DESIGN AND DEVELOPMENT OF Nb_3Sn SINGLE-LAYER COMMON COIL DIPOLE MAGNET FOR VLHC*

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Abstract

Common coil dipole magnets based on Nb_3Sn conductor and the react-and-wind technology are a promising option for the next generation of hadron colliders. The react-and-wind technology has potential cost benefits related to less expensive cable insulation, structural materials and magnet fabrication. A common coil design allows the use of pre-reacted Nb_3Sn superconductor with low critical current degradation after bending. Fermilab in collaboration with LBNL is involved in the development of a single-layer common-coil dipole magnet with maximum field of 11 T and 40-50 mm aperture for a future VLHC. This paper reports the current magnetic and mechanical designs of the dipole model, the magnet parameters and the status of the program.

1 INTRODUCTION

The design study of a staged Very Large Hadron Collider (VLHC) has been recently accomplished at Fermilab [1]. The goal is to build a 40 TeV collider (stage 1), in a 233 km long tunnel, that will become, in a second phase, the injector to a 175 TeV collider (stage 2) installed in the same tunnel. The stage 2 collider will require arc dipoles with a nominal operating field of 10 T in a bore aperture ≥ 40 mm, operating at 4.5 K. The study foresees the use of single-layer common coil dipoles with coils made of Nb_3Sn superconductor. The use of pre-reacted Nb_3Sn allows cost savings in the insulating materials, in the structural materials and in the fabrication. A single-layer design has a lower inductance than similar two-layer designs and allows the adoption of longer magnets with the same maximum voltage during a quench. The design developed at Fermilab, introducing collars reinforced by bridges, was presented in [2,3]. The current magnet design, the assembly procedure and the status of the program are presented. Quench protection issues are discussed in [4].

2 MAGNETIC DESIGN

A 3D view of the single-layer common coil dipole magnet for VLHC is shown in Figure 1. The cable, 22 mm wide, consists of 60 strands with 0.7 mm diameter. The coil and yoke geometry were re-optimized with respect to the previous version [2], in order to provide the required field quality within 0-11 T field range with a modified collar structure. In particular, the number of turns per coil was increased from 56 to 58 in order to increase the maximum field and optimize the block sizes.

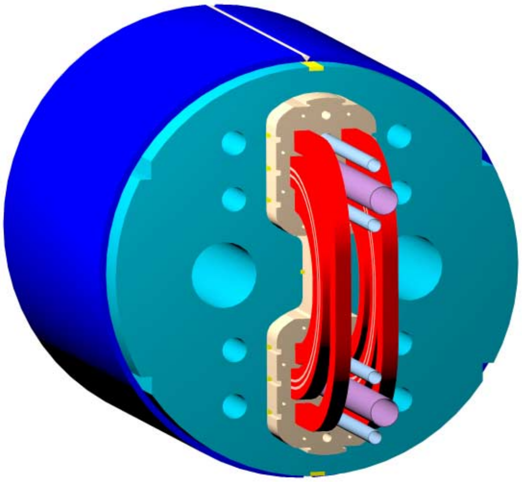

Figure 1: 3D view of the single-layer common coil dipole magnet.

The large 90 mm diameter holes in the magnet midplane were introduced for correction of the skew quadrupole caused by the iron yoke saturation. Simultaneously they serve as helium and electrical bus channels. The small holes close to the coil are used for correction of the sextupole component. Optimizing the hole size and position along with bore separation distance and yoke outer diameter made it possible to restrict skew quadrupole and sextupole deviations in 0-11 T field range.

The main magnet parameters are listed in Table 1. A critical current density (J_c) of 2400 A/mm^2 at 12 T and 4.5

Table 1: Magnet parameters

Parameter	Unit	Value
Aperture	mm	40
Bore separation distance	mm	290
Number of turns per coil		18+22+18
Conductor area per aperture	cm^2	27.7
Bore quench field	T	10.85
Quench current	kA	25.6
Transfer function	T/kA	0.424
Inductance per aperture @ 11 T	mH/m	1.475
Stored energy per apert. @ 11 T	kJ/m	496

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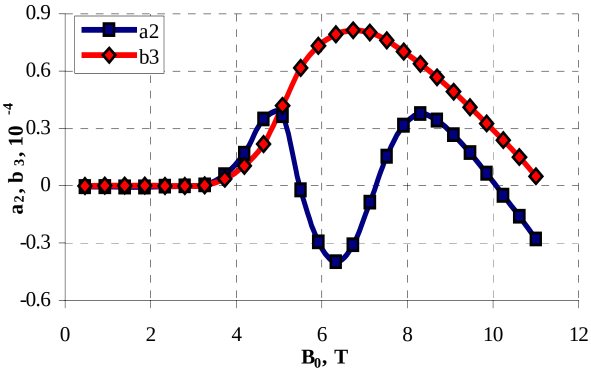

Figure 2: Field multipoles as function of bore field.

K was used for quench field calculation, assuming a strand J_c equal to 3000 A/mm^2, minus 20% for total degradation. Copper to non-copper ratio was 1. The maximum field of 10.85 T meets current VLHC requirements [1] providing 8.5% critical current margin which could be further augmented with an increase of the critical current density of the Nb_3Sn superconductor.

Table 2 summarizes geometrical and random field multipoles, calculated at low field and Figure 2 shows low-order multipole deviations due to the yoke saturation effect. The estimated value of the persistent current effect at 1 T field is $-1.5 \cdot 10^{-4}$ of sextupole [5], which is acceptable and does not require any special correction.

Table 2: Relative geometrical field multipoles @ 1 cm (10^{-4} unit). Random block displacements within ± 50 μm.

Order	Systematic		RMS
n	a_n	b_n	$\sigma_{an,bn}$
2	-0.0058	-	1.040
3	-	-0.0008	0.360
4	-0.0034	-	0.141
5	-	0.0011	0.046
6	0.0002	-	0.017
7	-	0.0031	0.006
8	0.0120	-	0.003
9	-	-0.0282	0.002
10	0.0003	-	0.000

3 MECHANICAL DESIGN

The large magnetic forces at maximum field (Fx=2949 kN/m, Fy=-1466 kN/m per aperture quadrant) require a strong mechanical structure in order to avoid an excessive stress in the coils and to restrain coil displacements within the acceptable limit for field quality. The laminated stainless steel collars reinforced by horizontal bridges, and a 10 mm thick stainless steel skin welded under a press are used for this purpose. The current mechanical structure with modified (with respect to the previous version [6]) collar laminations is shown in Figure 3. The collar and bridge laminations form a frame with rectangular windows for the coil blocks and round holes for the beam pipe and the cooling channels. This allows a redistribution of pre-compression during coil assembly and reduces the risk of damaging the brittle Nb_3Sn. During operation the frame intercepts a significant part of the horizontal component of the magnetic forces, reducing the force transferred to the yoke and skin. It also prevents an accumulation of the vertical component of the magnetic forces from one coil block to another.

The stress analysis [3] confirmed an acceptable maximum stress in the coils at all conditions (70 MPa after cooling down and 130 MPa at 11 T). All the structural elements operate in an elastic regime, and the coil displacements in the operating field range do not exceed 65 μm.

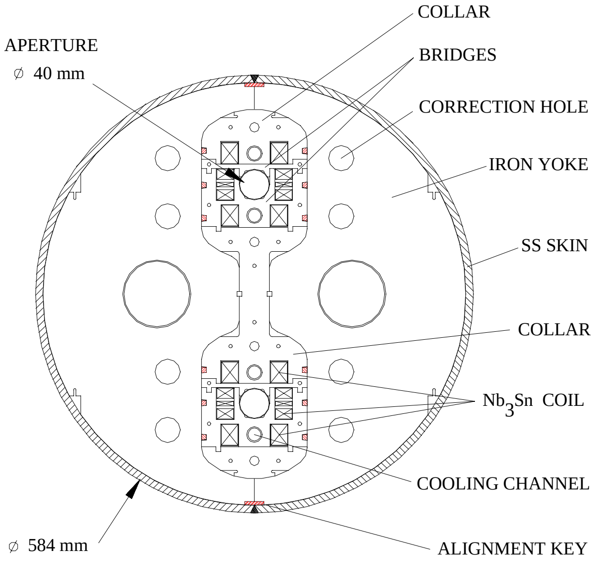

Figure 3: Magnet cross section in the straight section

Also in the ends each coil is divided into three blocks as is shown in Figure 4 for the return (non-lead) end. Each coil block is wound into a U-shaped groove in the stainless steel blocks that contain the horizontal component of the magnetic forces. The end blocks are reinforced by side plates in order to increase the stiffness of the end section.

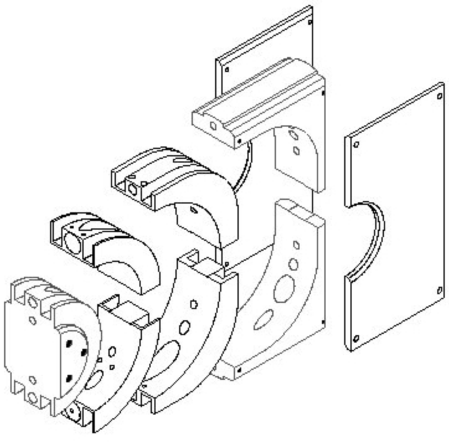

Figure 4: End parts (return end).

4 ASSEMBLY PROCEDURE

(i) Heat treatment and insulation: The cable for each coil is wound on a single-turn metallic spool resulting in a pancake-like winding. A mica-glass tape is wound together with the cable, in order to prevent sintering during the heat treatment. After the heat treatment, performed in an Argon atmosphere inside a retort, the cable is insulated using a 50 μm thick 12.5 mm wide E-glass tape with 50% overlap. Horizontal rollers set very close to the insulation application point prevent strands from popping out and protect the reacted cable. During insulation and winding the cable is straightened but never bent in the direction opposite to the bending during the heat treatment. The bending strain is minimized by using a reaction spool with a diameter that is twice the minimum diameter in the coil ends.

(ii) Winding and collaring: Coils are wound simultaneously into the collars in order to insert the bridges during winding. The collars consist of 2 mm thick laminations, spot welded to form 10 cm thick packages. Two independent tensioners are used to apply a tension of 15 kg to each cable. The ground insulation consists of two layers of Kapton with a layer of fiberglass in between. The layers are shaped in such a way that the fiberglass layer provides a channel for epoxy during impregnation. Mold release is applied on the Kapton layers in order to prevent bonding of the coils to the collars. After winding the innermost block of both coils, the collaring fixture is assembled around the coils. The first bridge and the first end part are inserted and the collaring fixture is used to lock them in the nominal position by means of keys. The fixture is then removed in order to wind the second block. The second bridge, the outermost part of the collars and the other end parts are inserted following the same procedure.

(iii) Impregnation and yoking: The collared coils are vacuum impregnated with CTD-101K epoxy. Impregnation is performed in a bath by slowly filling a box, slightly inclined, which contains the coils. After cleaning the collared coils of extra epoxy the yoke is assembled and the 10 mm thick skin is welded under a press.

5 STATUS OF PROGRAM AND PLANS

The first part of the R&D was centered on the cable development for the react-and-wind technology, and resulted in the choice of 0.7 mm wire, in the use of synthetic oil during heat treatment, and in the rejection of a stainless steel core (total degradation ≤ 20%) [7]. Further cable R&D was focused on the 60 strand cable. ITER leftover wire was used to optimize cable design and production and 450 meters of cable were made in a continuous run without any problem. Wire from Oxford Superconducting Technologies was then used and the cabling degradation was measured to be about 6%. A racetrack magnet consisting of two flat coils with a 5 mm separation was assembled and is being tested. Its design includes many features of the single-layer common coil: reacted and wound Nb_3Sn cable (wire from Intermagnetics General Corporation), winding of coils inside the mechanical structure and in-situ impregnation.

The engineering design of the first short common coil model and its tooling has been completed and procurement is on course. The fabrication will start this summer. Meanwhile a mechanical model, using cable made with ITER wire, is being assembled and tested. It consists of two different collar designs, and will be used to choose the best collar (for rigidity and simplicity of assembly), to check assembly procedures (excluding end parts) and to compare stress distribution (after assembly and cooling down at 4.2 K) with finite element analyses. A practice winding, using the parts procured for the first short model and a cable made with ITER wire, will be assembled (but not impregnated) in order to test winding and assembly procedures including the ends.

The present design has inherent capabilities for further improvement: bore size may be increased up to 50 mm by slightly bending the cables of the outer blocks around the beam pipe, and bore separation could be reduced, decreasing magnet outer diameter and weight. These and other issues will be addressed during the short model R&D phase.

6 CONCLUSION

The design of a single-layer common coil dipole using Nb_3Sn conductor and the react-and-wind technology was completed at Fermilab. This design meets the current VLHC requirements (10 T nominal field, aperture ≥ 40 mm) and has inherent capabilities for further improvement. An intense R&D program is underway and the production of the first short model is close to start.

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