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Conceptual Design of a 70 mm Aperture Quadrupole for LHC Insertions *

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Abstract – Due to their detrimental effect on the LHC dynamic aperture, the random multipole errors of the LHC insertion quadrupoles need to be lower by a factor of five than the corresponding errors in the lattice. For achieving this level of random errors, we propose to increase the aperture of the insertion quadrupoles. A novel approach for achieving a quadrupole strength of 250 T/m in an aperture of 70 mm, based on a graded multi-layer coil wound from NbTi conductor cooled at 1.8 K, has been investigated. The design concept of the coil, which incorporates a shell-like structure composed of a high current density block imbedded in a low density shell, is developed. The coil design, parameters of the superconducting cable, and the yoke and collar design are described, both for a two-in-one and a single quadrupole geometries.

I. INTRODUCTION

The Large Hadron Collider (LHC) [1], proposed as the future extension of the CERN accelerator complex, has been accompanied by an intensive superconducting magnet development program [2]. Recent studies of the dynamical aperture of the LHC have drawn attention to the fact that the quality of the internal triplet quadrupoles in the current arrangement of the cleaning and dump insertions may be the limiting factor of the machine performance [3]. In fact, if the dynamic aperture is to be dictated by the lattice magnets, then the b_7 and b_9 random errors of the inner triplets of the dump and cleaning insertions need to be reduced approximately by the ratio of the respective β_{max} values in the arcs and insertions, i.e. by a factor of $\simeq 1/5$. As the random errors in these multipole coefficients are already assumed quite small, $1\text{--}2 \cdot 10^{-6}$ at 10 mm radius, this requirement is clearly not trivial.

One of the possibilities is to profit from the scaling laws to reduce the random multipole errors by increasing the aperture of the insertion quadrupoles. In this case, for reasons related to the LHC two-in-one magnet design, it would be preferable not to substantially increase the outer diameter of the coil. Under these constraints, a possibility to achieve the nominal insertion quadrupole strength of 250 T/m is to grade the coil. Hence the question: to what

extent can grading of the coil help in increasing the coil aperture beyond 56 mm of the lattice quadrupoles?

This aspect of the quadrupole design was treated in a recent note [4], where the effects of different current densities in the coil blocks, in view of balancing otherwise large differences in field margins of the conductors at the edge and in the bulk of a uniform current density quadrupole coil, were analyzed. These studies indicated that with two graded layers, the aperture of the LHC type quadrupole can be increased to about 65 mm, but that a considerable improvement in quadrupole strength, or in operational safety, can be achieved with a shell-like structure, where a low density shell encloses and magnetically shields the high density block. In this case, under certain conditions on coil splitting and current density ratio in the blocks, a 250 T/m quadrupole strength may be achieved in a coil aperture of 70 mm. Furthermore, this analysis indicated that several coil configurations, optimized for low systematic multipole errors, result in equivalent magnetic performance, so that the block configuration may be chosen on the basis of ease of construction of the quadrupole.

In this report, as an alternative to previous studies [5], the principle of a graded-shell coil structure is applied in the case of a single and two-in-one quadrupoles with an aperture of 70 mm, which are of interest for the LHC cleaning, dump and low- β experimental insertions.

II. COIL DESIGN

A. General Principles

In order to achieve high magnetic field gradients in a large aperture quadrupole, we propose a configuration with two arched layers. The outer layer is divided in two blocks, so that the inner layer and the outer block form a low current density shell, which contains the inner, high density block. In this concept, the inner layer should be ideally arched, with a maximum packing factor. Only in this case can a high average current density and a high field gradient be achieved.

Besides these guidelines, the following criteria for quadrupoles under consideration here, based on the performance of LHC NbTi cables at 1.8 K [2], should be ob-

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served:

- Current densities less than 500-550 A/mm² in the low density blocks, and 800-850 A/mm², in the high density block.
- Ratio of current densities lower than 1.8. (This value depends on the ratio of layer widths, and is lower for a shallow shell).
- Block angles in the range of 20-24 degrees for the high density and 32-36 degrees for the low-density blocks.

A graded-shell quadrupole coil is schematically shown in Figure 1. Given the coil internal and external radii, the coil splitting ratio $\Delta r_2/\Delta r_1$, the angles defining the three blocks, $\theta_1 - \theta_4$, and the ratio of current densities j_2/j_1 may be used to minimize the multipole errors and to adjust the quadrupole transfer function. Depending on the relation between the limiting block angles, ($\theta_3 = \theta_4$, $\theta_3 > \theta_4$, or $\theta_3 < \theta_4$) several solutions satisfying the requirements on field quality and quadrupole strength are possible.

Figure 1: The geometry of a graded-shell quadrupole

B. Block Definition and Cable Parameters

After considering possible winding procedures, we have chosen to pursue the analysis of the 70 mm aperture graded-shell quadrupole for the LHC insertions on the basis of the following:

- low density blocks wound from identical cable in double pancake technique
- internal splice between high and low density blocks
- Blocks 1 and 2 wound as arches
- excitation current of the order of 5000 A

The first of these choices suggests a coil layout in which low density Blocks 1 and 3 are wound starting from a planar pole surface ($\theta_3 = \theta_4$). The second implies that the

high density Block 2 is wound from an odd number of conductor layers; for the imposed excitation current, three layers are necessary. Finally, due to their arched structure, the widths of Blocks 1 and 2 determine the keystone angle, and the cable parameters in general.

In principle, the width of the low density cable (Cable 1) is chosen in accordance with the desired excitation current. However, a wide Cable 1 implies a large inner radius of Block 2, and a narrow high density cable (Cable 2). Both of these factors influence the keystone angle and the strand diameter of Cable 2. Thus, the requirement of arched windings constrains the width of Cable 1 to less than 9 mm. The lower limit is derived from the shielding efficiency of Block 3, and equals 4 mm. Based on these considerations, we have chosen a width of 6.7 mm for both cables. With a current density ratio of 1.55, this particular choice corresponds to the coil splitting which results in the lowest attainable systematic multipole errors, $b_6 \equiv 0$, $b_{10} \simeq 3 \cdot 10^{-7}$ and $b_{14} < 10^{-9}$.

When determining the block angles, it should be noted that there is no unique solution to the general problem of multipole compensation in a graded quadrupole, and that the block angles $\theta_1 - \theta_4$ which minimize systematic b_{10} and b_{14} errors with the b_6 multipole constrained to zero, are within an interval which depends on the allowed b_{10} error. For b_{10} below 10^{-6} , this interval is narrow, but nevertheless sufficiently wide to give some flexibility in the choice of fabrication techniques. As criteria for selecting a particular block arrangement, number of turns per block and cable parameters, we have considered the following :

- number of turns in Block 3 within 5% of the fractional turn number
- number of turns in Block 2 giving a current density within 5% of the nominal value
- minimal width of multipole compensation wedge between Blocks 2 and 3 greater than 0.5 mm

In conjunction with the excitation current, these requirements, which in fact preserve the low multipole content of the coil when passing from an idealized block geometry to a realistic conductor arrangement, considerably reduce the choice of block and cable parameters. After a thorough analysis, the block layout which is considered satisfactory both in terms of field quality and cable parameters, is shown in Figure 2. The block geometry and the multipole coefficients of the quadrupole field for the $\mu \rightarrow \infty$ approximation of the yoke are given in Tables 1 and 2. The parameters of the cables for the proposed graded-shell quadrupole, chosen on the basis of similarity with successfully employed cables, are given in Table 3.

Table 1: Block parameters

Block	Turns	r_{i1} (mm)	α_i (deg)	ϕ_i (deg)
1	16	35.00	0.00	0.00
2A	16	42.58	0.00	0.00
2B	19	50.16	0.00	0.00
2C	21	57.74	0.00	0.00
3	6	42.58	23.535	21.270

Table 2: Systematic multipoles at $r_0 = 10$ mm for nominal excitation of 5047 A

Multipole	B_n (T)	b_n (units)
2	-2.500552	10000.
6	-0.000014	-0.0548
10	0.000002	-0.0076
14	0.000001	-0.0006

C. Estimate of Random Multipole Errors

The estimate of random multipole errors was made on the basis of random modification of coil geometry. The model employed assumes that the cable, insulation and manufacturing tolerances of the blocks are statistically uncorrelated. Modifications in quadrant windings result then from a random choice of the insulated conductor and wedge dimensions, and of the block positions. Having in mind the prestress in the coil, it is assumed that the conductors are always in contact and that they build up at the coil-collar interface within collar tolerances. Furthermore, no interference at facing quadrant surfaces is allowed.

Of all the errors, the tolerances in conductor width are found to have by far the largest influence on the random multipoles. For conductor width tolerance of 0.1 mm, the b_7 and b_9 random errors are 0.017 and 0.0014 units,

Figure 2: Block layout of the graded-shell quadrupole

Table 3: Parameters of Cables 1 and 2 proposed for the graded-shell quadrupole (all dimensions in mm)

Parameter	Cable 1	Cable 2
No of strands, n	18	28
Strand diameter, d	0.73	0.47
Cu/SC Ratio	1.6	1.6
Minor edge, h_1	1.11	0.74
Major edge, h_2	1.37	0.88
Mid-thickness	1.24	0.81
Width, w	6.7	6.7
Cross-section	8.31	5.43
Minor edge ratio ¹⁾	0.76	0.79
Major edge ratio ²⁾	0.94	0.94
Width ratio ³⁾	1.02	1.02
Keystone angle (deg)	2.25	1.20
Packing factor ⁴⁾	0.93	0.90
Twist pitch	65	60
Cabling angle, ψ (deg)	12	13

$$1) \frac{h_1}{2d} \quad 2) \frac{h_2}{2d} \quad 3) \frac{2w}{nd} \quad 4) \frac{n\pi d^2}{2w(h_1+h_2)\cos\psi}$$

which is only 5% lower than when all block and conductor tolerances are set to 0.1 mm. It is clear then that for the required level of random multipole errors, the tolerances of conductor dimensions must be very tight. In the case of standard LHC cable tolerances of 0.02 mm, and with the block positioning tolerances of 0.1 mm and 0.05 deg, the b_7 and b_9 random multipole errors are lower than 0.005, as required. The random multipole errors, based on 1000 quadrupole random configurations are shown in Table 4.

Table 4: Random multipole errors at nominal current

Multipole	b_n (units)	a_n (units)
1	6.33612	6.23686
2	0.00000	2.94669
3	0.96166	0.96393
4	0.21808	0.29295
5	0.08065	0.08228
6	0.03126	0.02265
7	0.00451	0.00410
8	0.00093	0.00097
9	0.00020	0.00021
10	0.00005	0.00005

III. YOKE DESIGN

In considering the yoke design of the 70 mm insertion quadrupoles, it has been assumed as a general guideline that the yoke should follow as much as possible, both

in concept and main parameters, the design of the main quadrupoles for the LHC. For these reasons, we considered in this conceptual design stage only those modifications which are a direct consequence of the larger aperture of the insertion quadrupole.

A. Two-in-one quadrupole

The present design of the LHC two-in-one lattice quadrupoles [6] features a beam-to-beam separation of 180 mm. For reasons of collar symmetry, the diameter of the coil assembly opening in the 70 mm quadrupole is taken as 180 mm also. The position and diameter of the cooling ducts, bus-bar passages, yoke mounting and alignment bars, and collar positioning pins are taken to be identical to those in the main quadrupoles. For design optimization, the yoke diameter, the width of the return yoke and the height of the insert between the two magnets have been considered as free parameters. A satisfactory design, shown in Figure 3, features a return yoke of 70 mm and an insert height of 30 mm. The outer diameter of the yoke is 500 mm as compared to 444 mm for the lattice quadrupole. In this design, the saturation reduces the quadrupole strength by 1.22% and induces a dipole field error corresponding to a misalignment of $33 \mu\text{m}$.

Figure 3: Layout of the 70 mm aperture two-in-one quadrupole for the LHC cleaning and dump insertions

B. Single quadrupole

The 70 mm aperture single quadrupole for the LHC low- β experimental insertions, Figure 4, follows the same design concept as the two-in-one quadrupole. The collared coil assembly is identical, while the outer diameter of the yoke is decreased to 360 mm. This is a consequence rather of the size of the cooling ducts, which are assumed to have the same diameter as in the LHC main dipoles and quadrupoles, than of the need to compensate the saturation effects in the yoke.

Figure 4: Layout of the 70 mm aperture single quadrupole for the LHC low- β experimental insertions

IV. CONCLUSIONS

Motivated by the requirements of low random multipole errors for the LHC cleaning and dump insertion quadrupoles, the concept of a graded-shell coil has been developed, which allows apertures up to 70 mm for 250 T/m quadrupole wound from a NbTi cable cooled at 1.8 K. Within this concept the design of a 70 mm aperture single and two-in-one quadrupoles, which seem appropriate for the LHC machine and experimental insertions, has been pursued. The design takes into account a number of technical requirements, such as the winding and joints techniques. A requirement with especially wide consequences is that of a low excitation current of around 5000 A, essential for stand-alone units, which leads to a four layer coil and stringent requirements on cable parameters and tolerances.

V. REFERENCES

- [1] The LHC Study Group, *Design Study of the Large Hadron Collider (LHC)*, CERN 91-03, May 1991.
- [2] R. Perin, "The Superconducting Magnet System for the LHC", *IEEE Trans. on Magnetics*, vol.27, pp.1735-1742, June 1991.
- [3] Z. Guo, T. Risselada, W. Scandale, "Dynamic Aperture of the CERN Large Hadron Collider with Injection Optics", *Particle and Field Series No. 48, Conf. Proc. No. 255*, AIP, New York, 1991, pp.50-65.
- [4] R. Ostojic, "Grading of the Coil: An Approach for Reducing Quadrupole Random Errors in the LHC Dump Insertion", *Internal Note CERN-AT/MA*, November 1991.
- [5] W. Scandale and T.M. Taylor, "A Design Concept for the LHC Insertion Quadrupoles", *Proc. 1991 IEEE Particle Accelerator Conference*, San Francisco, May 1991, vol. 4, pp.2260-2262.
- [6] J.M. Baze *et al.*, "Design and Fabrication of the Prototype Superconducting Quadrupole for the CERN LHC Project", *IEEE Trans. on Magnetics*, vol.28, pp.335-338, January 1992.