FIELD QUALITY ANALYSIS OF THE NEXT GENERATION IR QUADRUPOLE FOR THE LHC*

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Abstract

Lawrence Berkeley National Laboratory (LBNL) is carrying out a conceptual design study of a Nb_3Sn quadrupole for the next generation LHC Interaction Region (IR). The choice of a gradient of 205 T/m and an increased bore size of 90 mm represents a promising strategy towards increasing the luminosity up to an ultimate goal of 2.3×10^{34} cm^{-2}s^{-1}. At the present time Nb_3Sn is the only conductor with sufficient current density for this application. Coil designs with either two or four layers are being considered. Previous studies have examined cable and coil parameters, systematic harmonics, support structure and quench protection system. In this paper the issue of field quality is further discussed.

INTRODUCTION

NbTi quadrupoles for the Interaction Regions of the Large Hadron Collider (LHC) are being fabricated at KEK (MQXA) [1] and at FNAL (MQXB) [2]. An aperture of 70 mm with an operating gradient of 205 T/m allow for a luminosity of 10^{34} cm^{-2}s^{-1}. During the past year, conceptual design studies were carried out by LBNL [3], FNAL [4] and BNL [5] to analyze a second generation Nb_3Sn LHC IR quadrupole magnet capable of increasing the luminosity of the machine up to an ultimate goal of 2.3×10^{34} cm^{-2}s^{-1} [6]. In this paper, further design studies are reported focusing in particular on field quality issues. Iron saturation, random errors and impact of yoke misalignments on field harmonics are considered. Different strategies of correcting both allowed and non-allowed multipoles are discussed, and future plans of the magnet R&D are outlined.

MAGNET DESIGN

The magnet cross-section is shown in Fig. 1. Nb_3Sn superconducting cables are wound around bronze poles and supported during assembly by four bolted stainless steel pads (30 mm thick). A 5 mm gap separates the pads from a four-piece iron yoke, contained within an aluminum shell 18 mm thick. The outer diameter of the shell is limited to 500 mm, the same as in MQXA, and therefore compatible with the existing cryostat.

From a structural viewpoint, the main characteristic is the absence of supporting collars. The assembly is done by means of the key and bladder technology [7], implemented here for the first time in a cos(2ϑ) magnet.

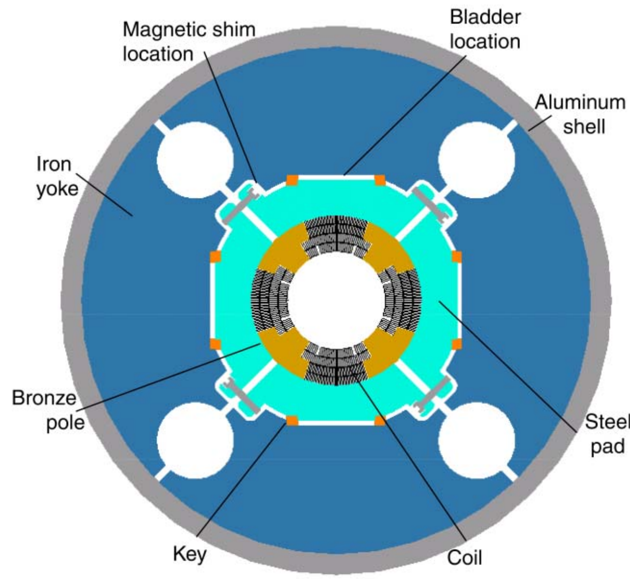

Figure 1: Cross-section of the quadrupole magnet.

The bladders are inserted and inflated in the gap between pads and yokes, providing an initial pre-stress to the coil. Interference keys are then used to lock in the pre-stress and allow bladder removal. During assembly, this technology provides about half of the required coil pre-stress, with little spring back. During cool-down, the different thermal contraction between aluminum and iron increases the coil pre-stress. Preliminary computations with an aluminum pad have shown that it could replace the stainless steel pad still maintaining sufficient pre-compression. A detailed study of the stresses inside the magnet during assembly, cool-down and excitation was presented in Ref. [3].

With respect to the previous analysis, some design modifications were implemented. The pad material was changed from iron to stainless steel. The inner radius of the yoke was reduced by 10 mm and the G10 spacer was removed. The yoke includes four 70 mm diameter holes for longitudinal heat transfer within the cold mass. We point out that the gaps between the pads and the yokes, and between the four pads provide additional space for cooling. A reference coil aperture of 90 mm was chosen for the analysis. However, changes in the coil aperture can be easily accommodated in this design concept.

Superconducting coil

The baseline design of the quadrupole features a four-layer cos(2ϑ) coil (Fig. 2, left). For consistency with previous analyses, we have assumed a critical current density of 2.4 kA/mm^2 at 12 T and 4.2 K, a conservative

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value compared to the current carrying capacity of recent Nb_3Sn strands. The short sample gradient at 1.9 K is 267 T/m (30 % design margin). At an operational temperature of 4.2 K, the short sample gradient decreases to 249 T/m (20 % design margin). Details on the magnetic parameters are given in Ref. [3].

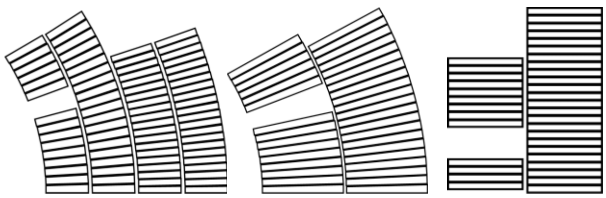

Figure 2: Coil cross-sections: four-layer cos(2ϑ) (left), two-layer cos(2ϑ) (center) and block-type (right).

The proposed four-layer coil design was based on magnetic efficiency and cable design considerations [3]. However, alternative designs of both shell-type and block-type coils are being developed. A two-layer cos(2ϑ) design (Fig. 2, center) reduces the number of parts and the magnet inductance, but requires the development of a new fully-keystoned cable with a special keystone-shaped core. It provides a short sample gradient of 247 T/m at 1.9 K, with a margin of 20 %. Block-type geometries have advantages in terms of conductor compatibility, separation between high field and high stress points, reduction of peak stress, simplification of support structures and assembly techniques [8]. In fact, a block coil was originally proposed for the LHC inner triplet [9]. The design (Fig. 2, right) consists of two layers of a flat cable with 35 strands. One potential issue of this coil is the minimum-bending radius of the cable in the ends. This issue will be addressed in future R&D magnet programs. This design generates a short sample gradient of 230 T/m at 1.9 K with a margin of 12 %. A less conservative critical current density in the superconductor, an increase of the conductor area and the use of a four-layer graded coil can push the margin above 20 %.

FIELD QUALITY ANALYSIS

The three coil geometries, optimized with ROXIE [10], limit the geometric harmonics to 0.05 units at a reference radius of 22 mm. For an effective filament diameter of 100 μm, the magnetization effect on b_6 during the start-up of the second excitation cycle is about + 30 units at 400 A (about 1/15 of I_{op}), decreasing to a minimum of – 12 units at 1400 A. A reduction of the filament diameter by at least a factor of two is being pursued by the DOE Conductor Development Program. A correction scheme such as the one based on a ferromagnetic ring [11] can also be used to reduce magnetization above 1200 A. It should be noted that the field quality of the IR quadrupoles at injection is not critical for the machine. In the present yoke and pad design the effect of iron saturation on b_6 (evaluated with OPERA-2d [12]) was reduced to less than 0.1 units from injection to short sample.

Random harmonics

To estimate the multipole errors produced by fabrication tolerances, random displacements of the conductor blocks with respect to the design geometry were applied in the range of ± 50 μm. The calculated errors for the four-layer design and for the MQXB design were compared (Fig. 3), considering for both cases a reference radius of half the magnet aperture (22 and 17 mm respectively). The amplitude of the displacements is about 2.5 times greater than the one observed in the short models of the first generation MQXB quadrupoles [13]. This conservative assumption takes into account the difficulties of controlling Nb_3Sn coil dimensions during the high-temperature reaction phase.

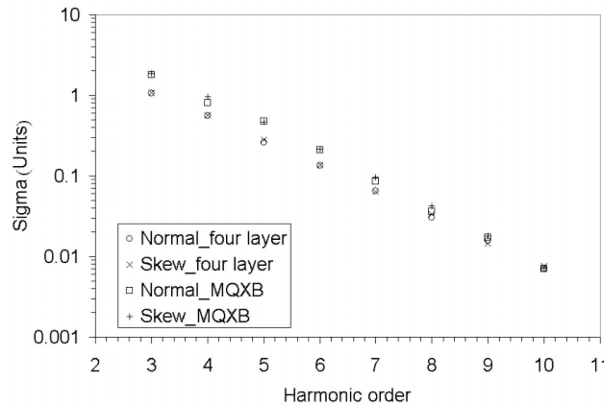

Figure 3: Numerical estimates of the geometric random multipoles (10^{-4} units) due to a random block displacement of 50 μm for the four-layer design (at R_{ref} = 22 mm) and the MQXB (at R_{ref} = 17 mm).

As pointed out in Ref. [14], the numerical estimates present a very regular pattern and can be well fitted by second order polynomials on a semi-logarithmic scale. The small discrepancy observed for the low-order harmonics can be explained by the different block sizes in the two designs.

Yoke misalignments

During assembly, the inflation of the bladders creates an interference gap between the pad and the yoke of about 0.5 mm. This interference is defined by the key thickness and is maintained during cool-down and through excitation, providing the required coil pre-stress. A sensitivity analysis of the effect of radial and azimuthal displacements of the yoke on field harmonics with respect to the nominal position was performed for the four-layer design. A positive radial displacement of one yoke quadrant by 0.1 mm produces a b_3 of – 0.08 units and a b_4 of – 0.02 units. On the other hand, the effect of a similar azimuthal displacement will produce only negligible harmonics. The impact of yoke misalignments on field quality seems therefore significantly lower than the effect of fabrication tolerances (Fig. 3).

FIELD QUALITY CORRECTION

In order to achieve the level of field quality required in the IR quadrupole, methods for correction of field errors will be tested in prototypes. Systematic deviations of the allowed harmonics will be corrected by simple modifications to the coil cross-section. Correction of the low-order non-allowed harmonics can be obtained with magnetic shims, as successfully demonstrated in previous IR quadrupole R&D programs [15-16].

Allowed harmonics

Systematic variations of b_6 can be corrected by changing the coil shim patterns at the pole and mid-plane, with little or no impact on coil pre-stress [13]. In Tab. 1 the variations of b_6 corresponding to a variation of the mid-plane insulation for the four-layer design are reported. The corresponding change in b_{10} is very small.

Table 1: Variation of allowed harmonics at nominal current (10^{-4} units at R_{ref} = 22 mm) due to an increase of 100 μm of the mid-plane insulation thickness.

Mid-plane shim	**Inner layer**		**Outer layer**	
[μm]	Δb_6	Δb_{10}	Δb_6	Δb_{10}
+ 100	-1.44	-0.01	-0.34	0.00

For correction of systematic deviation of b_{10} from the design values, the proposed coil design features a copper wedge at the optimal position in the innermost layer. A change in the wedge azimuthal dimension of + 100 μm results in a change in b_{10} of + 0.05 units. The corresponding change of b_6 is well within the range that can be corrected by pole/mid-plane shims.

Low-order non-allowed harmonics

The quadrupole design incorporates magnetic shims for correction of low-order non-allowed harmonics generated by conductor positioning errors. The magnetic shim location is indicated in Fig. 1. In Tab. 2 the changes of the low-order non-allowed harmonics produced by a single shim are given.

Table 2: Variation of sextupole and decapole at nominal current (10^{-4} units at R_{ref} = 22 mm) vs magnetic shim thickness.

mm	$\mathbf{\Delta b_3}$	$\mathbf{\Delta a_3}$	$\mathbf{\Delta b_4}$	$\mathbf{\Delta a_4}$
- 5	-0.49	0.22	-0.07	0.11
+ 5	0.96	-0.45	0.12	-0.22

Relative to the expected RMS spread σ (Fig. 2), independent corrections of b_3/a_3 in the range ± 4 σ and of b_4/a_4 in the range ± 2 σ are possible with 8 tuning shims at operational conditions [16]. Due to saturation effect, the field errors at injection cannot be reduced with this method. However, the field quality of the IR quadrupoles at injection is not critical for the machine.

FUTURE PLANS

In order to test the assembly procedure and to check the stress distribution at full pre-compression after cool-down, a mechanical model of the quadrupole loading structure will be fabricated (Fig. 4). The model will incorporate the components of the proposed quadrupole design; an aluminum tube will replace the coil. This inner tube and the outer shell will be instrumented with strain gauges. The recorded data will be compared to the computed stresses.

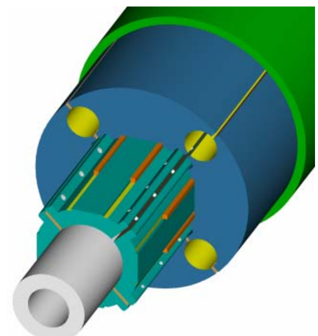

Figure 4: Mechanical model of the quadrupole.

CONCLUSIONS

An analysis of the field quality in the next generation LHC IR quadrupole has been performed. The study focused on field errors that may arise from fabrication tolerances of the components and from misalignments of the yoke. Changes in coil cross-section and magnetic shims were proposed as a correction strategy for the allowed and low-order non-allowed harmonics.

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