

Common Coil Dipoles for Future High Energy Colliders

R. Gupta, M. Anerella, J. Cozzolino, W. Sampson, J. Schmalzle, P. Wanderer, J. Kolonko, D. Larson, R. Scanlan, R. Weggel, E. Willen and N. Maineri

Abstract—This paper presents several magnetic designs for a 16 T, 50 mm aperture Nb₃Sn dipole based on the common coil design for a Future Circular Collider (FCC). It has an aperture-to-aperture spacing of 250 mm, a yoke outer diameter of 700 mm and uses a similar or less conductor amounts than cosine theta or block designs. All field harmonics are about an order of magnitude better than specified at the design field and well below the specification in the entire range of operation. Initial results of mechanical design and analysis are also encouraging. They indicate that the proposed structure is able to support the pole coil blocks against the vertical Lorentz forces and that the maximum stresses in all coils remain generally below 150 MPa. Given several inherent advantages of the common coil design, the development presented here should make this approach a leading candidate for very high field magnets in future colliders.

Index Terms—Superconducting Magnets, High Field Magnets, Accelerator Magnets, Nb₃Sn Magnets, Common Coil Design.

I. INTRODUCTION

HIGHER FIELD and lower cost dipoles are two principle requirements for the realization of the future high energy particle accelerators such as the proposed designs of Future Circular Collider (FCC) at CERN [1] and Super proton-proton Collider (SppC) in China [2]. The common coil design [3] is a conductor friendly design based on simple racetrack (mostly flat) coils with large bend radii. The common coil design is attractive for high field magnets, as the coil modules move as a whole under large Lorentz forces, causing much smaller strain on the conductor in the end region. This offers a potential for significantly reducing the amount of expensive support structure as the common coil design may be able to tolerate much larger deflections than the conventional designs. The common coil design also offers easier segmentation which should help (a) in support structure design and (b) in designing hybrid magnets using different conductors (Nb₃Sn, NbTi and HTS). The common coil design is compatible with both “Wind & React” and “React & Wind” technologies. The common coil design was the baseline design of the earlier US proposal for a Very Large Hadron Collider (VLHC) [4] and is used in the preliminary design report [5] of SppC.

*Work supported by Brookhaven Science Associates, LLC under contract Number DE-SC0012704, with the U.S. Department of Energy and SBIR/STTR contract DOE Grant Number DE-SC0011348 and DE-SC0015896. Corresponding author: Ramesh Gupta, gupta@bnl.gov.

R. Gupta, M. Anerella, J. Cozzolino, W. Sampson, J. Schmalzle and P. Wanderer are with the Brookhaven National Laboratory, Upton, NY 11973 USA (phone: 631-344-4805; fax: 631-344-2190; e-mail: gupta@bnl.gov).

J. Kolonko, D. Larson, R. Scanlan and R. Weggel are with Particle Beam Lasers, Inc., 18925 Dearborn Street, Northridge, CA 91324-2807 USA.

N. Maineri, Science Undergraduate Laboratory Internship at BNL and the State University of New York at Geneseo, Geneseo, NY 14454 USA.

Magnet design studies in Europe [6, 7] are evaluating the “common coil design [8]” along with the “cosine theta design [9]” and the “block coil design [10]” under the EuroCirCol program [11] for a 50 mm aperture, 16 T dipole. This paper presents several magnetic designs based on the common coil geometry using similar conductor and other design parameters. These designs satisfy all physical requirements (aperture spacing, yoke outer diameter), use similar or less amounts of conductor and produce similar or better field quality.

Field quality in accelerator magnets is expressed in terms of the normal and skew harmonics (b_n and a_n) as defined in the following expression:

$$B_y + iB_x = 10^{-4} \times B_{R0} \sum_{n=1}^{\infty} (b_n + ia_n) [(x + iy)/R]^{n-1},$$

where B_x and B_y are the components of the field at (x, y) , and B_{R0} is the magnitude of the field due to the most dominant harmonic at a “reference radius” R (17 mm).

II. MAGNETIC DESIGN

A key part of the common coil design is the optimization of the pole coil blocks (or auxiliary coils) which are located between the main coils [3] (see Fig. 1). In this paper we present the ongoing optimization of one of the several coil configurations suggested in an earlier paper [12]. An optimized iron yoke is also presented.

A. Superconductor

The coil designs are based on rectangular Nb₃Sn cables with strands having a diameter of either 1.05 mm or 1.1 mm, and copper to superconductor (non-copper) ratios for inner layer of 1.0 and for outer layers of 1.5, 2 or 2.7 depending on the design. The critical current of the superconductor is always assumed to be 1500 A/mm² at 4.2 K and 16 T, and the drop in critical current with field, 500 A/mm²/T. The insulation thickness is 0.15 mm on either side. For easy comparison, we used the same cable parameters that were used in the common coil magnet design study for EuroCirCol program [11].

B. Design #1

Design #1 is optimized for larger cables to help in quench protection and to reduce number of coils. Simple coil geometry with large bend radii allows the use of larger cables in the common coil design. Based on the same strands as those used in EuroCirCol common coil, we designed cables that produce 16 T field at ~16 kA. These wires have a diameter of 1.1 mm. The number of strands in the inner layer (and pole coils) is 36 (below the guideline of 40) for a width of ~21.3

mm and in the outer three layers is 22, for a width of ~13 mm.

Numerous coil and yoke iterations were carried out using the program ROXIE [13] to see how good field quality can be achieved in the common coil design for the case when the aperture-to-aperture spacing (250 mm) and the yoke outer diameter (700 mm) are the same as in the other designs (cosine theta and block coils) in the EuroCirCol study. The optimized coil design is shown in Fig. 1. It has less than 0.3% peak enhancement (maximum field on the conductor with respect to the field at the center of the bore). Computed harmonics at the design field of 16 T are given in Table I at a reference radius of 17 mm. All harmonics are below the specifications of less than 3 units at the design field of 16 T [14] by about an order of magnitude. Harmonics not listed in the table are zero by symmetry.

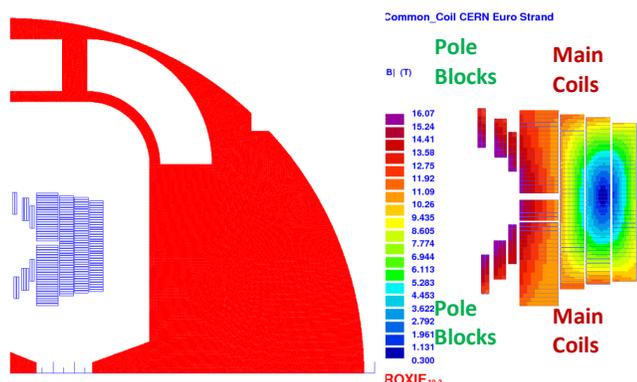


Fig. 1. $\frac{1}{4}$ model of the 2-in-1 common coil design ($\frac{1}{2}$ of the upper aperture) on the right and the magnitude of the field superimposed on the conductors on the left when the field at the center of aperture is 16.034 T. Conductors in the main coils are stacked vertically. Conductors in the pole blocks are stacked horizontally and lifted sideways to allow a bend in the easy direction to clear the bore.

TABLE I

SKEW AND NORMAL HARMONICS AT 17 MM RADIUS AT 16 T IN DESIGN #1							
a_2	a_4	a_6	a_8	a_{10}	a_{12}	a_{14}	a_{16}
0.00	0.00	0.00	0.27	0.21	-0.07	-0.31	0.07
b_3	b_5	b_7	b_9	b_{11}	b_{13}	b_{15}	b_{17}
0.00	0.00	0.01	-0.16	-0.10	-0.35	-0.32	0.03

Variation of the harmonics having significant change as a function of current is plotted in Fig. 2. The iron yoke (see Fig. 1 right) optimization was carried out by N. Maineri as a part of the DOE Science Undergraduate Laboratory Internship (SULI) program during the summer of 2016. Small saturation induced harmonics were achieved ($b_3 < 7$ units, specification < 10 units and $a_2 < 6$ units, specification < 20 units). Enough space was left for the support structure. The yoke geometry may be further iterated for better mechanical properties as a part of further optimization. Fringe field outside the yoke is similar to that in other designs.

Key parameters of the initially optimized design #1 are given in Table II. The total number of turns per aperture (which includes turns in both upper and lower coil halves) is 179. It has a stored energy of 1.7 MJ/m/aperture and inductance of 13 mH/m/aperture.

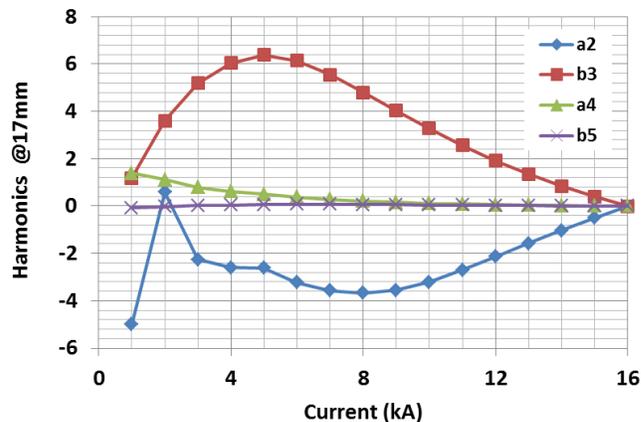


Fig. 2. Field harmonics at 17 mm reference radius as a function of current.

TABLE II
KEY PARAMETERS OF THE DESIGN #1 AND DESIGN #2

Operating current	(kA)	15.96
Field in the aperture	(T)	16.0
Margin at 4.2 K	%	8.5
Intra-beam spacing	(mm)	250
Yoke outer diameter	(mm)	700
Stored energy per unit length/aperture	(MJ/m)	1.7
Inductance/aperture	(mH/m)	13
Strand diameter (inner and pole layer)	(mm)	1.1
Strands/cable (inner and pole layer)	-	36
Cu/Non-Cu (inner and pole layer)	-	1.0
Strand diameter (outer layers)	(mm)	1.1
Strands/cable (outer layers)	-	22
Cu/Non-Cu (outer layers)	-	1.5
Total number of turns per aperture		179
Total area of Cu/aperture	(mm ²)	5029
Total area of Non-Cu/aperture	(mm ²)	4026

C. Design Optimization #2

In design optimization 2, we incorporate a space of 3 mm (see Fig. 3) between the pole coil blocks and main coils to accommodate support structure to support them against the vertical Lorentz forces. To create this space, one turn each was removed from the set of upper and lower pole blocks. The total number of turns is preserved by adding two turns in the main coil blocks. Field harmonics were optimized with ROXIE. Even though the level of optimization was not as exhaustive as in design #1 (only a few cases were examined), the design meets all specification. The results of optimization are given in Table II. Saturation-induced harmonics and other design parameters remain essentially the same as in design #1. Therefore, Table II and Fig. 2, which were made for the design #1 are also valid for the design #2.

Mechanical analysis of this design will be discussed in the next section.

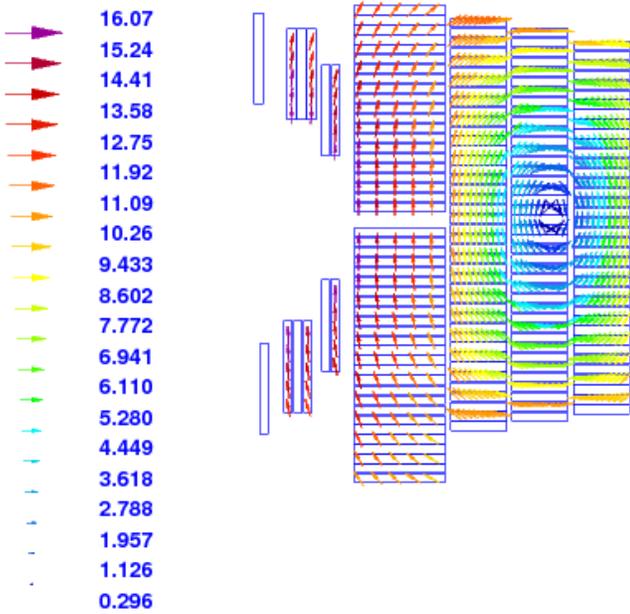


Fig. 3. Optimized design #2 with field vector superimposed over the conductor. A minimum 3 mm gap is left between the pole coils and main coils to allow a support structure to contain vertical forces on the pole blocks.

TABLE III

SKREW AND NORMAL HARMONICS AT 17 MM AT 16 T IN DESIGN #2

a_2	a_4	a_6	a_8	a_{10}	a_{12}	a_{14}	a_{16}
0.00	0.00	0.00	0.00	0.04	-0.89	-0.30	0.19
b_3	b_5	b_7	b_9	b_{11}	b_{13}	b_{15}	b_{17}
0.00	0.00	0.37	2.01	0.10	-1.06	-0.30	0.16

D. Design Optimization #3

We also made a few optimization runs of a design with the same cable parameters as those were used by Toral et al. [15] for the common coil design under the EuroCirCol program. The intra-beam spacing in our design is 250 mm, and the yoke outer diameter is 700 mm. The design generates 16 T field at a current of 8.672 kA. Field harmonics for this preliminary optimized design (see Fig. 4) are given in Table IV. All harmonics except b_{11} (which is 4.2 rather than 3) meet the specifications. One should be able to further reduce all harmonics (including b_{11}) with more cases examined for optimization. The number of turns per aperture in this design is 343. The stored energy per unit length is ~ 1.8 MJ/m/aperture, and the inductance per unit length is ~ 50 mH/m.

TABLE IV

SKREW AND NORMAL HARMONICS AT 17 MM AT 16 T IN DESIGN #3

a_2	a_4	a_6	a_8	a_{10}	a_{12}	a_{14}	a_{16}
0.00	0.00	0.18	0.82	-0.05	0.15	0.27	0.03
b_3	b_5	b_7	b_9	b_{11}	b_{13}	b_{15}	b_{17}
0.00	0.00	0.06	-0.02	4.21	0.26	-0.59	-0.08

III. MECHANICAL DESIGN AND ANALYSIS

Fig. 5 (left) shows the winding and layout of the main coils

(light brown) and pole (auxiliary) coils (pink). In a common coil design the main coils always consist of turns (rectangular cable) stacked horizontally returning from one aperture to another aperture to form simple racetrack coils. The pole coils, in this particular design, consist of turns laid in the vertical direction which are first bent in the easy direction to clear the bore and then return to the other aperture bent along a large radius. The coils themselves on either side of the aperture (left or right) are allowed to move as a whole, causing little strain in the ends. This is the major benefit of the common coil design over the other designs.

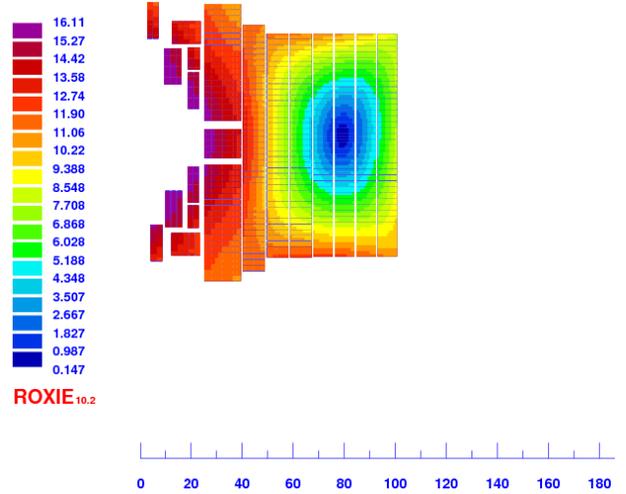


Fig. 4. Optimized design #3 with field superimposed over the conductor. The design is based on the same cable as those used in the EuroCirCol study.

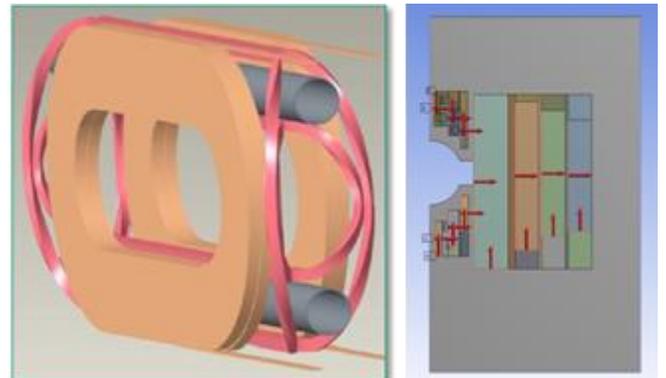


Fig. 5 (left). Layout of the main coils (light brown) and pole coils (pink) is shown on the left and Fig. 5 (right) simple ANSYS model showing the structure considered and forces applied.

Fig. 5 (right) shows a simplified 2d ANSYS Workbench model. Forces are applied to the edges of the coil blocks. To quickly examine the basic issues related to the support structure in this design, a simplified one-piece stainless steel collar is assumed with no joints or connections. The coil modulus of a fiberglass/epoxy impregnated Nb_3Sn is taken to be 20 GPa. Symmetry (frictionless) is assumed at the horizontal split line and also at the vertical split line. The thickness of the the collar is 37 mm. However, a frictionless support is assumed on the right edge of the collar.

Fig. 6 shows the stresses on the coil. The maximum stress

on the main coil (see left) is 144 MPa around the midplane of the outermost coil. This value remained about the same when collars were free to move with no support at the right edge. Stresses on the pole coils (see right) are also generally below 150 MPa, except at the local area in the right-most pole coil blocks marked “X”. This is to be reduced in future iterations of the structure.

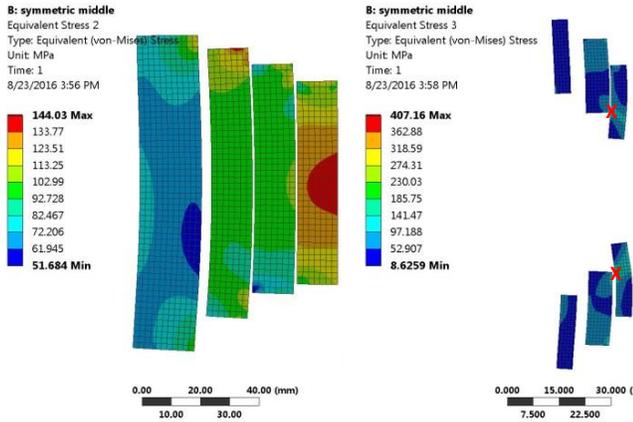


Fig. 6. Stresses in the main coil (left) and pole coils (right).

Fig. 7 shows the deflections in the main and pole coils under the Lorentz forces at 16 T. We plot the horizontal deflections for the main coil (left) and vertical deflections for the pole coil (right). The maximum horizontal deflection is ~ 0.77 mm which is acceptable, if the coil moves as a whole (a major benefit of the common coil design), as long as the relative deflections are small. The goal of future iterations will be to make deflections more uniform. The vertical deflections are less than 0.1 mm, which indicates that the type of support structure considered for the pole coils should be able to hold them.

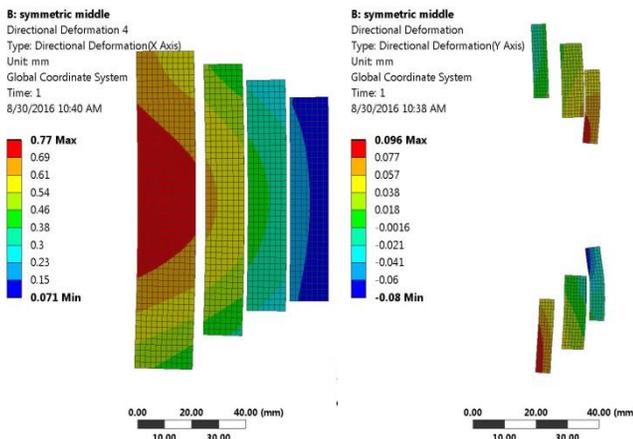


Fig.7. Horizontal displacements of the main coils (left) and vertical displacement of the pole coils (right).

IV. INFLUENCE OF DISPLACEMENT ON FIELD HARMONICS

Deflections due to Lorentz forces, as shown in Fig. 7, have an impact on field harmonics as well, and the change in field harmonics may be significant when the deflections are as large as in the last section. However, the change is expected to be

small if deflections are more horizontal rather than vertical, as is the case here. We performed a number of calculations to quantify these impacts. If all blocks are allowed to move horizontally, then a displacement of 1 mm primarily causes a change in the sextupole (b_3) harmonic only. The impact is linear as a function of displacement and is computed to be ~ 9 units/mm. However, the field harmonics also change due to iron saturation. A proper yoke optimization would accommodate both if the combined changes in harmonics due to non-linear iron saturation and conductor displacement due to Lorentz forces are to be minimized. This can be accommodated in the iron optimization so that the net values of harmonics remain within the specifications of 10 units. We don't expect deflections over 1 mm.

V. CONCLUSION

Three common coil designs have been optimized for achieving good field quality with the inclusion of one configuration of pole coils. The iron yoke has also been optimized. A design with the large cables is preferred for lower inductance. Another added benefit of this is in the reduction in the number of coils to be manufactured. The main features of this design are (a) it meets all field quality requirements (geometric and saturation-induced), (b) has a low inductance (13 mH/meter/aperture), (c) has an intra-beam spacing of 250 mm, (d) has a yoke outer diameter of 700 mm and (e) has an stored energy of 1.7 MJ/m.

Initial mechanical design work has started. The structure examined would be able to hold vertical forces on the pole (auxiliary) coils. Mechanical structure and assembly optimization work will continue.

The common coil design offers several inherent technical and cost advantages. The progress presented in this paper should make the common coil design a leading candidate for high field magnets in the future high energy colliders.

ACKNOWLEDGMENT

We appreciate the help and support provided by Fernando Toral of CIEMAT and Susana Izquierdo Bermudez of CERN with ROXIE and on other useful discussion on the design. We also appreciate the encouragements from Luca Bottura and Lucio Rossi of CERN.

REFERENCES

- [1] Future Circular Collider Study Kickoff Meeting, Geneva, Feb. 12-14, 2014, <http://indico.cern.ch/event/282344/timetable/#20140212>
- [2] CEPC/SppC study in China, <http://indico.cern.ch/event/282344/session/1/contribution/65/material/slides/1.pdf>
- [3] R. Gupta, "A common coil design for high field 2-in-1 accelerator magnets," Particle Accelerator Conference, Vancouver, BC, pp. 3344-3346 vol.3, 1997.
- [4] "Design Study for a Staged VLHC" Fermilab TM-2149 (June 4, 2001) <http://tdserver1.fnal.gov/TDlibrary/TD-Notes/VLHC/fermilab-tm-2149.pdf>.
- [5] CEPC-SppC Preliminary Conceptual Design Report, Volume II: Accelerator, <http://cepc.ihep.ac.cn/preCDR/volume.html>.
- [6] FCC Week 2016, Rome, April 11-15, 2016 <http://indico.cern.ch/event/438866/>.

- [7] D. Tommasini, et al., "The 16 T dipole development programme for FCC," this conference, Paper 1L0r3C-02.
- [8] Fernando Toral, Javier Munilla, Teresa Martinez, Luis Garcia-Tabares, "The EuroCirCol 16 T common-coil dipole option for the FCC," this conference, Paper 2LPo1D-08.
- [9] Massimo Sorbi, Giovanni Bellomo, Pasquale Fabbriatore, Stefania Farinon, Vittorio Marinozzi, Giovanni Volpini, "The EuroCirCol 16 T cosine-theta dipole option for the FCC," this conference, Paper 2LPo1D-02.
- [10] Clément Lorin, Maria Durante, Michel Segreti, "EuroCirCol 16 T block-coils dipole option for the Future Circular Collider," this conference Paper 2LPo1D-03.
- [11] EuroCirCol – The European Circular Energy-Frontier Collider Study, <https://fcc.web.cern.ch/eurocircol/Pages/default.aspx>
- [12] Gupta, R.; Ramberger, S.; Russenschuck, S. "Field quality optimization in a common coil magnet design," Applied Superconductivity, IEEE Transactions on, p 326 – 329, Volume: 10, Issue: 1, March 2000.
- [13] S. Russenschuck, et al., "ROXIE: Routine for the Optimization of magnet X-sections, Inverse field calculation and coil End design," <https://espace.cern.ch/roxie/default.aspx>
- [14] D. Tommasini, 1st Review of the EuroCirCol WP 5, "Introduction," <https://indico.cern.ch/event/516049/contributions/2029291/attachments/1269286/1882716/WP5Review-Introduction.pdf>
- [15] Fernando Toral, "Common coil: electromagnetic," https://indico.cern.ch/event/516049/contributions/2029294/attachments/1271104/1883658/Common_coil_electromagnetic_20160511.pdf

PRE-PRINT ASC2016