FIELD ANALYSIS OF LHC INSERTION QUADRUPOLE MODEL MAGNETS AT KEK

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Abstract

Three short models of the MQXa quadrupole magnets for the LHC interaction regions have been built and their field qualities have been measured at KEK. In this paper we compare the measured field values with those of the numerical models of the quadrupoles and estimate the precision of the magnet coil assembly. The effects of the coil radius change and magnetic characteristics of the collar and yoke on the field gradient, and the effects of the coil block displacement on the measured harmonics are investigated.

1 INTRODUCTION

As part of the collaboration program between CERN and KEK for the Large Hadron Collider (LHC), high-field gradient superconducting quadrupole magnets for the interaction regions of LHC are being developed at KEK. These large bore (70 mm) magnets are intended to operate in superfluid helium at 1.9 K with a nominal field gradient of 215 T/m. To date three short models have been built and their field qualities have been measured. The design and construction of the magnets have been described in previous reports[1,2,3]. The magnets have four-layer coils wound with two types of 11 mm wide NbTi/Cu keystoned cables with a graded current density. The coils are surrounded by a 4-split collar made of high-Mn steel and a horizontally split yoke. The resulting cross section of the magnets is shown in Fig. 1. The first two models (#1-a and #2) were built with one wedge in the second innermost layer coil. The difference between the #1-a and #2 magnet is in their coil size. Small coil shims, which were not in the baseline design, were introduced in the #1-a magnet to get enough coil pre-stress while sacrificing the design field quality. In the #3 model, one more wedge was introduced in the first layer coil to reduce a higher order multipole, b_{10}.

The field measurements were performed using a vertical drive, rotating coil system. The rotating coil has 7 windings on a precisely machined G-10 probe form: 1 tangential, 3 dipole bucking, and 3 quadrupole bucking windings. The probe used to obtain the multipoles has a nominal diameter of 44.0 mm and a length of 200 mm. Details about these measurements have been reported in other papers[4,5].

In this paper our study is confined to 2-dimensional field characteristics. The measured field gradients and multipoles are compared with calculations and the precision of the magnet coil assembly is estimated.

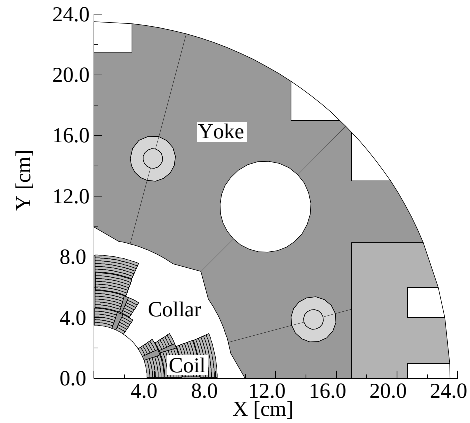

Figure 1: Cross section of the #3 model magnet.

2 2-D FIELD CALCULATION

2.1 Calculation Model

In order to compare the measured field values with calculations, it is necessary to make cold state calculation models with reasonable accuracy. However, in general it is not so easy to estimate the cold state cross section of the magnet because of the different thermal contractions of the constituents. The models used for this study were constructed as follows: the thermal shrinkage of yoke, collar, and others (coil, G-10, etc.) were assumed to be 0.198 , 0.17 and 0.30 %, respectively. First the shrunken yoke was drawn by CAD and then the shrunken collars were installed into the yoke aperture to fit the inner surface of the yoke. Then, the shrunken shims at mid-plane and pole sides were added on the drawing and the cave for the coil block was defined. Next the conductors were piled up on the mid-plane shim by using Roxie. If the conductors didn't fit into the cave for the coil block, the pile-up process was iterated changing the thickness of the conductor and the resultant cold state model was constructed. Using the data of the conductor position obtained from Roxie, the calculation model for Opera-2d was created. Table 1 shows the field values of the #3 magnet calculated by Roxie and Opera-2d, which give us an idea of the accuracy of the calculation model. The multipoles are expressed in units of 10^{-4} of the

Table 1: Comparison of Roxie and Opera-2d calculations. In this comparison an infinite permeability and a circular inner surface of the yoke were assumed.

	Roxie	Opera-2d
G (T/m)	238.505	238.668
b6 (units)	0.0282	0.0791
b10(units)	-0.0003	0.0005

Table 2: Effect of yoke permeability on the field characteristics. (#2 model magnet)

	ultra low-carbon steel		**SS400**	
I (kA)	2	7	2	7
TF(T/m/kA)	33.244	31.681	33.229	31.387
b6 [units]	0.412	0.321	0.411	0.310
b10[units]	-0.931	-0.977	-0.932	-0.986

quadrupole field at a reference radius r=17 mm. The differences between calculations are very small; $\Delta G/G<$ 0.07 % and $\Delta b6 < 0.01$ units. Therefore, we can conclude that the created model has enough accuracy for the present analysis since the accuracies of the measured values are about 0.1 % for G and 0.05 units for b6 [6].

2.2 *Effect of Yoke and Collar Permeability*

One parameter which may cause differences between measured and calculated field values is magnetic characteristics of the yoke. Therefore, we extensively studied the effect of the yoke permeability on the field characteristics by using Opera-2d. Table 2 shows the calculated field values when we used different types of yoke material. One is a case of ultra low carbon steel with μ_r=14000 at B=1 T, which was adopted for our model magnets, and the other is of extremely low grade steel (SS400) with μ_r=800 at B=1 T. As can be seen in the table, the differences in transfer function at low field (2kA) and higher multipoles are almost negligible. Only in transfer functions at high current (7kA), we can see a difference of the order of 0.9 %. From this study we can conclude that the effect of yoke permeability on the field characteristics is very small for the realistic ranges of the permeability change.

Another parameter we have studied is the permeability of the collar. In general it had been thought that the effect of collar permeability might be small, however, there have been a few reports mentioning its effect[7,8]. Therefore, we studied the effect by calculation and performed a permeability measurement of the collar material (high-Mn steel) at 5 K. Figure 2 shows the results of this calculation. The measured permeability of the collar at 5 K was 1.0013 and there was no significant dependence on the external field. Through this investigation it became clear that the effect of the high-Mn collar permeability is rather small ($\Delta G < 0.02$ T/m, $\Delta b_{10} < 0.005$ units), although the effect on b_6 is relatively large compared to that of the yoke permeability, $\Delta b_6 < 0.15$.

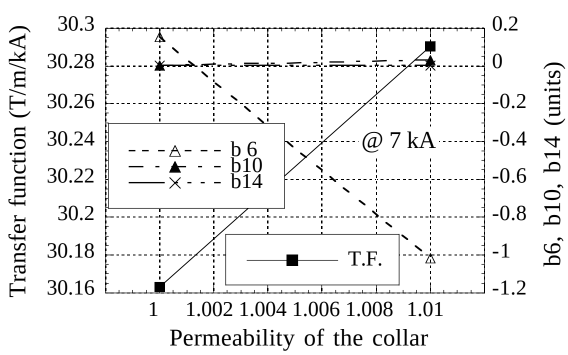

Figure 2: Variation in field characteristics as a function of collar permeability. (#3 model magnet)

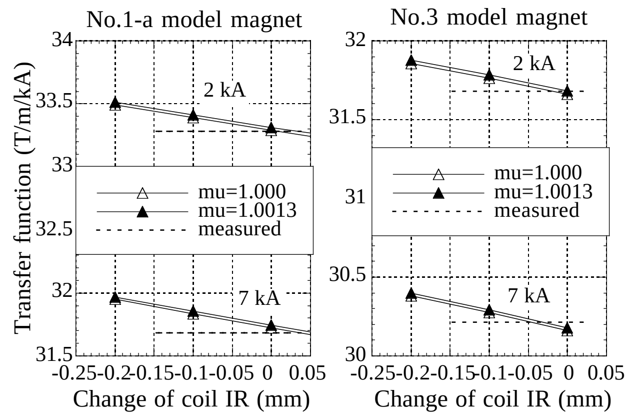

Figure 3: Variation in transfer function as a function of coil IR change. The effect of the collar permeability and the measured values are also plotted.

2.3 *Effect of Coil IR Change*

The field gradient is more sensitive to a change of the coil inner radius (IR) compared to the previous two parameters. The effect was carefully studied by using a cold state model in Opera-2d. Examples of this study are plotted in Fig. 3. The same plot for #2 magnet was very similar to that of the #1-a magnet. From these plots we can estimate the deviations of the coil IR from the design value. In all model magnets they were less than 50 µm. Since the precision of the magnet coil assembly is expected to be within 50 µm [9], these values are very consistent with and support our expectations of the fabrication error.

3 ANALYSIS OF MEASURED HIGHER MULTIPOLES

Field measurement of the model magnets showed the existence of some amount of unwanted multipole terms. In order to estimate the geometrical deformation of the coil that can explain the origin of the multipoles, we performed an analysis. One method to study it is to solve the inverse problem by using Roxie[10]. However, the uniqueness of the solutions remains uncertain with this method. Therefore, we took another method which was originally developed for the HERA dipole analysis[11]. In this method various conceivable distortions of the coil geometry can be characterized by a set of transformations, which influence either only on the normal multipoles or the skew poles, and thus we can easily find solutions which explain the origin of the measured unwanted multipoles. The analysis was performed for two cases: each octant coil block can move either in azimuthal direction or in radial direction. In both cases, an azimuthal displacement with quadrupole symmetry was introduced to reproduce the measured b_6. Figure 4 shows

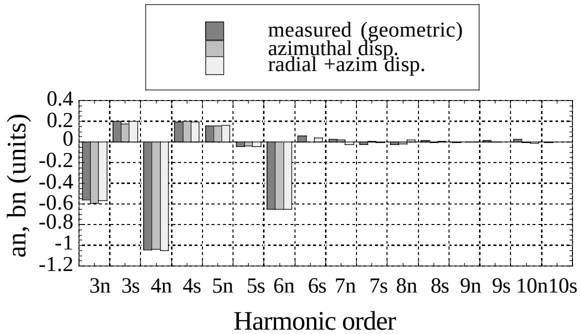

Figure 4: Measured and reconstructed multipoles of the #3 magnet .

an example of how well the obtained coil block displacement can reconstruct the measured multipoles.

Figure 5 plots the azimuthal or radial displacements of octant coil blocks that reproduced the measured higher multipoles. Since we could find two solutions in each case, they are expressed as sol-1 and sol-2. In the case of azimuthal displacement, each octant coil moved to the pole side and average displacements were 0.08, 0.14 and 0.03 deg. in the #1-a, #2 and #3 magnets. For the radial displacement, average movements of about 30 μm are required to explain the measured unallowed multipoles and also a small symmetric azimuthal displacement of

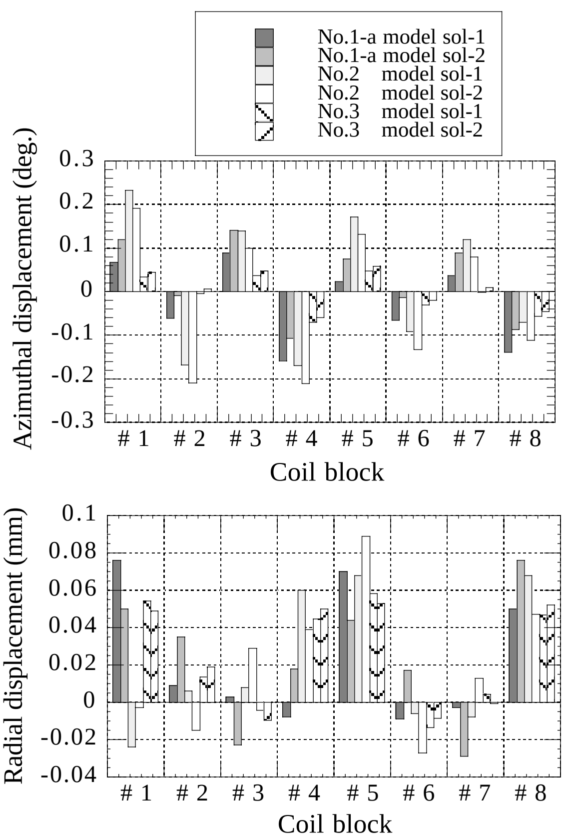

Figure 5: Azimuthal or radial displacement of the octant coil blocks estimated from the measured multipoles.
The coil block numbers are counted from a mid-plane (positive x-axis) to the counterclockwise direction.

0.08, 0.145 and 0.03 deg. for #1-a, #2 and #3 magnet was required to explain the b_6. We can also see a trend where the octant coils around the mid-plane (#1, #4, #5 and #8 coil block) move largely outward. This trend seems to be related to the 2-split yoke structure.

4 CONCLUSION

Two-dimensional field analysis has been performed for the three model magnets fabricated at KEK. Precise field calculation using Opera-2d, where thermal contraction and permeability of the constituents of the magnet were taken into account, showed good agreement with the measured transfer function. Through this analysis, the estimated coil IR change from the design value was less than 50 μm in all model magnets. The most probable coil block deformation was studied by extending the method developed for the HERA dipoles and it was found that coil block displacements of the order of 50 μm could easily explain the measured unwanted higher multipoles.

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