MAGNETIC-FIELD CALCULATIONS OF THE SUPERCONDUCTING DIPOLE MAGNETS FOR THE HIGH-ENERGY STORAGE RING AT FAIR

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Abstract

For the High-Energy Storage Ring (HESR) to be established at the FAIR facility at GSI in Darmstadt, Germany, magnetic field calculations have been carried out for the layout of the superconducting dipole magnets. Four configurations have been considered for the 3 m long magnets: straight ones and bent ones with a bending radius of 15.279 m, respectively, both for the cos(θ)-layout and for the double-helix dipole (DHD) layout. This contribution will focus on the advantages and disadvantages of the individual configurations in terms of field quality in the dipole regions.

INTRODUCTION

GSI is planning the new accelerator facility FAIR [1] for nuclear investigation with heavy ions and antimatter to be established around the year 2017. Forschungszentrum Jülich manages the setting up of part of this facility, the High-Energy Storage Ring (HESR) within the FAIR consortium. An overview of the design of this ring together with the present status has been given elsewhere [2]. In particular, HESR will comprise about 100 quadrupole magnets and 32 dipole magnets. The nominal flux density in the center of the dipoles will be 3.6 T. The necessary dipole field strength and space considerations lead to the preference of curved dipole magnets over straight ones, which have been favoured for other accelerators in the past. Bent magnets in principle offer the advantage that the particles can travel in the good field region along nearly the entire length of the magnet, instead of coming close to the beam tube both at the ends and in the center and experiencing inhomogeneous fields there. Therefore, the use of bent superconducting magnets has been envisaged for HESR. This policy poses new questions both in terms of manufacturability and bend-induced field distortions compared to the field in straight magnets. Studies are being carried out to assess both of these questions. This publication reflects our effort to assess the changes in the field quality of the dipole magnets and measures to compensate for these effects.

SIMULATION PREREQUISITES

A cross section depicting the upper part of the yoke together with the superconductor is given in Fig. 1. To avoid larger redesign efforts for the dipole magnets we want to adopt the successful D0 design of the superconducting magnets of the RHIC facility at BNL [3]. Therefore, the positions of the conductors in the cross section are not to be changed, which also has the advantage that the design of the head sections will not be affected.

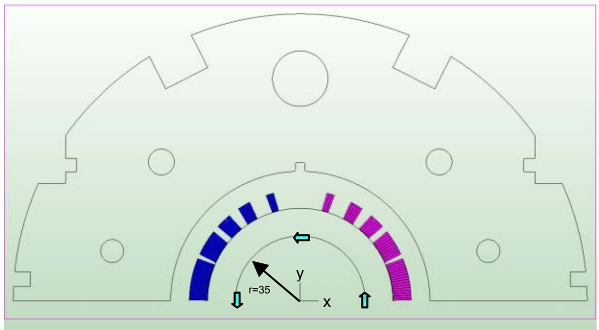

Figure 1: cos(θ)-dipole design: upper half of the cross section in the xy-plane of the iron yoke and positions of the superconducting cables (red and blue).

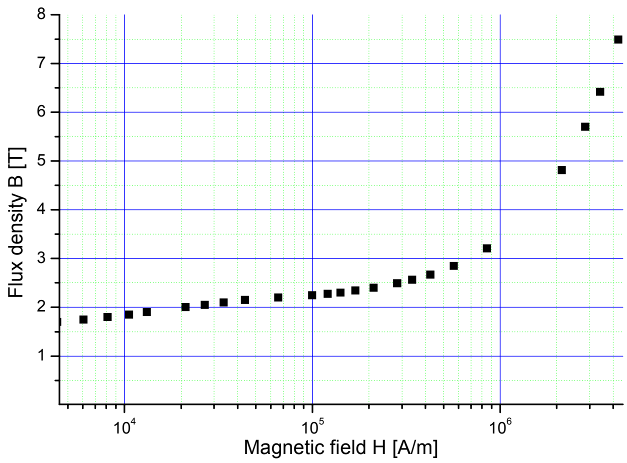

Figure 2: B(H) characteristics of the dipole yoke iron. Note the semi-logarithmic scale.

However, the position of the holes and notches on the circumference has been modified to easily accommodate bus bars and structural material during manufacture.

The nonlinear B(H) characteristics of the yoke iron has been specified and is depicted in Fig. 2.

A different approach for manufacturing dipole magnets has been discussed as well. It is based on the double–helix dipole design pointed out by R. Meinke *et al.* [4]. It is based on the observation that two coils wound in an oblique way defined by a skew angle α onto a cylinder cancel their axial fields but add their transverse field, yielding a dipole field inside the cylinder. For a straight magnet, the field homogeneity far away from the head sections only depends on the winding density and may reach very high values even close to the cables. Figure 3 shows a winding scheme of a DHD with two oppositely tilted coils on a cylinder and a picture of a 3D example.

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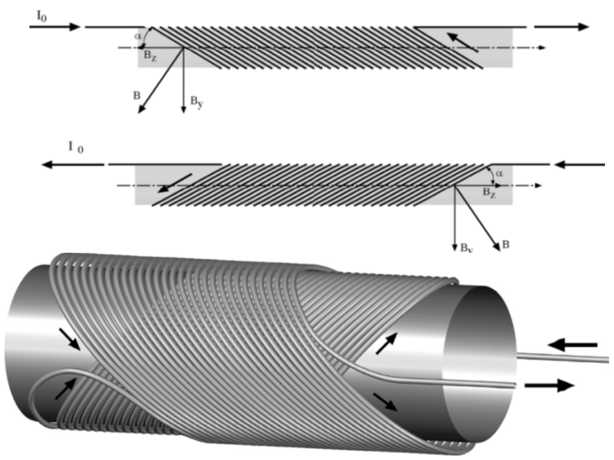

Figure 3: DHD winding scheme (upper part) and 3D example (lower part) (Courtesy R.B. Meinke)

For the electromagnetic field calculations, two different codes have been employed to assess the reliability of the results. For the D0 magnets both in the straight and the curved configuration the MAGNETO (BEM) software package by IES [5] and the ANSYS (FEM) package by Ansoft [6] have been used. In the case of the DHD only calculations with MAGNETO have been carried out. Both MAGNETO and ANSYS permit the calculation of two dimensional models of plane and axisymmetric designs. The required field homogeneity inside a reference circle of 35 mm radius was defined to be 1 x 10^{-4}. We show the variation of the y component of the flux density on this circle as a reference: the variation inside the circle is smaller than along the circle due to the fact that each component of B is a harmonic function in free space, which attains its extreme values on the boundary.

RESULTS

Cos(θ)-type Dipole Magnets

Figure 4 shows the variation of the B_y field along the semicircle shown in Fig. 1 for the case of a straight magnet with the current through the conductors as parameter indicated in the inset. The orientation of the path is given by the arrows in Fig 1. The ANSYS results are represented by crosses of the same color as their square counterparts obtained by MAGNETO. As can be seen from this figure, the relative differences of the results for the two codes are on the order of 10^{-4}. Larger deviations from homogeneity occur above 3500 A, which corresponds to a flux density of about 2.5 T as can be seen from the current–to-flux conversion depicted in Fig. 5. Figure 6 shows the asymmetry imposed on the curves, when a bending radius of 15.279 m is introduced. The axis of rotation is parallel to the y-axis is at x = -15.279 m and y = 0 m.

Though for our purposes the bending radius is fixed, it is interesting to ask, how the asymmetry behaves with the bending radius. Figure 7 shows the difference to the along the semicircle for bending radii from 10 m to 100 m.

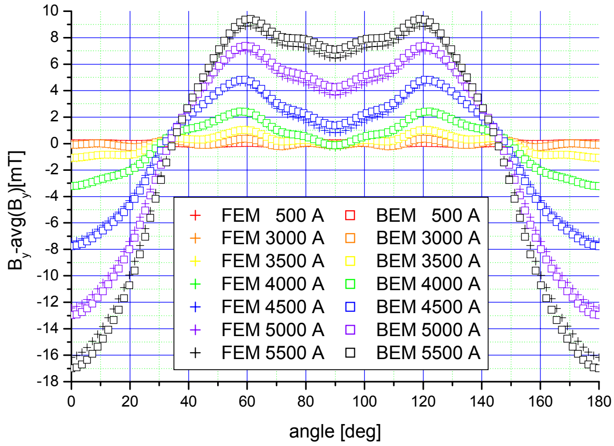

Figure 4: Variation of the field along the semicircle calculated by the FEM and the BEM code for the straight cos(θ)-dipole. Excitation current as parameter.

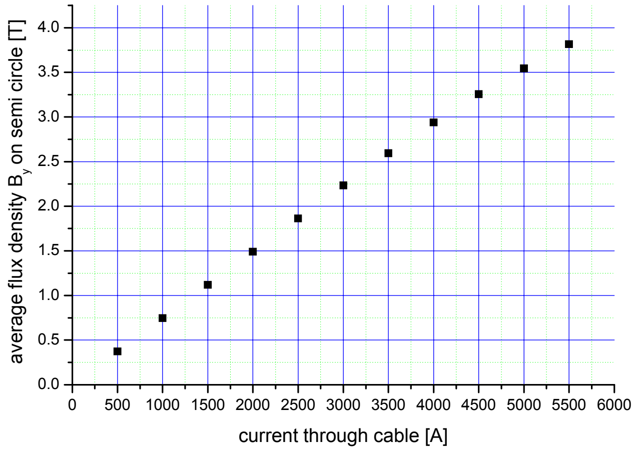

Figure 5: Excitation curve B(I) for the cos(θ)-dipole magnet.

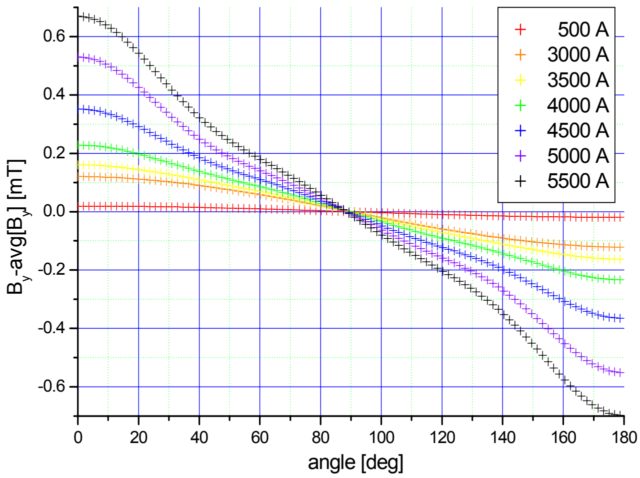

Figure 6: Difference of flux densities between the bent and the straight magnet along the semi-circle. (FEM data). Excitation current as parameter.

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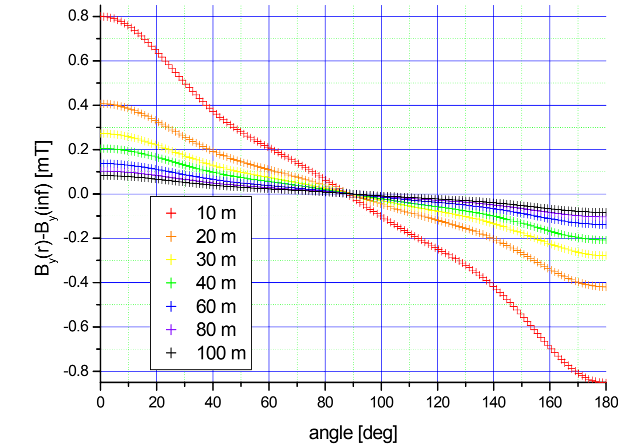

Figure 7: Difference of the B_y values along the semi-circle of the bent and the straight dipole for I = 5000 A (FEM data). Bending radius as parameter.

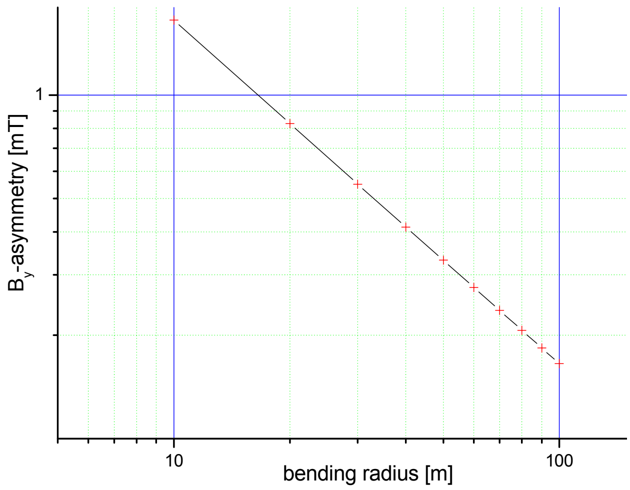

Figure 8: Dependence of maximum B_y differences on bending radius r (FEM data) for I = 5000 A.

Fig. 8 shows maximum variation of the individual curves (ΔB_y (0°) – ΔB_y(180°)) of Figure 7. The r^{-1} dependence can directly be verified from this logarithmic plot.

DHD dipole

One filament of a cos(θ)-dipole can be described by a space curve with the following components

$$\vec{r}(\theta) = a \cdot \left(\cos(\theta), \quad \sin(\theta), \quad \frac{\delta / a}{2 \cdot \pi} - \frac{\sin(\theta)}{\tan(\alpha)} \right),$$

where a is the radius of the DHD, δ is the pitch between two adjacent turns of the cable, and α is the skew angle (see Fig. 3). The first two components describe a circle in the xy-plane, while the third one is responsible for the translation in the z-direction. The conjugate filament is obtained by replacing $\alpha \rightarrow \pi - \alpha$ and for the current $I \rightarrow -I$ in current density calculations. When the thickness of the conductor is t, the joint current density j has only a z component given by

$$j_z(\theta) = \frac{2 \cdot I}{\delta \cdot t} \cdot \frac{\sin(\theta)}{\tan(\alpha)},$$

which is an ideal cos(θ)-dependence, yielding an ideal dipole field on the inside. This is confirmed by field calculation carried out with MAGNETO in the case of the straight magnet.

DISCUSSION

The FEM and BEM codes show a good level of agreement for this type of problem. The differences are only in the range of a few 10^{-4}. Therefore, we believe that the predicted effect of the bending – the introduction of a gradient inversely proportional to the bending radius - will also be present in the real magnets. However, for our bending radius this effect changes the field on the order of 10^{-4}. This effect will have to be compensated for in future optimizations by the introduction of a slight asymmetry in the yoke by introducing new bores or shifting the location of existing ones.

Although the DHD layout appears quite promising we have already discarded this option for implementation in HESR, mostly because of the tight project schedule and the fact that this type of magnet has not been employed in accelerator facilities yet. The technological risk of having to develop such a new type of superconducting magnet with a non-negligible bending radius seemed too high for us. However, future projects may show that this type of magnet may be reliably operated for medium-field applications.

ACKNOWLEDGMENTS

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