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SUPERCONDUCTING DIPOLES FOR SIS100

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Abstract

The international facility for antiproton and ion research (FAIR) is currently being developed in Darmstadt, Germany, for fundamental research in various fields of modern physics. Its main accelerator, the SIS100 heavy ion synchrotron, utilizes fast-cycling superconducting magnets operated at cryogenic temperatures. An intense measurement program of first of series (FoS) module revealed excellent behaviour with respect to, e.g., quench performance and AC losses. With an optimized fabrication technique, the geometrical accuracy was improved to be sufficient to provide a highly homogeneous field. Consequently, the series production of 110 dipoles was released. First significant results on the reproducibility and the variation of physical properties along the series production gained at the test facility of GSI are presented.

INTRODUCTION

The FAIR facility is currently under construction at the campus of GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt, Germany [1]. It will enable a broad variety of experiments, e.g., in atomic, nuclear, baryonic matter and antiproton physics. From existing pre-accelerators, heavy-ion beams are injected into the main synchrotron SIS100 to supply high energy and, in particular, high intensity beams [2]. Basic design requirements of SIS100 are fast cycling, and ultra-high vacuum to limit beam loss. As a consequence, fast-cycling superconducting magnets were chosen for beam optics with the benefit of low energy consumption in operation and low installation space.

PRODUCTION OF SIS100 DIPOLES

According to the requirements of SIS100, the fast ramped Nuclotron magnets [3, 4] developed at joint institute for nuclear research (JINR), Dubna, Russia, served as the archetype for the development of the SIS100 dipoles. Those magnets employ superconducting coils for the field generation and a window-frame iron yoke for the field shaping. The cables are made of strands with NbTi filaments wrapped around copper-nickel tubes to conduct the forced flow of two-phase helium. By such design, a high and continuous cooling capacity is realized.

Basic Design and FoS

In order to account for the total AC losses and field requirements a common R&D program of JINR and GSI was conducted. Major changes of the FoS dipole for SIS100 [5–7] are the reduction of the cooling tube length to increase the

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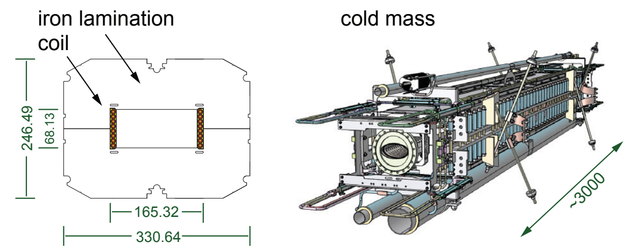

Figure 1: Cross section of the dipole iron yoke (left). CAD model of the cold mass with yoke, coil and busbars, cooling tubes, and beam vacuum chamber (right). Dimensions are given in mm.

cooling efficiency. Therefore, the coil design was changed from two layers to single layer which was enabled by a novel high current NbTi cable. Moreover, the yoke was designed in a curved shape along the particle path to reduce the aperture width and limit the cryogenic losses. In the final design the FoS employs a yoke of 3 m length with an aperture of 68.13 mm × 165.32 mm at room temperature, see Fig. 1. The field strength reaches 1.9 T at the nominal current of 13.2 kA.

The FoS showed excellent quench behaviour, and cryogenic AC losses better than expected which basically proves the suitability of the chosen concept [5]. However, due to an initially insufficient production process, the field quality did not reach the level required for accelerator operation [8]. A comprehensive survey on alternative design options and production strategy guided by theoretical investigations of consequences of manufacturing errors [9] resulted in a new production technique for the yoke. The main changes to the original process are:

- The lamination is stamped to the final geometry without further processing to a guarantee high precision of the yoke's cross section.
- Application of automated laser-welding in order to limit the distortion of the yokes.
- Removal of a gap between the yoke halves at the back-legs at 300 K. For this, the coil is clamped within its elastic range and the vertical assembly of the yoke halves is controlled precisely.

The new yoke was subject to an intensive measurement campaign in which the yoke's geometry and, thus, the magnetic-field quality was revealed to be substantially improved [8, 10]. Besides the main changes of production mentioned above more than 100 measures were defined to improve design details, the production process, and quality control. With this, the series production of 110 dipoles was released in 08/2016. In Sept. 2017 the first dipole of the series production was delivered to GSI and the further de-

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livery will be conducted with a rate of approximately one dipole module per week.

Manufacturing of the Series Magnets

Of most concern in series production is the variation of the total magnetic field integral $BL = \int B(l)\mathrm{d}l$, where for beam physics reasons the variation among the dipoles is required to be $\sigma_{BL}/BL < 4 \times 10^{-3}$. The main sources of deviation are controlled in the following way:

The yoke lengths of the individual magnets have to match in the order of mm to each other which is easy to meet. The packing factor has to be above 98 % which is safely reached by stacking and pressing in a standard way. With regard to the aperture height variation, the manufacturer is obliged to fulfill −0, +100 µm in the aperture-height of each magnet to be on the safe side. For the whole production a single melt of iron is used to minimize the variation of material properties. Samples were taken, the coercive force H_c and the BH curves were measured and μ_r was calculated as a function of the excitation. For the magnets driven at the injection level with low field and moderate μ_r across their lamination a dedicated sorting strategy was chosen to minimize the variation of H_c along the series production. At the same time a variation of 25 % in μ_r is tolerable at those low fields which is fulfilled by the sorting, too. For moderate fields with maximum μ_r across the lamination and for extraction fields, where μ_r drops down due to saturation, the variation between the samples is small enough even without sorting.

TESTING OF SIS100 DIPOLES

For the testing of the dipoles an extensive program was defined to ensure functionality, to reveal operation parameters, and to ensure safe operation. A comprehensive overview of the testing program and capability is given in [11].

FAT and SAT

The testing is substantially divided into the factory acceptance test (FAT) performed by the manufacturer and the site acceptance test (SAT) at GSI. For FAT, the testing is performed at room temperature only to identify sources of performance loss in the manufacturing process as early as possible. For instance, the yoke geometry is controlled to high precision at the stamping of the lamination, after welding of the yoke halves and, finally, after the assembly of the yoke.

For SAT, the modules are cooled down to check the cryogenic operation for the first time. In total about 30 parameters are checked by the testing team. They range from highly precise geometrical checks, electrical integrity tests, leak testing, to checking of the quench performance, the cryogenic losses and, most important, the magnetic-field characteristics.

Results

The following section is focused on the most prominent data derived in the course of FAT and SAT of the first magnets of series production. Special attention is paid to reproducibility of the parameters critical for synchrotron operation.

Quench Performance: In order to guarantee stable operation, each superconducting magnet is subjected to a training campaign. The following criteria are applied: The nominal current of 13.2 kA has to be reached at latest at the 3rd quench in the first thermal cycle. In the next cycles the nominal current has to be reached at the first quench. Moreover, de-training should be limited to less than 5 % of the nominal current compared to the previous quench and the quench current should stabilize at least at 108 % of the nominal current.

Figure 2 shows the training curves of the first seven dipoles. All tested magnets reached the nominal current at the second quench at least and the quenching current stabilised at 14.7 kA or higher. No significant de-training was observed, which proves a high mechanical stability of the coil structure assembled into the cold mass. The series magnets were trained to 16.90 kA (limit of power converter) which is close to the short sample limit of 17.8 kA [8].

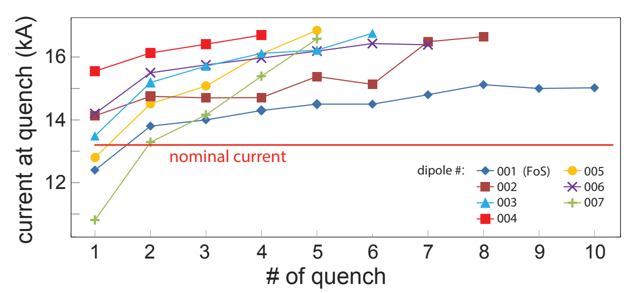

Figure 2: Quench training data for the first seven dipoles within the first thermal cycle.

Yoke Geometry: As of highest importance for the field quality of an iron dominated magnet, the geometry of the aperture of the SIS100 dipoles is carefully checked during and after production (FAT and SAT). This is of special significance due to the small aperture and the disadvantageous ratio between yoke cross section and length. In Fig. 3 the aperture height of dipole #002 is tracked precisely by a sophisticated measurement tool [8]. The result is very well within the specified tolerances.

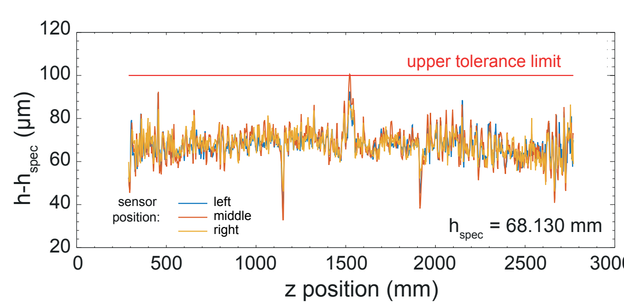

Figure 3: Aperture height along the dipoles axis for #002.

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The survey of the aperture height variation along the series production in Fig. 4 shows that an precision of 100 µm is kept safely for all dipoles produced. Moreover, the inclination of the pole surfaces measured by the difference of the aperture height on the right and left side of the aperture is well below 20 µm which limits higher order contributions in the field spectrum. Similar, the lateral shift of the yoke halves to each other is controlled to be below ±400 µm by utilizing an advanced assembly technique of the manufacturer. In order not to limit the dynamic aperture of the beam, the sag of the yoke is required to be below 0.4 mm which was proven by 3D laser tracker measurements. The same applies to the deviation of the magnet's axis from the ideal radius of SIS100.

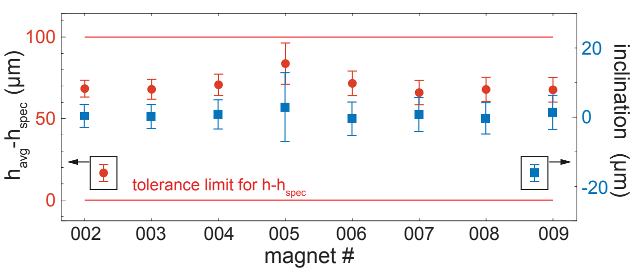

Figure 4: Avg. aperture height and inclination of the pole surfaces (hight difference from left to right side).

Magnetic-field Quality: At the center of interest, the magnetic-field characteristics is carefully checked and completed for the first five magnets up to now. For this, a dedicated measurement system of rotating coils was developed by an collaboration with CERN for the measurement at cryogenic conditions in the aperture [11]. The transfer functions of the first magnets are shown in Fig. 5 revealing an outstanding reproducibility. The variation of the magnetic integral σ_{BL}/BL is below 3×10^{-4} for all currents which meets the requested limits for synchrotron operation an order of magnitude better than required. From the spectral

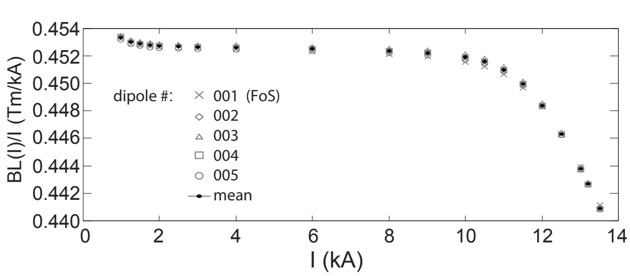

Figure 5: Total magnetic field integral as a function of the excitation current.

point of view, the field harmonics $C_n = B_n + iA_n$ defined by $B(z = x+iy) = \sum_{n=1} C_n \left[(x+iy)/R_{\mathrm{ref}}\right]^{n-1}$ can be extracted directly from the measurement signals with $R_{\mathrm{ref}} = 30$ mm as the radius of the rotating coils. In Fig. 6, the harmonics are given in units defined by the scaled normalization $10^{-4}/C_1$. The higher-harmonic field content at the center of the magnet is very low and within its range of precision of 0.2 units it agrees well with the dedicated simulation. Slight deviation from expectation is only present for the sextupole component, where the origin is currently under investigation. Within the total integral along the magnet the spectrum is dominated by the normal quadrupole resulting from the end field of the magnet design. Generally, the field quality was proven to be close to the design values and its high reproducibility results from a well controlled production process. The suitability of the final results for accelerator operation is discussed in [12].

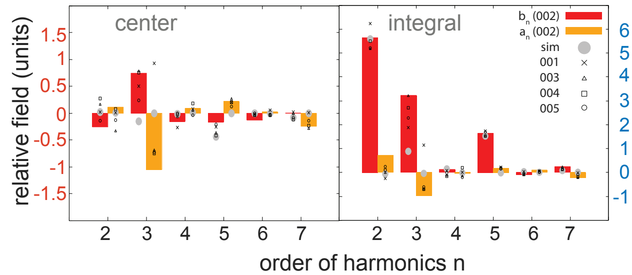

Figure 6: Magnetic-field harmonics for the magnet center (left) and for the total (right) at 6 kA.

CONCLUSION

Based on the results of an intense measurement campaign on the first of series fast-cycled superconducting dipole, an optimized production process accompanied by a tight program for quality assurance was established for the SIS100 dipoles. In Summer 2016, the series production was started and the first series dipole was delivered to GSI in Sept. 2017. The delivery rate is approximately one module per week. Each dipole is subjected to a comprehensive study of functional and operational parameters at the manufacturers site and at GSI. Safety of operation is assured by dedicated verification measures. So far, the measurement results reveal an excellent performance of the chosen design and a high quality of production. An outstanding quench performance was found by training close to the short sample limit of the cable verifying a high stability of the coil structure in the yoke. As the defining element of the magnetic-field quality, the geometrical properties of the aperture geometry are tracked down to the sub-mm level as a matter of routine for all series magnets. The specified values of the main parameters are safely kept with very good reproducibility. As a consequence, the magnetic field shows very low variation in terms of the field integral and the low harmonic content is satisfactory for the beam physics requirements in the synchrotron. With the presented performance of the series dipoles a successful operation of SIS100 will be enabled.

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