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SINGLE-LAYER HIGH FIELD DIPOLE MAGNETS*

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Abstract

Fermilab is developing high field dipole magnets for post-LHC hadron colliders. Several designs with a nominal field of 10-12 T, coil bore size of 40-50 mm based on both shell-type and block-type coil geometry are currently under consideration. This paper presents a new approach to magnet design, based on simple and robust single-layer coils optimized for the maximum field, good field quality and minimum number of turns.

1 INTRODUCTION

A large number of superconducting magnets required for a future Very Large Hadron Collider (VLHC) [1] makes it vitally important to simplify the design and develop manufacturing technology of main magnets, aimed at high reproducibility of magnet parameters, cost reduction, increasing their efficiency and reliability. The most critical part in the conductor-dominated superconducting magnets is a coil that serves as flux driving and field forming element. Usually the coil is subdivided onto several layers and blocks, whose position and size are optimized in order to achieve a required field and field quality in magnet aperture. It gives more free parameters for field tuning and also reduces the magnet operation current. On the other hand, it complicates the fabrication technology, increases fabrication time and cost, reduces accuracy of the turn/block position because of accumulation of many small errors, puts restrictions on the magnet length due to quench protection problems, etc. Experience with the single-layer RHIC magnets [2] demonstrated significant technical and economical advantages of reducing a number of layers in coils. This approach was successfully used in the Nb_3Sn single-layer common coil dipole developed for VLHC [3,4].

The approach described in this paper expend the single-layer concept to high filed accelerator magnets and, in addition to a minimization of number of layers, also involve a minimization of number of blocks and turns in the coil. Although a small number of turns will leads to a high magnet operating current, a recent progress in the semiconductor technologies, HTS current leads and superconducting power transmission lines reduces the importance of these limitations for modern and future accelerators [1].

2 MAGNET DESIGNS

The design goals were reaching the field of 11-12 T in 40-50 mm bore Nb3Sn dipole magnets with a single-layer coil and a minimal number of turns. The number of turns was reduced to a value, required for achieving a desired field and field quality by increasing the cross-section area of a single cable.

Two types of single layer coils (cos-theta and block) were considered in this study and referred as design I and design II. The coil cross-section was optimized using the ROXIE code [5] with round inner surface of the iron yoke and iron permeability μ_r=1000. The iron yoke designs and results of their optimization are reported elsewhere [3].

2.1 Coil cross-section

Figure 1 presents the optimized coil cross-sections with the field quality diagrams. Magnet parameters are summarized in section 2.3.

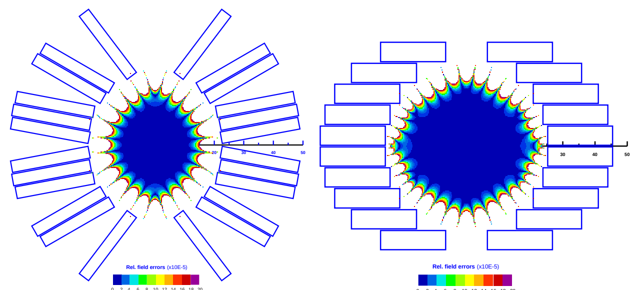

Figure 1: Coil geometry and field quality:
(design I – left, design II - right)

The design I coil is based on the shell type (cos-theta) geometry with turns distributed azimuthally on a round surface forming the coil bore. In order to approximate the cos-theta azimuthal current distribution minimum six turns grouped in tree blocks per quadrant as shown in Figure 1 (left) are required. The chosen coil bore diameter of 45 mm and the target field of 12 T defines the cable thickness of 2.200 mm and width of 26.717 mm for 0.25-mm thick insulation. A rectangular cable was used in this design based on the fabrication considerations that will be explained in the next section. The azimuthal block position and block tilt angle were optimized for the best field quality in the bore. The slightly elliptical coil bore helps increasing the coil efficiency and also reaching better field quality with respect to the round bore.

The design II coil is based on the block type geometry with turns positioned horizontally and stacked in one block (see Figure 1, right). In order to approximate the cross-section area of two intersecting ellipses five turns were chosen. The chosen number of turns, the coil bore diameter and the target field define the cable thickness of 3.350 mm and width of 20.233 mm for 0.25 mm thick cable insulation. The horizontal shift of each turn was optimized for the best field quality in the bore.

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2.2 Coil support structure and fabrication

Figure 2 shows possible coil support structures for the design I and design II.

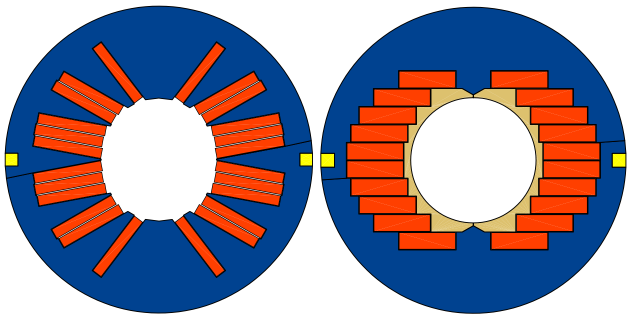

Figure 2: Collared coil mechanical structures.

The coil support structure for design I consists of collar laminations with rectangular slots for each block similar to stators of electrical motors. These slots unsure the nominal position of turns. The parts of collar separating the coil blocks provide a stress management preventing an accumulation and transfer of the azimuthal component of Lorentz force to the midplane blocks. In case of design II coil support structure consists of outer collar laminations and an inner insert. The collars and inner insert have rectangular steps for placing of each turn in the coil in their nominal position. The inner inserts also serves for the reaction of the vertical component of Lorentz force maximum in the pole turns. The large horizontal component of Lorentz forces will be reacted in both designs by the iron yoke and thick outer skin.

Due to small bending radii of turns in coil ends the design I is better suited for the wind & react fabrication technique. Each half-coil is wound directly into the coil support structure. After that, the two collared half-coils are assembled around the mandrel and collars are locked together by keys, providing some small radial prestress. All the gaps between turns and collar necessary for the easy turn installation into the slots will be removed and some small azimuthal prestress in each block can be created due to the Nb_3Sn cable expansion during reaction. After reaction the collared coil will be impregnated with epoxy and assembled with iron yoke.

The horizontal turn orientation in design II coil makes it well suited for the react & wind fabrication technique in the common coil configuration. Two coils are wound simultaneously into the coil support structure similar to the technique developed for the single-layer common coil dipole [4], slightly prestressed in vertical and horizontal directions, impregnated with epoxy and assembled with iron yoke.

2.3 Magnet parameters

Table 1 presents the major magnet parameters. These parameters were calculated at 11 T bore field with a round inner surface of the iron yoke and low constant iron permeability μ~5 chosen to fit the finite element results.

Table 1: Magnet parameters

Parameter	Unit	Design I	Design II
Coil bore in midplane	mm	45.0	50.0
Available round bore	mm	45.0	45.0
No. of turns/aperture		12	10
Coil area/aperture	cm^2	22.6	22.8
Iron yoke ID	mm	120	110
Bore quench field	T	11.79	11.84
Maximum current	kA	81.36	92.28
Transfer function	T/kA	0.1352	0.1192
Inductance/aperture	mH/m	0.076	0.057
Stored energy/aperture	kJ/m	251.5	242.7
Horiz. force/quadrant	MN/m	2.62	2.62
Vert. force/quadrant	MN/m	1.07	1.10

Minimum distance of 8 mm between the outer coil and the inner yoke surface was the same as in the two-layer shell-type dipole model [3]. The quench field was calculated for Jc(12T,4.2K)=2000 A/mm^2 and Cu/nonCu=0.85:1.

Both designs have nearly the same coil bore diameter, coil areas and quench fields. These parameters are similar to the double-layer shell type magnet and exceed by 10-20% the corresponding parameters of the single-layer common-coil magnet [3]. Minimum number of turns in both designs result in low transfer functions and higher currents, which is however less than the 100 kA – the nominal current of the first stage VLHC magnets [1].

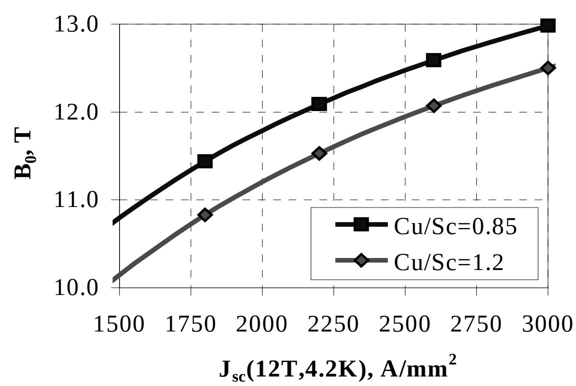

Figure 3: Bore quench field as a function of critical current density in the coil at 12 T and 4.2 K.

The maximum (quench) field in the magnet aperture at 4.2 K vs. the critical current density of SC strands in the coil is shown in Figure 3. For the expected critical current density in Nb_3Sn strands of 3000 A/mm^2, Cu:nonCu=1.2:1 required for magnet quench protection and critical current degradation in the coil ~10% for the design I (wind and react approach) and 15% for the design II (react and wind approach and common coil configuration) the maximum bore field is 12.2 T and 12.0 T respectively. It meets the VLHC stage II requirements and provides 20% critical current margin.

Table 2 summarizes the systematic and random geometrical field multipoles due to ±50μm random turn displacements.

Table 2: Relative field multipoles @ 1 cm in 10^{-4}

n	Design I		Design II	
	b_n	σ_{an}/σ_{bn}	b_n	σ_{an}/σ_{bn}
1	10000	1.66/-	10000	2.05/-
2	-	0.92/1.02	-	1.01/1.07
3	-0.0001	0.47/0.47	0.0005	0.49/0.47
4	-	0.21/0.22	-	0.18/0.19
5	0.0011	0.09/0.10	0.0003	0.07/0.08
6	-	0.04/0.04	-	0.03/0.03
7	0.0019	0.02/0.02	0.0005	0.01/0.01
8	-	0.01/0.01	-	0.00/0.00
9	-0.0035	0.00/0.00	0.0008	0.00/0.00
10	-	0.00/0.00	-	0.00/0.00
11	-0.0219	0.00/0.00	-0.0013	0.00/0.00

Design II has better field quality and as a result a larger good field region (see Figure 1) than Design I due to the larger number of free parameters available for adjusting the low order harmonics (five vs. three in design I). Nevertheless, both of the designs have excellent geometrical harmonics, better than previously developed Nb_3Sn magnets [3]. Possible restrictions of random turn motion in the precise collar structure described above offer a reduction of the harmonics RMS spread.

2.4 Strands and Cables

The parameters of the Rutherford type cables used in the design I and II are summarized in Table 3. Both cables have small aspect ratio that unsure good cable mechanical stability. However, such cables require quite large strands of 2-3.5 mm in diameter that is by factor of 2-3 larger than currently used Nb_3Sn strands. As a result, such cables may have rather high mechanical rigidity that may create some problems during coil winding. In case of the react and wind technique the large strand diameter would require too large bending radii or lead to the large critical current degradation.

Table 3: Cable parameters

Parameter	Units	Design I	Design II
Strand diameter	mm	2.200	3.350
No. of strands		24	12
Cable width	mm	26.717	20.233
Cable thickness	mm	3.942	5.935
Aspect ratio		6.78	3.41

In order to avoid the above problems and decrease the Nb_3Sn strand diameter to the level convenient for the magnet fabrication, multistage cable with sub-strands shown in Figure 4 can be used. Using such strands allows reducing Nb_3Sn strand diameter to the level of 0.7-0.45 mm comfortable for the strand production, increasing the cable mechanical flexibility and minimizing bending degradation. Combination of Nb_3Sn strands with quite low Cu:nonCu ratio and pure Cu strands allows achieving a Cu:nonCu ratio in final cable required for magnet quench protection and reducing the cable cost.

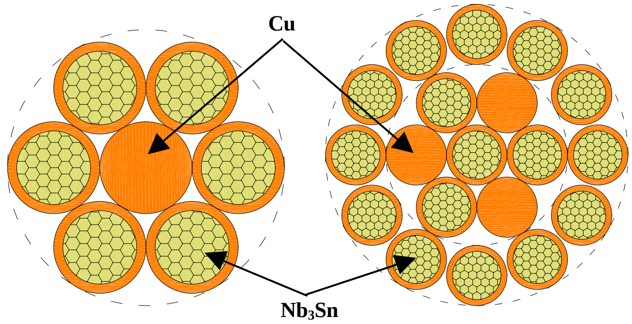

Figure 4: Examples of strand structure combined with copper and Nb_3Sn strands with low Cu:nonCu ratio.

3 CONCLUSIONS

High field dipoles based on the shell-type and block-type single-layer coils with minimum number of turns have been developed. Both designs achieves 11-12 T field level with Nb_3Sn coil and provides the accelerator field quality. A simple single-layer coil geometry and minimum number of turns allow significant reduction of manufacturing time and cost that is essential for magnet mass production. The collar structures, used also as a coil-winding fixture, provide precise conductors positioning and support. It offers improving a reproducibility of the field quality and quench performance. Magnet designs are well suitable for both "wind and react" and "react and wind" techniques. A low coil inductance simplify the problems related to the magnet quench protection.

Since both coils are based on the cable with a small aspect ratio, the cable width can be easy increased by factors of 1.5-2 to achieve higher fields. However, an increase of maximum field from 12 T to 14 T requires doubling the coil area. Using the SSC-type NbTi strands with a critical current density of 2750 A/mm^2 at 5 T and 4.2 K in these designs allow reaching the maximum bore field of ~7 T at 4.2 K, or ~10 T at 1.8 K.

4 REFERENCES

[1] Design Study for a Staged Very Large Hadron Collider, Fermilab-TM-2149, June 4, 2001.

[2] P. Wanderer et al., "Construction and testing of arc dipoles and quadrupoles for the Relativistic Heavy Ion Collider (RHIC) at BNL", Proc. of the 1995 Particle accelerator conference and International conference on High-Energy Accelerators, v. 2, p.1293, May 1995.

[3] V.V. Kashikhin, A.V. Zlobin, "Magnetic designs of 2-in-1 Nb_3Sn dipole magnets for VLHC", IEEE Transactions on Applied Superconductivity, Vol. 11, No. 1, 2176, March 2001.

[4] I. Novitski et al., "Design and mechanical analysis of a single layer common coil dipole for VLHC", IEEE Transactions on Applied Superconductivity, Vol. 11, No. 1, p. 2276, March 2001.

[5] S. Russenchuck, "A Computer Program for the Design of Superconducting Accelerator Magnets", CERN AT/95-39, LHC Note 354, Geneva, Switzerland, 26 September 1995.