MAGNETIC FIELD CHARACTERISATION OF THE FIRST SERIES DIPOLE MAGNET FOR THE SIS100 ACCELERATOR OF FAIR

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Abstract

The first magnet out of the series of SIS100 dipoles was intensively tested at the test facilities at GSI. The measurements include mechanical alignment accuracy, geometrical surveys, electrical stability and determination of the magnetic field behaviour along the magnets dimensions under various conditions. The presented results in this article focuse on the magentic field characterisation.

INTRODUCTION

The Facility for Antiproton and Ion Research (FAIR) is currently under construction at GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt, Germany. For its main accelerator, the heavy ion synchrotron SIS100 [1], fast ramped superconducting dipole magnets [2] following a Nuclotron design will be manufactured by industry and has to be tested in terms of accuracy and functionality to guarantee the desired performance before their final assembly in the accelerator tunnel. The SIS00 synchrotron magnets will consist of 108 dipoles, 168 quadrupoles and various corrector magnets.

The GSI test facility [3] with their cryogenic infrastructure [4] provide the possibility to test the magnets at warm (300 K) and cold temperatures (4.5 K). Together with a quench protection system, a high current power converter supply currents up to 20 kA during superconducting conditions. These are allowing intense electrical tests like leakage, AC losses or quench behaviour as well as the exploration of the magnetic field behaviour.

THE SIS100 DIPOLE MAGNETS

The SIS100 main dipoles are iron dominated superconducting (superferric) magnets with a forced-flow two phase helium cooling provided by Nuclotron-type cables [5]. The magnets are fast ramped with rates of 4 T/s and cycle frequencies of 1 Hz. The nominal magnetic field is 1.9 T with an applied current of 13.2 kA. 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 supression of higher order multipole field components [6]. The desired geometrical precision concerning yoke gap height variations is $\Delta h = \pm 0.1$ mm. The first magnet of this series was delivered to GSI in June 2013. It was tested from December 2013 to the end of 2014 and then again in October 2015 after the iron yoke was replaced (the two versions are called here FoS1 and FoS2, respectively).

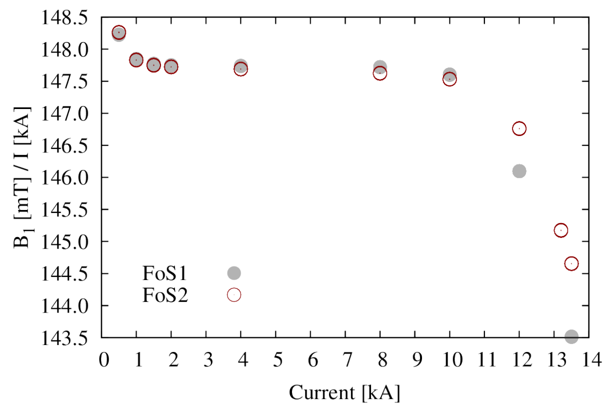

Figure 1: Current dependence of the transfer function.

ROTATING COIL MEASUREMENTS

The rotating coil system [7] consists of a cylindrical carrier for several radial coils with different central radii with a length of 600 mm. A coil with $r = 14.53$ mm was used to measure the absolute magnetic field. A second channel of the data acquisition records a combined signal of the same coil together with a central coil to compensate the dipole contribution in order to realize an improved precision for higher harmonics.

The signals are caused by the time derivative of the magnetic flux going through the coils. The resulting induced

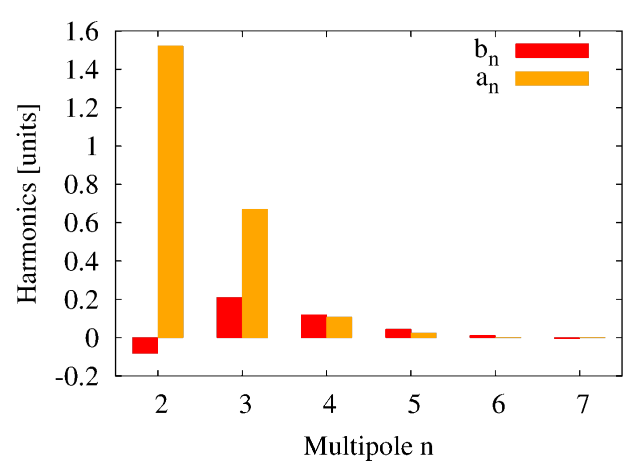

Figure 2: Multipole spectrum at the longitudinal center of FoS2 at $I = 8$ kA.

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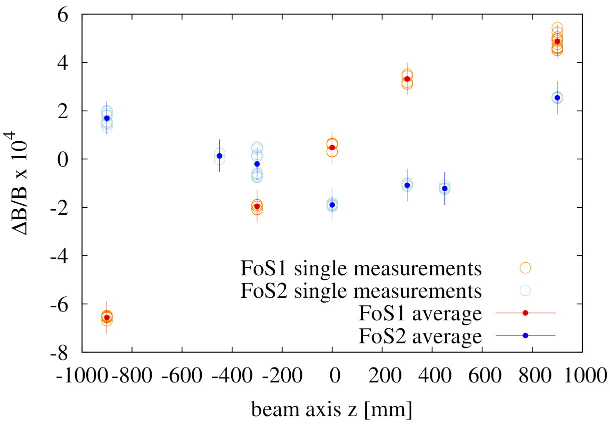

Figure 3: Relative magnetic field deviations at I = 8 kA, for FoS1 and Fos2. The z-values are referring to the center of the rotating coil.

voltage is recorded by a voltage integrator and is Fourier transformed to calculate the harmonic field coefficients $\mathbf{C}_n = B_n + iA_n$. Using this multipole expansion one can write the magnetic field as

$$\mathbf{B}(x+iy) = B_y + iB_x = \sum_{n=1}^{\infty} \mathbf{C}_n \left(\frac{x+iy}{R_{\text{ref}}}\right)^{n-1}$$

where $x + iy$ is the complex representation of a 2D-plane orthogonal to the beam axis. The value of the reference radius is chosen to $R_{\text{Ref}} = 17$ mm given by the dimensions of the measurement coil.

Several measurements were done with different currents ranging from 0.5 kA up to 13.5 kA. The current dependence of the transfer function B/I is shown in Fig. 1, confirming a linear behaviour (apart from expected influences of hysteresis and saturation effects at lower and higher currents, respectively). A typical multipole spectrum is shown in Fig. 2.

To explore the magnetic field along the whole length of the magnet, the rotating coil was installed at different longitudinal positions, varying from the magnets center (beam axis $z = 0$) to both ends of the magnets ($z = \pm 1500$ mm). The results of the measurements for the inner part are shown in Fig. 3. To determine relative deviations, the single results have to be compared to a reference value B_0. The latter can be defined essentially arbitrarily and is chosen to be the mean value of all inner measurements to realize an easier comparison of the results (this is also important for Fig. 6).

At each z-position, the measurements were repeated a few times to observe statistical variances. Moreover, the measurement at $z = -300$ mm was done twice. These both data sets can be regarded as almost independent since in between the complete measurement system was dis- and remounted. The difference is used to estimate the systematic uncertainty, which is combined with statistical fluctuations to determine the error bars.

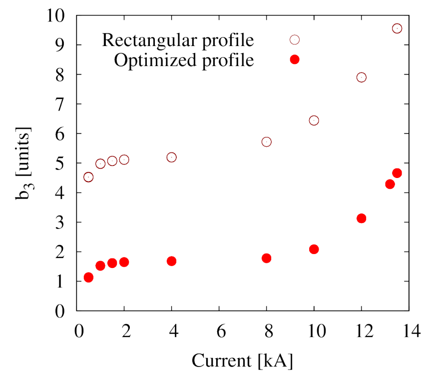

Figure 4: Comparison of sextupole b_3 contributions between two different endblock designs.

TEST OF ENDBLOCK DESIGNS

At both ends of the magnet yoke, the magnetic field is distorted by edge effects resulting in an increase of undesirable higher multipole contributions. To supress them to a tolerable level, an optimized endblock shape was designed by simulations [8]. This endblock shape was realised on both sides of FoS2. On the other hand, FoS1 was constructed with a non-shaped rectangular profile which allows a comparison of the different designs with the present measurement data. The rotating coil was placed at the end of the yokes (beam axis $z = 1500$ mm), which means that about the half of the coil was located outside of the magnet ensuring to include all edge effects in the measurements. The focus of the optimization was put on a supression of the sextupole term b_3, which is shown in Fig. 4 verifying an adequate reduction with a factor of ~ 2.5 between optimized and non-optimized profile.

YOKE GAP HEIGHT VS. MAGNETIC FIELD

The geometrie of the yokes of the SIS100 dipole magnets FoS1 and FoS2 were extensively surveyed with mechanical and capacitive sensor systems, providing highly resoluted gap height deviations ($\sigma = 7\,\mu$m) along the complete length of the yokes. The sensors are mounted on a carrier, which is moved along the yoke typically in steps of a few centimeters (here $\Delta z = 7$ mm (FoS1) and $\Delta z = 2$ mm (FoS2), respectively). The results are given in Fig. 5 as dots.

The rotating coil used for magnetic field measurements has a length of $L = 600$ mm, therefore the results represent an averaged field strength integrated over the coil length. To consider the same integration for the geometrical data, a moving average was applied on the data, shown as lines with 1σ-error bands in Fig. 5.

To compare these geometrical data with the results obtained by rotating coils, we use the general relation between magnetic field strength and gap height inside an iron yoke, which is given by

$$B(h) = \frac{\mu_0 N I}{h} ,$$

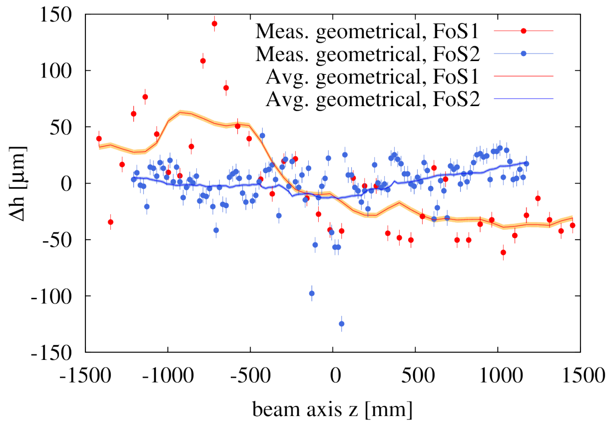

Figure 5: Geometrical measurements of the gap height (dots) and moving average (lines).

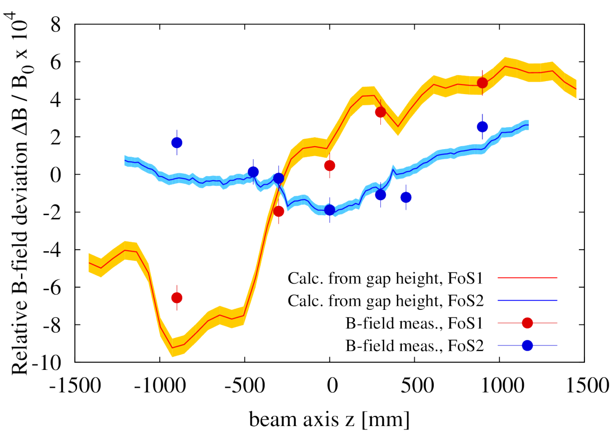

Figure 6: Comparison of gap height variations and magnetic field measurements (with 1σ-error bands and bars, respectively).

where $N = 8$ is the number of coil windings, I is the applied current and μ_0 the magnetic constant $\mu_0 = 4\pi \times 10^{-7} \frac{\mathrm{N}}{\mathrm{A}^2}$. This translation allows a combination of Fig. 3 and Fig. 5 which is (after some arbitrary offset corrections) realized in Fig. 6 and shows a good agreement.

STRETCHED WIRE MEASUREMENTS

With a stretched wire, one measures the integrated field strength along the complete magnet including the distorted edge fields at both ends of the magnet. Taking the central field strength B_0 as determined with the measurements using the rotating coil system, one could calculate an effective length L_{eff} of the magnet. This length is expected to be 3.062 m from specifications, which is slightly longer than the geometrical yoke length of 3.002 m. For currents in the medium range (2 – 8 kA) the average value is calculated from the stretched wire measurement to

$$L_{\mathrm{eff}} = (3.072 \pm 0.008)\,\mathrm{m}\,,$$

where the given uncertainty (in the sense of a gaussian σ) of ±0.25% is dominated by systematics estimated by a comparison of two repeated and mostly independent measurements.

ACKNOWLEDGMENT

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