2. SIS100 Dipole Development

The SIS100 dipole magnet was delivered and tested [14, 15, 16]. In generally the magnet showed good performance, but soon tests showed that modifications were required to obtain the required field quality. First we present the electrical performance and then show the slight deficiencies of the mechanism. We describe the developed tooling next to the improvements made to the manufacturing process and the identified field performance.

2.1. Electrical Performance

During the first test campaign the magnet was subjected to an intensive power test. During the first ramp up the first quench occurred slightly below nominal current (see Figure 1). All following quenches only occurred at higher current levels. Thermal cycles only showed limited detraining, which was well below acceptable limits; thus no impact on machine performance is expected. After the yoke had been replaced and the magnet was tested again, a first quench only occurred above nominal current; the power training reached then even larger currents as at the previous training. At the largest values the training was stopped as further measurements were more urgent to be executed. The last currents (see Figure 2) were already at 90% of the short

![Figure 1. SIS100 magnet quench performance as obtained during the first test campaigns (“first yoke”) and after the yoke was refurbished (same coil) (“second yoke”).](image-url)
Figure 2. Short sample limit of the FoS dipole and limit of the superconducting wire sample limit. Further tests will be executed later to test the total power limit of the magnet.

As this magnet is a synchrotron magnet and ramped with 4 T/s from 0 to 1.9 T with a repetition rate of 1 Hz, the AC losses of this magnet are of primer importance. Similar as for the first yoke [17] the losses are well within control. The dissipated power can be well described by

\[ P = q_h (B_{\text{max}}) f + q_e (B_{\text{max}})^2 f^2, \quad f = 1/\tau_\lambda \]

with \( \tau_\lambda \) the time required to complete a triangular cycle starting at \( B = 0 \) to \( B = B_{\text{max}} \) and then back to \( B = 0 \). The coefficients are then given by

\[ q_h = h B_{\text{max}}^2, \quad q_e = e B_{\text{max}}^{2.5}. \]

\( q_h \) was derived from the measurements to \( q_h = 4.2 \pm 0.5 \) J and \( q_e = 6.0 \pm 0.2 \) Js. This model allows predicting the AC losses for any cycle with sufficient accuracy. Assuming that the losses proportional to \( f \) are mainly caused by hysteresis effects and losses proportional to \( f^2 \) are mainly caused by eddy current effects, one would expect that eddy current losses [18, 19] only occur as soon as the iron starts to saturate at the ends and thus significant losses occur in the magnet end. The measurement results on the FoS dipole magnet did not support these assumptions nor the measurement results obtained on the model dipole [18]. The first yoke was manufactured from silicon steel M600-100 delivered by Thyssen while the second yoke was manufactured from silicon steel M600-100 delivered by CDW. The measured losses do not show significant difference between these two materials.

2.2 Tooling development
Along to all these measurements magnetic measurements were conducted which indicated that the magnetic field did not yet achieve the desired performance. Thus the gap geometry was precisely remeasured using two tools:

(i) one based on 3 tactile mechanical sensors, which were used to measure the gap height or width at three different positions,
(ii) and one based on capacitor sensors, which measured the gap height at three different positions at the top and bottom of the sensor box. This capacitor instrument was used for measurements at room and cryogenic temperature.

Further a laser tracker system was used for measuring the geometry of the magnet gap. The design of the tactile system is presented in Figure 4 and the system based on the capacitor sensors in Figure 5. The measurements with the different systems gave results which were matching each other with sufficient accuracy and thus confidence in the reliability of the different systems was obtained. The gap height was measured at different yoke temperatures using the capacitor sensor system (see Figure 6). One can see that the gap variation slightly decreases as the magnet yoke is cooled down to cryogenic temperatures. Similarly gap variations between the magnet sides were measured, which showed that the field quality will be less then required for operating the SIS100 machine.

2.3. Measurement results for the improved magnet yoke

The measurements executed above indicated that the magnetic field could benefit significantly if the manufacturing of the yoke was revised. So together with the manufacturer the welding procedures were reviewed and dedicated tests executed. These tests allowed deducing a manufacturing process which reduced the forces introduced by the welding seems within the

![Figure 3. Expected AC losses for the SIS100 dipole magnet](image-url)
Based on these tests a second yoke was built. Using the original FoS components including the magnet coil, the magnet was assembled together and retested. The tools were used again to measure the magnet’s geometry. For the original yoke (see Figure 7) the gap height varied for a significant portion above 0.1 mm, while for the improved yoke the variation was reduced for the largest part of the magnet to below 0.05 mm; only two small sections with a slight variation were observed. This parameter affects mainly the average magnet strength. So for the machine its of highest importance that its average value varies little over the whole series production.

Similarly the gap tilt was measured (see Figure 8). Here one can see again that the original yoke had a variation of above 0.05 mm for a significant portion of the yoke while for the new yoke the variation is well controlled to below ± 0.02 mm. Only a small outlier was found.

These measurements showed that the magnet manufacturing process has significantly improved the mechanical quality of the yoke all across its length. This asserts that the manufacturer has now a tight and sincere control on the yoke manufacturing process matching the results already obtained in the coil production and thus the magnet power performance.

3. Conclusion
The SIS100 dipole magnet is being procured with the first magnet already delivered. It has been tested thoroughly. The power performance surpassed the specification and the AC losses were significantly smaller than expected. The mechanical properties of the magnet yoke, originally delivered, did not quite match the desired characteristics.

Tools for investigating the gap geometry were developed within a short time scale and
implemented. These tools showed that the geometry could be improved. Appropriate yoke assembly procedures were developed and a new yoke built. This yoke was integrated into the magnet and this magnet was tested again.

The test results of the improved magnet yoke showed that the originally obtained parameters were matched or even further improved (quench performance, AC losses). The variation of the magnet gap is now much smaller. This shows that the magnet production processes are well under control and thus a basis for the release of series production.

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Figure 6. The gap height variation as measured for the first yoke at different temperatures.
Figure 7. Gap height variation for the original and the improved FoS magnet.

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