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. A coil is the most critical part in the conductor-dominated superconducting magnet that serves as flux-driving and field-forming element. Usually the coil is subdivided into 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 the necessary free parameters for field tuning and also reduces the magnet operation current. On the other hand, it complicates the fabrication technology, increases manufacturing time and cost, reduces accuracy of the turn/block position due to accumulation of many small errors, sets 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 reduction a number of layers in coils. This approach is being used in the Nb_3Sn single-layer common coil dipole developed for VLHC [3,4].

This paper further expands the single-layer concept for minimum number of blocks and turns in both shell and block-type geometry. Although a small number of turns leads to a high magnet operating current, a recent progress in the power converters, HTS current leads and superconducting power transmission lines does not make it and issue for modern and future accelerators [1].

2 MAGNET DESIGNS

The design goal was reaching the field of 11-12 T in 40-50 mm bore Nb_3Sn dipole magnets with single-layer coils and a minimum number of turns. The number of turns was reduced to a value, required for achieving the desired field level and quality by increasing the cross-section area of a single cable.

Two types of single layer coils (shell and block) were considered in this study are referred to 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 constant permeability μ_r=1000. The iron yoke designs and 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.

The design I coil is based on the shell-type (cos-theta) geometry with turns azimuthally distributed on an elliptical surface forming the coil bore. In order to approximate the cos-theta current distribution a minimum of six turns grouped into three 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 drives the cable thickness to 2.200 mm and width to 26.717 mm. A rectangular cable shape used in this design was based on the fabrication consideration that is explained in the next section. The azimuthal block positioning and tilt angles were optimized for the best field quality in the bore. A slight ellipticity of the coil helps increasing the field quality with respect to a round bore case.

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 ideal cross-section area of two intersecting ellipses, five cables per coil quadrant were chosen. Such number of turns, the coil bore diameter of 50 mm and the target field of 12 T drive the cable thickness to 3.350 mm and width to 20.233 mm. The horizontal shift of each turn was optimized for the best field quality in the bore.

The cable insulation thickness was 0.25 mm in both designs.

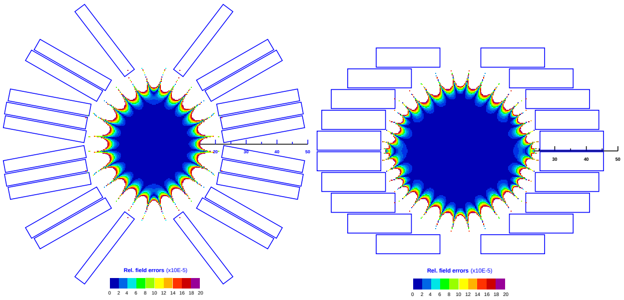

Figure 1: Coil geometry and field quality: (design I – left, design II - right)

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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.

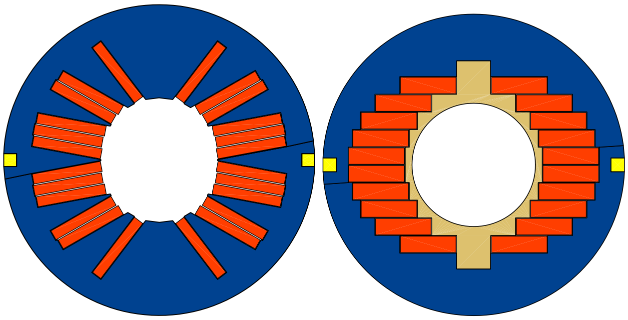

Figure 2: Collared coil mechanical structures.

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 ensure 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 the coil support structure consists of outer collar laminations and an inner insert. The collars and inner insert have rectangular steps for placing of each coil turn in its nominal position. The inner inserts also serve for interception of the vertical Lorentz force component, which is maximal in the pole turns. The horizontal Lorentz force component is constrained by the iron yoke and outer skin in both designs.

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]. A minimum number of turns in both designs leads to low transfer functions and high current, which is however less than 100 kA – a nominal current of the first stage VLHC magnets [1].

The maximum (quench) field in the magnet aperture at 4.2 K as a function of the critical current density in strands is shown in Figure 3. For the expected critical current density in Nb_3Sn strand 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 for common-coil configuration) the maximum bore fields are 12.2 T and 12.0 T respectively. It meets the VLHC stage II requirements and provides 20% bore field margin.

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

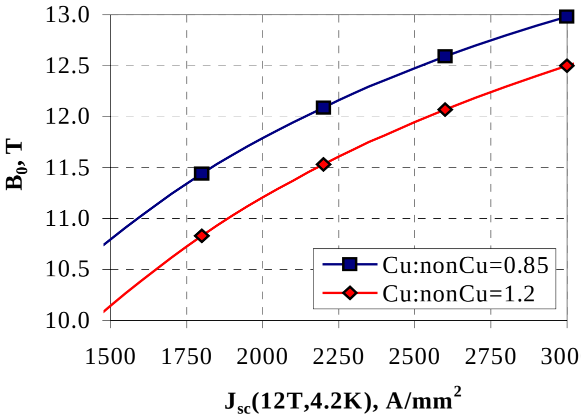

Figure 3: Bore quench field as a function of critical current density in the coil at 12 T and 4.2 K.

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

As it can be seen from table above, Design II has a better field quality and a larger good field region (see Figure 1) than Design I. Nevertheless, both of the designs have excellent geometrical harmonics, better than in 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 II and I 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 a level convenient for the magnet fabrication, multistage cable with sub-strands shown in Figure 4 can be used. Such strands allow reducing Nb_3Sn strand diameter to a level of 0.7-0.45 mm, comfortable for the strand production, increasing the cable mechanical flexibility and minimizing bending degradation. Combination of the Nb_3Sn strands with minimum Cu:nonCu ratio necessary for the strand production and pure Cu strands allows achieving a Cu:nonCu ratio in final cable required for magnet quench protection and reducing the cable cost.

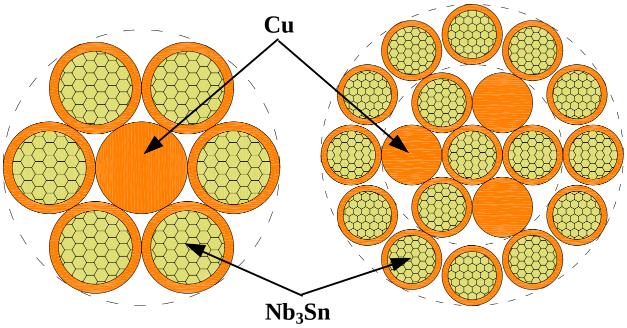

Figure 4: Examples of combined strand structures made of copper and Nb_3Sn strands with low Cu:nonCu ratio.

3 CONCLUSIONS

High field dipoles based on the shell-type and block-type single-layer coils with a minimum number of turns have been developed. Both designs achieve 11-12 T field level with Nb_3Sn coil and provide 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 coil-winding fixtures, provide precise conductors positioning and support. It offers improving a reproducibility of the field quality and quench performance. Coil designs are well suited for both “wind and react” and “react and wind” techniques. A very low coil inductance simplifies 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 of 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 allows reaching the maximum bore field of ~7 T at 4.2 K or ~10 T at 1.8 K.

4 REFERENCES

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