Common Coil Dipoles for Future High Energy Colliders

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***Abstract*—This paper presents several magnetic designs for a 16-T 50-mm aperture Nb_3Sn dipole based on the common coil design for a future circular collider. 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, Nb_3Sn 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 (Nb_3Sn, 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.

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 Nb_3Sn 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/mm^2 at 4.2 K and 16 T. Built-in routine

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Manuscript received September 5, 2016; accepted December 1, 2016. Date of publication December 6, 2016; date of current version December 28, 2016. This work was supported by Brookhaven Science Associates, LLC under Contract DE-SC0012704, with the U.S. Department of Energy and SBIR/STTR Contract DOE Grant DE-SC0011348 and Grant DE-SC0015896.

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Digital Object Identifier 10.1109/TASC.2016.2636138

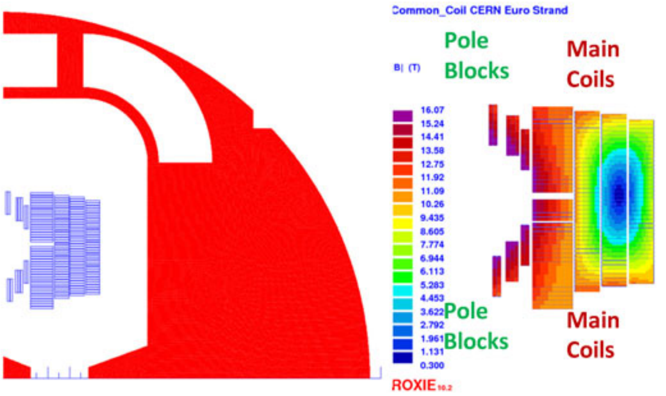

Fig. 1. ¼ model of the 2-in-1 common coil design (½ of the upper aperture) on the left and the magnitude of the field superimposed on the conductors on the right when the field at the center of aperture is 16.034 T. Conductors in the main coils are stacked vertically. Conductors in the pole blocks are 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

of ROXIE has been used to compute the short sample field at an operating temperature of 1.9 K. 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.

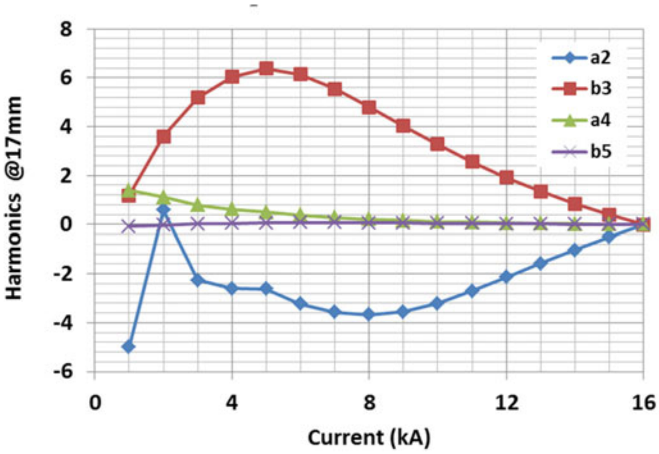

Fig. 2. Field harmonics at 17 mm reference radius as a function of current.

TABLE II
KEY PARAMETERS OF THE DESIGN #1 (DESIGN #2 HAS SIMILAR VALUES)

Parameter	Units	Value
Operating current	(kA)	15.96
Field in the aperture	(T)	16.0
Margin at 1.9 K	%	19.3
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
Total weight of conductor for all FCC dipoles	(tons)	10300

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 a young student as a part of the DOE Science Undergraduate Laboratory Internship (SULI) program [15]. 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 at a radius 150 mm outside the yoke is ∼0.25 T when the yoke o.d. is 700 mm (as in the design presented here), ∼0.2 T when the yoke o.d. is 750 mm, and ∼0.12 T when yoke o.d. is 800 mm. These fringe field values will become lower when the coldmass is placed inside the cryostat.

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.

TABLE III
SKEW 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

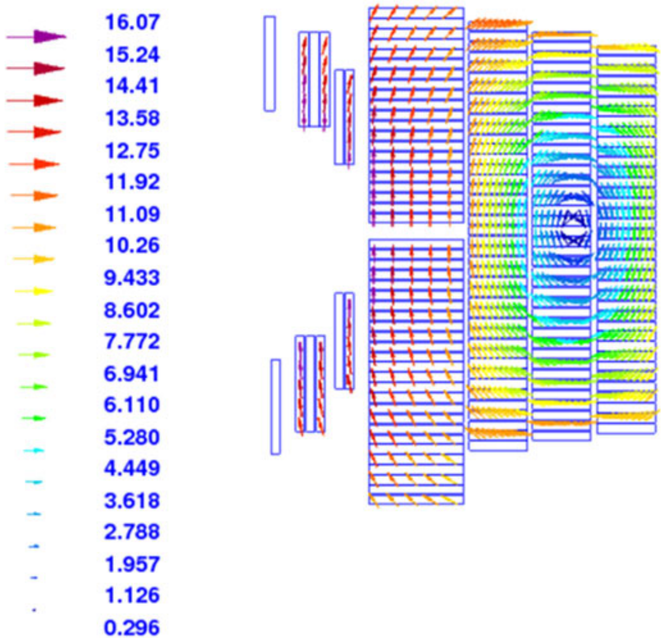

Fig. 3. Optimized design #2 with field vector superimposed over the conductor. A minimum 3 mm gap is left between the pole coils and main coils to allow a support structure to contain vertical forces on the pole blocks.

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 III. 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.

D. Design Optimization #3

We also made a few optimization runs of a design with the strand and cable parameters the same as those used by Toral *et al.* [16] (strand diameter 1.05 or 1.1 mm and the number of strands in cable 12, 14 or 24) for the common coil design developed under the EuroCirCol program [11].

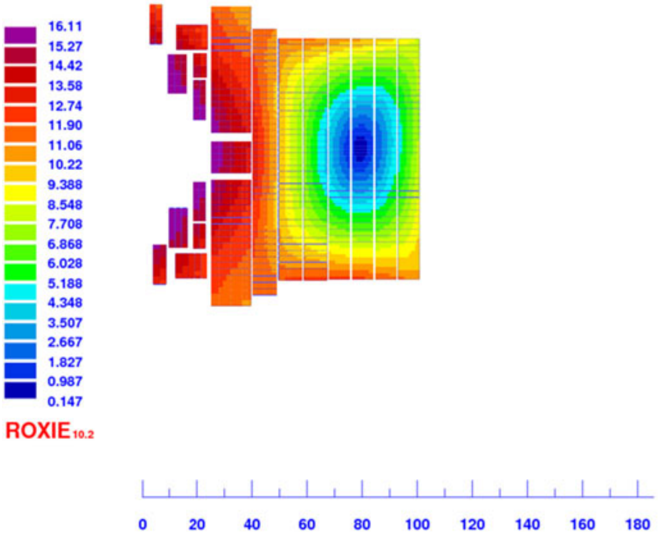

Fig. 4. Optimized design #3 with field superimposed over the conductor. The design is based on the same cable as those used in the EuroCirCol study.

TABLE IV
SKEW 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

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. 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.

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.

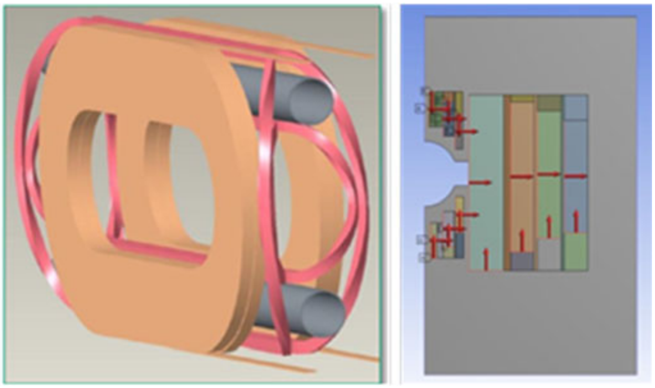

Fig. 5. (Left) Layout of the main coils (light brown) and pole coils (pink) is shown on the left and Fig. 5 (right) simple ANSYS model of design #2 showing the structure considered and Lorentz forces applied.

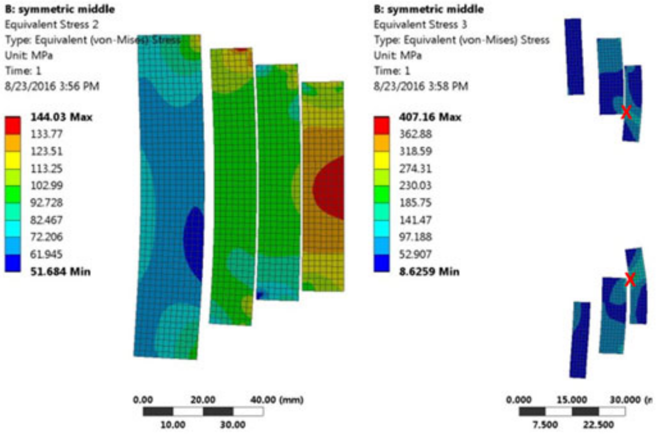

Fig. 6. (left) Stresses in the main coil and (right) pole coils.

Fig. 5 (right) shows a simplified 2d ANSYS Workbench model of design #2. Lorentz 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 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. 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 (in the main coils) 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 to keep the strain within the acceptable limit. The horizontal deflection of the pole coil blocks will be limited by the main coils and the support structure. 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 against the vertical Lorentz forces.

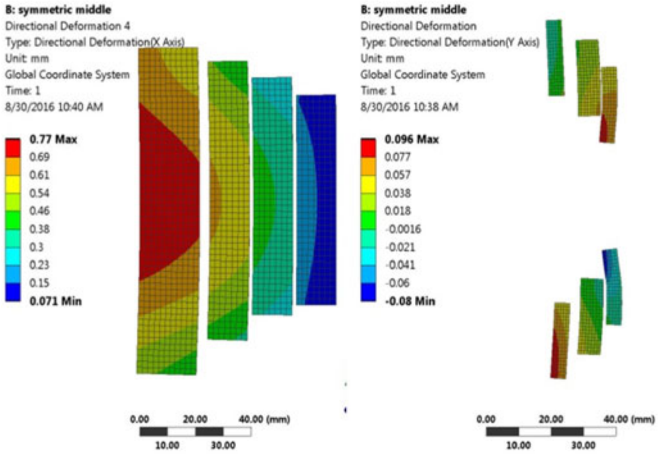

Fig. 7. (left) Horizontal displacements of the main coils and (right) vertical displacement of the pole coils.

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 which helps in quench protection. Future work will examine magnet protection in more detail, including the computation of hot spot temperature, etc. which will quantify the advantages of using a higher current cable. 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 Lorentz forces on the pole (auxiliary) coils. Mechanical structure and assembly optimization work will continue. Future work will also include the optimization of the 3-d magnetic as well mechanical design.

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

The authors would like to thank F. Toral of CIEMAT and S. I. Bermudez of CERN for their help and support with ROXIE and on other useful discussion on the design. They would also like to thank L. Bottura and L. Rossi of CERN for their encouragements.

REFERENCES

[1] (2014, Feb. 12–14). *Future Circular Collider Study Kickoff Meeting*. Geneva, Switzerland. [Online]. Available: http://indico.cern.ch/event/282344/timetable/#20140212

[2] CEPC/SppC study in China. [Online]. Available: 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,” in *Proc. Particle Accelerator Conf.*, Vancouver, BC, Canada, 1997, vol. 3 pp. 3344–3346.

[4] (2001, Jun. 4). Design study for a staged VLHC. *Fermilab TM-2149*. [Online]. Available: http://tdserver1.fnal.gov/TDlibry/TD-Notes/VLHC/fermilab-tm-2149.pdf

[5] CEPC-SppC Preliminary Conceptual Design Report, vol. II: Accelerator. [Online]. Available: http://cepc.ihep.ac.cn/preCDR/volume.html.

[6] (2016, Apr. 11–15). FCC Week 2016. Rome, Italy. [Online]. Available: https://indico.cern.ch/event/438866/

[7] D. Tommasini *et al.*, “The 16 T dipole development programme for FCC,” in *Proc. Appl. Supercond. Conf.*, Denver, Colorado, Sep. 4-9, 2016, Paper 1LOr3C-02.

[8] F. Toral, J. Munilla, T. Martinez, and L. Garcia-Tabares, “The EuroCirCol 16 T common-coil dipole option for the FCC,” in *Proc. Appl. Supercond. Conf.*, Denver, Colorado, Sep. 4-9, 2016, Paper 2LPo1D-08.

[9] M. Sorbi, G. Bellomo, P. Fabbricatore, S. Farinon, V. Marinozzi, and G. Volpini, “The EuroCirCol 16 T cosine-theta dipole option for the FCC,” in *Proc. Appl. Supercond. Conf.*, Denver, Colorado, Sep. 4-9, 2016, Paper 2LPo1D-02.

[10] C. Lorin, M. Durante, and M. Segreti, “EuroCirCol 16 T block-coils dipole option for the future circular collider,” in *Proc. Appl. Supercond. Conf.*, Denver, Colorado, Sep. 4-9, 2016, Paper 2LPo1D-03.

[11] EuroCirCol. The European Circular Energy-Fr ontier Collider Study. [Online]. Available: https://fcc.web.cern.ch/eurocircol/Pages/default.aspx

[12] R. Gupta, S. Ramberger, and S. Russenschuck, “Field quality optimization in a common coil magnet design,” *IEEE Trans. Appl. Supercond.*, vol. 10, no. 1, pp. 326–329, Mar. 2000.

[13] S. Russenschuck *et al.*, ROXIE: Routine for the optimization of magnet X-sections, inverse field calculation and coil end design. [Online]. Available: https://espace.cern.ch/roxie/default.aspx

[14] D. Tommasini. 1st Review of the EuroCirCol WP 5. Introduction. [Online]. Available: https://indico.cern.ch/event/516049/contributions/2029291/attachments/1269286/1882716/WP5Review-Introduction.pdf

[15] N. Maineri, *DOE Science Undergraduate Laboratory Internship (SULI) Program Report*, (unpublished).

[16] F. Toral. Common coil: Electromagnetic. [Online]. Available: https://indico.cern.ch/event/516049/contributions/2029294/attachments/1271104/1883658/Common_coil_electromagnetic_20160511.pdf