MAGNETIC FIELD CHARACTERISTICS OF A SIS 100 FULL SIZE DIPOLE*

P. Schnizer†, E. Fischer, GSI, Darmstadt, Germany
G. Sikler, W. Walter, BNG, Würzburg, Germany
P. Akishin, JINR, Dubna, Russia
R. Kurnyshov, Elektroplant, Moscow, Russia
P. Shcherbakov, IHEP, Protvino, Russia

Abstract

FAIR will feature two superconducting fast ramped synchrotrons. The dipole magnets for one of them, SIS 100, have been designed and full size magnets were built. The properties of the magnetic field were analysed using OPERA (for DC operation) and ANSYS for dynamic calculations. Elliptic multipoles fulfilling the Laplace Equation in plane elliptic coordinates describe the field within the whole aperture consistently within a single expansion. Further circular multipoles, valid within the ellipse, can be calculated analytically from the elliptic multipoles. The advantage of this data representation is illustrated on the FEM calculation performed for SIS 100 dipoles and quadrupoles currently foreseen for the machine.

INTRODUCTION

The Facility of Proton and Iron Research (FAIR) will construct a set of accelerators and storage rings at GSI. The SIS 100 synchrotron, the core component uses superferric magnets, operated at 4 T/s and 1.9 T maximum field. The coil of these magnets use the Nuclotron type cable, where superconducting wires are wrapped around a NiCr tube cooled by a forced two phase Helium flow. The whole concept of the SIS 100 follows the JINR/Nuclotron design, but used the opportunity of the second generation machine to improve various parameters. These include: the loss per magnet, improved field quality and thorough investigation using commercial Finite Element Codes [1]. The first SIS 100 full size dipole was produced last year and is ready for testing (see Fig. 1). A concise description of the fields is required to model the accelerator before building it as the closed cryostat of SIS 100 makes it tedious to add additional magnetic elements after first operating experience is gained. Thus elliptic multipoles were developed for elliptic coordinates of the type $x = e \cosh \eta \cos \psi$, $y = e \sinh \eta \sin \psi$ with x and y the Cartesian coordinates and η and ψ the elliptic coordinates with $0 \leq \eta \leq \eta_0 < \infty$ and $-\pi \leq \psi \leq \pi$. The field $\mathbf{B} := B_y + iB_x$ can be described within the whole ellipse using

$$\mathbf{B}(\eta, \psi) = \sum_{q=0}^{M} \mathbf{E}_q \cosh[q(\eta + i\psi)]/\cosh(q\eta_0), \quad (1)$$

* This work is supported by the EU FP6 Design Study (contract 515873 - DIRAC secondary beams)
† p.schnizer@gsi.de

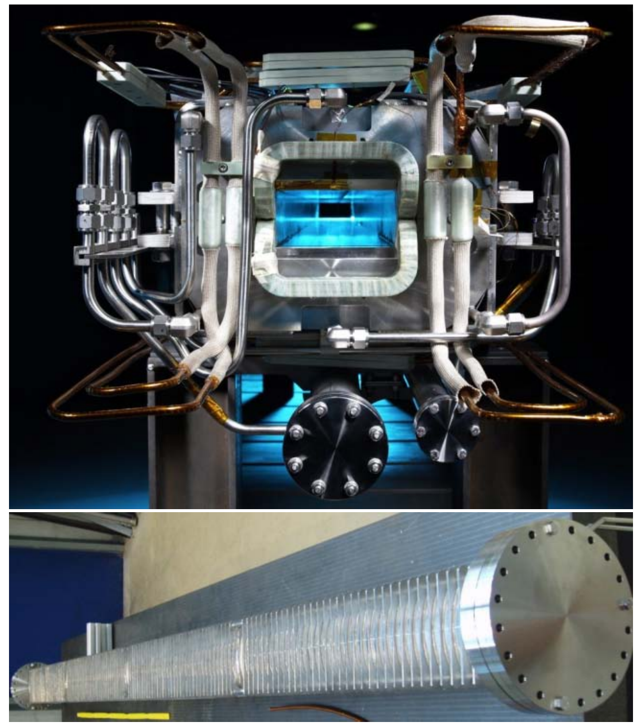


Figure 1: The first SIS 100 full size dipole (top) and the vacuum chamber (bottom).

with $\eta_0 = \tanh^{-1}(b/a)$ the reference ellipse and a and b its half axes [2, 3, 4] (here $a = 65\,mm$ and $b = 30\,mm$). These $\mathbf{E}_q$ can be recalculated to circular multipoles

$$\mathbf{B}(\mathbf{z}) = \mathbf{B}_m \sum_{n=1}^{M} \mathbf{c}_n \, (\mathbf{z}/R_{Ref})^{n-1} \quad (2)$$

using an analytic linear transformation, with $\mathbf{B_m}$ the main field, $\mathbf{z} = x + i\,y$, R_{Ref} the reference radius and $\mathbf{c}_n = b_n + i\,a_n$ the relative higher order multipoles. The b_n's and a_n's are dimensionless constants. In this paper they are given in units i.e. $1\,unit = 100\,ppm$ at a R_{Ref} of $40\,mm$. We chose this free parameter such that the relative allowed harmonics b_n can then be represented as convenient numbers in the order of 1 to 10. Using (2) the field can be interpolated with sufficient accuracy within an ellipse with half axes a, b.

PRODUCTION REVIEW

The magnetic field quality is defined by the yokes geometry (in the centre) and by the yokes end shape and the coils' position (in the ends). Thus all magnets (108 dipoles) must match each other and the temporal evolution of their field on each cycle. This will be guarantied by a very reliable mechanical fixture of the superconducting cable, especially in the head parts of the coil.

A cable machine was dedicated to produce the Nuclotron-type cable, which was optimised to guarantee and maintain constant cable parameters. This cable is wound to half coils of $4 \cdot 2$ windings in two layers and is supported by a precisely machined surrounding mechanical fixture made of glass-fibre reinforced plastic (GRP). The poles are finally shaped in a combined heat pressure treatment with an accuracy of the outside dimensions $< 0.05mm$ (also in the coil ends) and thus the superconducting wires positions is predominantly defined by the manufacturing tolerances of the GRP structural elements ($< 0.1mm$).

The soft-magnetic iron yoke of this dipole is made of two half shells which are bolted together. This allows to insert and remove the beam pipe and the coils. The yoke laminations are of "electrical sheet metal" with a thickness of 1 mm. They were laser-cut and stacked to sub-packs of approximately 150 mm length. The laminations were covered with adhesive which is activated and hardening when heated. The sub-packs are glued together in a furnace under pressure to form a solid compound for further assembly. Each of these packs show a packing factor of 99.5 %. (Smaller packing factors can be reached controlling the pressure during the backing process). The sub-packs are set up in a string along with the two specially shaped end-packs and a compensating pack to reach the required magnet length. On the outside corners of the yoke cooling tubes and angular sheets of stainless steel are placed. The stainless steel- angels form an outside frame for the yoke. They are TIG-welded at various positions to each sub-pack along the whole length of the yoke. The heat introduced during the welding process can distort the shape, thus the welding pattern was optimised to keep the distortion small and the evenness of the relevant yoke surfaces within the tolerance of 0.3 mm (over the whole length of 2.8m).

EXPECTED FIELD QUALITY

Static

Many different models were built and investigated in 2 and 3 dimensions to obtain a magnetic field design providing a field quality according to the specifications. The design to prefer was chosen based on the circular multipoles calculated from the elliptic ones. A side to that the influence of the packing factor was studied for the dipole as foreseen for SIS 100 (see Fig. 2, gap height was 66 mm for this study). One can see that the influence of the packing factor on the field quality is rather small up to a field of

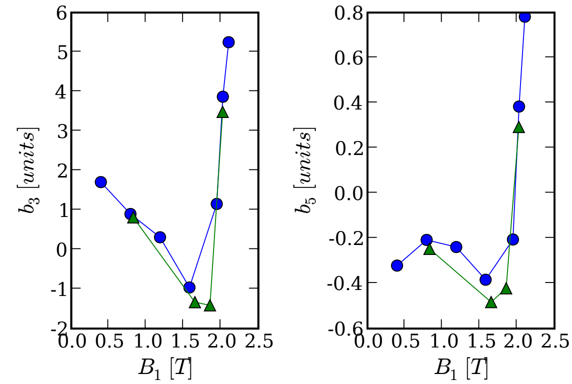
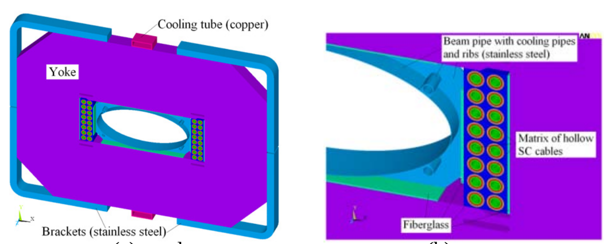


Figure 2: Relative 2D harmonics of the static field quality versus the main field for different packing factors (circles 98 %, tripods 100 %). The difference between the lines is not large compared to a maximum tolerable field error of 6 units.



(a) total (b) zoom

Figure 3: The model of the middle section of the dipole magnet and the vacuum chamber. The vacuum chamber is supported by ribs and equiped with separate cooling tubes.

$\approx 2.1\,T$ (roughly half a unit for b_3 and 0.1 unit for b_5) and less than 0.1 units at injection.

Dynamic

As the SIS 100 machine is designed to run with an frequency of roughly 1 Hz, the dipole magnets must be ramped from the injection field of $\approx 0.23\,T$ to $\approx 1.9\,T$ in the order of half a second. The ramping field generates eddy currents in different parts of the magnet [1] and also in the vacuum chamber [5]. The same model as in [5] was used again to calculate the magnetic field using ANSYS (see Fig. 3) in the "2D" section of the magnet. The model was evaluated for static operation without the vacuum chamber, for static operation with the vacuum chamber and for the dynamic operation with the vacuum chamber (see Fig. 4). One can see that the field does not change in the longitudinal position, but that the eddy currents create a distortion at least twice larger than the field the magnet provides (see also Fig. 5). The elliptic multipoles and the circular ones derived from the elliptic ones [3, 4] were calculated and the field was reconstructed using them. Fig. 5 demonstrates that the interpolation represents the original

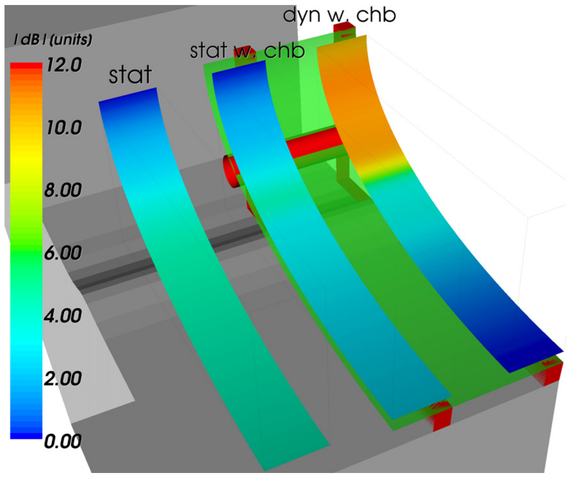


Figure 4: The field deviation in units (1 unit = 100 ppm) at injection is plotted along the ellipse. left $\rightarrow$ the static field without vacuum chamber, middle $\rightarrow$ static field with the vacuum chamber, right $\rightarrow$ the dynamic field with the vacuum chamber. The quater yoke is indicated in gray, the vacuum chamber in green and in red the supporting ribs and cooling tube. The eddy currents create the main distortion.

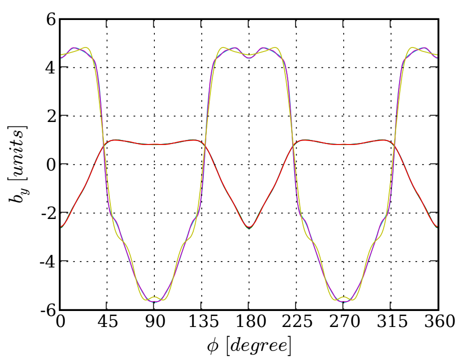


Figure 5: The field B_y at injection versus the angle ϕ around the ellipse. The static field (variation $\approx$ 2 units) versus the dynamic field (variation $\approx$ 10 units). The data calculated with ANSYS are plotted next to the interpolation using the elliptic multipoles and the circular multipoles derived from the elliptic ones.

field with sufficient accuracy. The multipoles along the load line on the ramp up are given in Fig. 6. One can see that the vacuum chamber adds the largest distortion at the injection field level (as the effect only depends on dB/dt and thus is constant for constant ramp rate).

CONCLUSION

The first SIS 100 full size dipole has been delivered and is made ready for testing at GSI. The calculated static and dynamic field quality were presented. The 2D static field quality is mainly determined by the imperfections of the magnets geometry whereas the dynamic field quality is

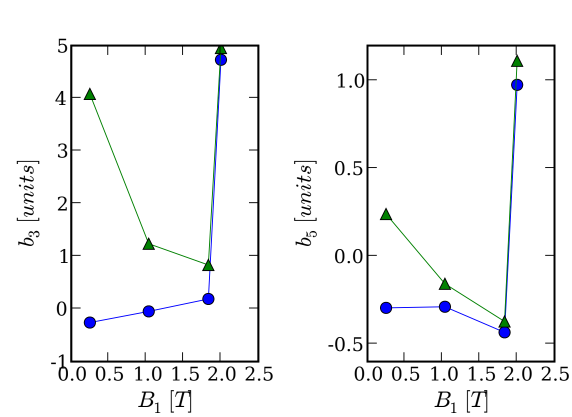


Figure 6: The sextupole and the octopole versus the main field for the static field without vacuum chamber (circles) and on the ramp with the vacuum chamber inserted (tripods). One can see that at injection all multipoles on the ramp are much larger on the ramp than in the static case.

considerably affected by the eddy currents in the vacuum chamber. This magnet will be tested this summer, measured magnetically and the results presented here will be checked with the measurement data. A second full size dipole is under construction at JINR / Dubna and will be tested there soon and afterwards retested at GSI [6].

REFERENCES

[1] E. Fischer, R. Kurnishov, and Shcherbakov P., "Finite element calculations on detailed 3D models for the superferric main magnets of the FAIR SIS100 synchrotron", *Cryogenics*, 47:583–594, 2007.

[2] P. Schnizer, B. Schnizer, P. Akishin, E. Fischer, "Magnetic field analysis for supperferric accelerator magnets using elliptic multipoles and its advantages", 20-th Magnet Technology Conference, August 27-30, 2007, Philadelphia, Pa., USA Paper 3L06 (to appear in IEEE Trans. on Appl. Sup.).

[3] P. Schnizer, B. Schnizer, P. Akishin, E. Fischer, "Field representations for elliptic apertures", February 8th, 2007. GSI Internal Communication. Revised January 16th, 2008.

[4] P. Schnizer, B. Schnizer, P. Akishin, and E. Fischer, "Theoretical Field Analysis for Superferric Accelerator Magnets Using Elliptic Multipoles and its Advantages" this conference

[5] E. Fischer, R. Kurnishov, and Shcherbakov P., "Analysis of coupled electromagnetic-thermal effects in superconducting accelerator magnets", In *8^{th} European Conference On Applied Superconductivity, 16 - 20 September 2007, Brussels, Belgium*, volume 97. IOP Journal of Physics: Conference Series, 2008.

[6] A. D. Kovalenko et. al, "Full size model magnets for heavy ion superconducting synchrotron SIS100 at GSI: status of manufacturing and test at JINR", this conference