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COMMON COIL MAGNET SYSTEM FOR VLHC*

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Abstract

This paper introduces the common coil magnet system for the proposed very large hadron collider (VLHC) [1]. In this system, the high energy booster (HEB), the injector to VLHC, is integrated as the iron dominated low field aperture within the coldmass of the common coil magnet design introduced earlier [2]. This 4-in-1 magnet concept for a 2-in-1 machine should provide a major cost reduction in building and operating VLHC. Moreover, the proposed design reduces the field quality problems associated with the large persistent currents in Nb$_3$Sn magnets. The paper also shows that the geometric field harmonics can be made small. In this preliminary magnetic design, the current dependence in harmonics is significant but not unmanageable.

1 INTRODUCTION

The efforts are underway to prepare a proposal for VLHC to be built after the completion of the Large Hadron Collider (LHC) at CERN. The main challenge is to develop approaches that would significantly reduce the cost [3]. The superconducting magnets [4] are the single most expensive and perhaps technically most challenging component of the high field option. In addition to the cosine theta designs [5], the other design approaches can be broadly divided in two categories. The low field design based on the low cost transmission line iron dominated magnet that is being pursued at FNAL [6] and the high field design based on a common coil geometry that is being pursued at LBNL [7,8] and BNL [9].

The common coil design [2] offers the possibility of a simple, high field, low cost magnet construction based on the racetrack coil geometry. This design, developed independently, has some features similar to the design presented earlier by Danby [10]. The block coil geometry is also favored for containing the large Lorentz forces generated by high fields. Moreover, the bend radius in the ends of common coil magnets is large as it is determined by the spacing between the two apertures rather than the size of aperture. This is an important consideration in high field magnets that must use brittle superconductors (Nb$_3$Sn or HTS) and may also use the "React and Wind" technology. The modular nature of the design also offers a unique facility to embark on a systematic and innovative magnet R&D.

2 COMMON COIL MAGNET SYSTEM

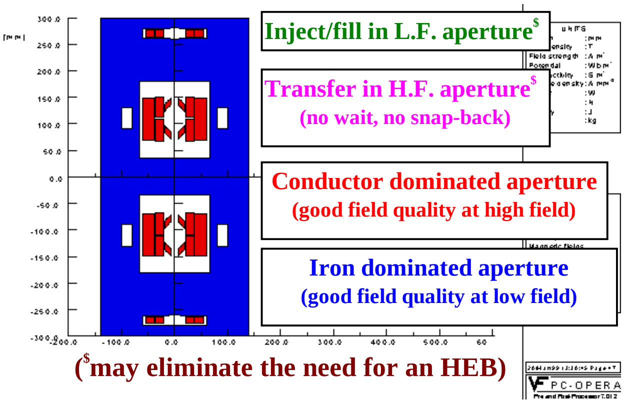

Figure 1: The common coil magnet system concept.

The proposed common coil magnet system concept is shown in Fig. 1. This has a total of four apertures: two iron dominated low field apertures (upper most and lower most) and two conductor dominated high field apertures (in the middle). The windings of one of the two pole blocks of the high field aperture (the one that is away from the center of coldmass) returns in the low field aperture and generates a part of the field. In the high field aperture, all racetrack coils are placed vertically with large bend radius and none cross the aperture horizontally. The later would have necessitated a small bend radius and eliminated various possibilities that exist now. The outer coil of the low field aperture may be independently powered for flexibility and/or de-linking the field between the low field and the high field aperture. In that case, the current in the outer coil of the low field aperture can also be used for controlling the saturation-induced harmonics in the high field aperture.

3 INJECTION AND BEAM TRANSFER

The beam is injected in the iron dominated window frame aperture at a field of 0.1 T (or perhaps even less if acceptable from beam dynamics considerations). Since the field quality at low field is determined by iron, the problem associated with the large persistent currents in a Nb$_3$Sn magnet is suppressed. The low field aperture in fact makes the high energy booster (HEB) based on the low field magnet design. Once the HEB is filled by several injection cycles of the machine before that (the medium energy booster), the beam is accelerated by ramping the magnets to 1.5-2.5 T. The field in the high field conductor dominated aperture (whose one coil block is shared with the low field aperture) goes up at a different rate particularly at fields over 2 T.

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The entire beam is transferred in a single turn from the low field aperture to the high field aperture when the field in the two apertures is identical and is somewhere in the range of 1.5-2.5 T. The field in the high field aperture continues to ramp up as the beam is continuously accelerated and the problem of “snap back” is avoided. The term “snap back” refers to the sudden change in field harmonics at the beginning of a conventional acceleration cycle when the field starts to rise from a steady state value of beam injection/fill. In addition to the large persistent current induced harmonics, the “snap back” could be a major problem in a VLHC based on conventional Nb_3Sn magnets. This is because of the fact that (a) at present, the persistent current induced harmonics in Nb_3Sn magnets based on cosine theta designs are an order of magnitude more than that in Nb-Ti magnets and (b) the VLHC will be an order of magnitude bigger machine than any hadron collider built so far. It may be explicitly mentioned that the beam in the conductor dominated aperture is not injected here in the conventional multi-turn injection; it is transferred on the fly in a single turn while the magnets are ramping up. This means that the beam does not stay at a lower field for a long time. Moreover, the minimum field for the beam in the conductor dominated aperture is 1.5-2.5 tesla rather than conventional 0.3-0.7 T. Since the size of the aperture is primarily determined by the injection conditions, the above two reasons should help reduce the high field aperture.

4 MAGNETIC DESIGN

The viability of the common coil design has been demonstrated in a Nb_3Sn 6 T magnet that was tested recently at LBNL and reached the cable short sample field without any training quenches [7]. The mechanical design work is now underway to develop a structure for a 14-15 T dipole [8]. Following the program outlined earlier [11], the next steps for developing an accelerator quality magnet are (a) first demonstrate through computer codes that a dipole based on the common coil design can produce the required field shape and (b) then measure and verify that the required field quality is obtained in a magnet of this design.

This paper presents an initial magnetic design developed with a goal of optimizing the field quality while minimizing the amount of conductor and the size of the coldmass. The preliminary design presented here is based on the similar cable that is used in the 14-15 T magnet now under engineering development [8]. The major parameters of this field quality design are given in Table 1. There are three full layers that go from midplane to pole with each containing 24 turns on the average and one partial layer that is at the pole (see Fig. 1) containing 8 turns only. A preliminary analysis shows that the amount of conductor required in this design is comparable to that in a similar field cosine theta design.

At low currents, the magnitude of the field in the low field and high field apertures is about the same. However, as the current is increased, the field in the high field aperture reaches the computed quench field of ~14.8 T (at 4 K, assuming no degradation in cable), the field in the low field aperture remains under 4.6 T due to iron saturation. This paper does not address the iron saturation and other field quality issues in the low field aperture. They will be addressed in the subsequent papers. The low field aperture can also be a combined function magnet.

In the high field aperture, the field harmonics at low to medium field (geometric harmonics) are optimized by using the following parameters: (a) spacers within the coil, (b) block heights of various layers, (c) slant angle of the pole blocks while keeping the inner and outer surfaces parallel (vertical) to other coils. In this hand optimized design, the harmonics are reduced to less than 0.2 unit (see Table 2). The skew (a_n) and normal (b_n) components of field harmonics are defined (in units) as:

$$B_y + iB_x = 10^{-4} B_o \sum_{n=0}^{\infty} \left[b_n + i a_n \right] \left[\frac{x+iy}{R} \right]^n ,$$

where B_x and B_y are the components of the field at (x,y) and B_o is the magnitude of the field at a reference radius R which is 10 mm here.

Table 1: Major parameters of the design.

Coil aperture	40 mm
Number of layers	3 + 1
Computed quench field at 4.2 K	14.8 T
Peak Fields, inner & outer layers	15.0 T & 10.5 T
Quench current	12.1 kA
Wire Non-Cu J_{sc} (4.2 K , 12 T)	2000 A/mm^2
Strand diameter	0.8 mm
No. of strands, inner & outer layers	40, 26
Cable width, inner & outer layer (insulated)	16.9 mm, 11.1 mm
Cu/Non-Cu ratio, inner & outer	0.7, 1.7
No. of turns per quadrant per aperture	80
Max. height of each layer from midplane	40 mm
Bore spacing	220 mm
Minimum coil bend radius (in ends)	70 mm
Yoke size (full width X full height)	280 mm X 600 mm

The computed field harmonics in the high field aperture remain practically constant till about 2 T (see Fig. 2). The odd normal and even skew harmonics are not allowed by the symmetry. Odd skew harmonics are the manifestation of the inherent up-down symmetry in an over-under design. The variation in harmonics (due to iron saturation) in this preliminary design is significant but manageable. The harmonics higher than decapole (n=4), show a variation of less than 0.1 unit. The variation in octupole and decapole is under 0.4 unit and in skew quadrupole is about 1 unit.

Table 2: Optimized harmonics at 1.8 T in an initial magnetic design of a common coil dipole at 10 mm.

N	SKEW(a_n)	NORMAL(b_n)
1	-0.01	--
2	--	0.00
3	0.01	--
4	--	0.04
5	0.02	--
6	--	0.05
7	0.01	--
8	--	-0.17
9	0.00	--
10	--	-0.03
11	0.00	--
12	--	0.00

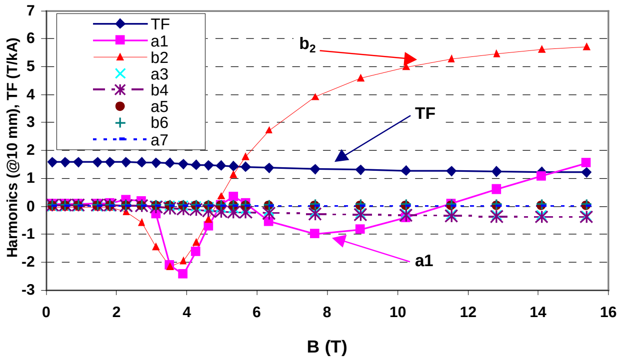

Figure 2: Current dependence of the field harmonics and Transfer Function (TF) as a function of the bore field in the high field aperture (preliminary design).

The maximum computed saturation is in normal sextupole harmonic (b_2). It is still, however, under 6 units till 15 T. This value is comparable to that in a conventional cosine theta design for a 12 T dipole [12]. It may be pointed out that the magnetic design of the common coil magnet is in early stages with the required tools (codes) still under development. The situation is expected to improve, as the computer codes get developed and the design matures. The computer code ROXIE [13] will be used to further optimize the 2-d coil geometry. ROXIE will also be used to design the ends of this magnet which do not have an up-down symmetry. The integrated up-down asymmetry, as seen by the beam along the axis, will be minimized. Conceptually, the up-down asymmetry in the magnet ends may be compensated by (a) an asymmetry in the axial length of conductor blocks relative to the midplane and (b) an asymmetry in the straight section (body) of the magnet.

5 DISCUSSION AND CONCLUSIONS

The common coil magnet system presented here has the potential of significantly reducing the cost of VLHC while improving the technical performance. The need for an HEB is eliminated, reducing the cost of building and operating a major sub-system. The design also mitigates the problem associated with the large persistent currents in conventional Nb_3Sn magnets. The conductor dominated high field aperture may be made smaller as the injection conditions (beam transfer, in this case) are significantly changed and the minimum field increased.

Strategies and tools are being developed for optimizing the field quality while minimizing the conductor and the size of coldmass in a common coil dipole. In the preliminary design presented here, the field harmonics are minimized using the first principles. As compared to this four aperture, 14.8 T common coil dipole, the single aperture, 13.5 T, D20 dipole [14] was 2.4 times bigger and the dual aperture ~9 T, 2-in-1, LHC dipole [15] is 1.4 times bigger. The common coil design should reduce the magnet cost due to its simplicity in construction and compactness in size.

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