Magnetic and Mechanical Design of a 16 T Common Coil Dipole for FCC

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***Abstract*—EuroCirCol is a conceptual design study for a post-LHC research infrastructure based on an energy-frontier 100 TeV circular hadron collider. In the frame of the high-field accelerator magnet design work package of this study, the feasibility of a 16-T dipole in common coil configuration is being studied. This paper shows the electromagnetic design optimization performed to achieve the required field quality while minimizing the superconductor volume and taking into account the input parameters and assumptions of EuroCirCol study. Finite Element Models (FEM) have been used to analyze the stress distribution and deformations under the large Lorentz forces due to the very high magnetic field. Several iterations have been necessary to obtain a feasible magnet design. 3-D electromagnetic calculations are also included in this paper.**

***Index Terms*— Accelerator magnets, FCC, high field magnets, superconducting magnets, 16 Tesla.**

I. INTRODUCTION

SEVERAL options are being examined in the ongoing design studies aimed to study and develop dipole magnets providing a field of 16 T with accelerator quality [1]. These magnets would be necessary for a Future Circular Collider (FCC) or an energy upgrade of the LHC (HE-LHC). High field common coil dipoles made with Nb_3Sn coils are being studied as an option in several laboratories [2]–[4]. CIEMAT is responsible of studying the feasibility of a 16 T common coil dipole in the framework of Work Package 5 (WP5) of the EuroCirCol collaboration. As a first stage of this work, the main design features were identified and the sensitivity of the different design parameters was analyzed [2]. At that time, the highest priority was to minimize the superconductor volume. Consequently, the nominal current was moderate and the coil voltage to ground in case of quench was above limits. Besides, the powering circuits were excessively challenging.

This paper describes magnetic optimizations to solve those problems. The magnet specifications and input parameters have remained unchanged. Additionally, mechanical analysis has been started to address the management of the large Lorentz forces.

II. 2-D ELECTROMAGNETIC DESIGN

A large strand diameter, internal grading of the high field coils, and the use of pole coils can minimize superconductor volume for a given bore field in common coil dipoles [2] (a sketch is shown in Fig. 1). Using the last design reported in [2], Design #10, only 8592 tons of bare superconductor cable are necessary for FCC dipoles, but the voltages in case of quench are well above limits because of the large self-inductance. In the next paragraphs, the design features will be reviewed to solve this problem.

A. Nominal current

A higher nominal current would decrease the voltages during quench because the self-inductance will be lower, since the number of ampere-turns hardly changes. A tentative value of the nominal current about 16 kA is a good compromise:

1) It allows reducing the number of main coils from four to two, for a constant number of ampere-turns. It is intrinsically more efficient, because the cables are placed closer to the aperture with higher engineering current density. However, grading is not so effective as with lower current.

2) It is the maximum current that a cable with 1.2 mm strands can carry in a background field of 16 T when used for a pole coil parallel to the main coils.

3) It is nearly twice the nominal current of Design #10, which means about one quarter of the self-inductance, for the same number of ampere-turns.

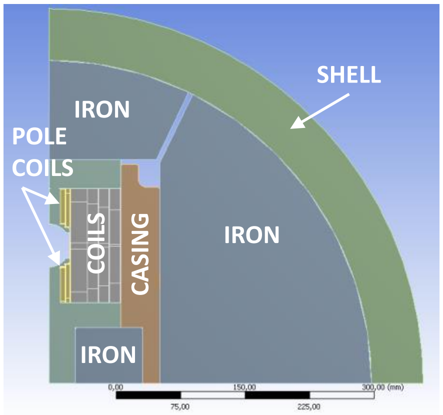

Fig. 1. Sketch of one quadrant of a common coil dipole.

Manuscript receipt and acceptance dates will be inserted here. This work has been partially supported by the European Union's Horizon 2020 Research and Innovation Programme under grant No. 654305, EuroCirCol project.

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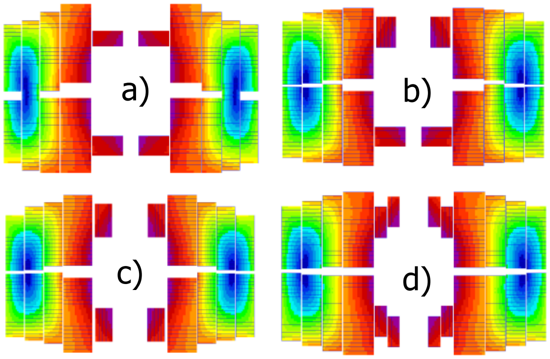

Fig. 2. Magnetic field map at different pole coil arrangements.

B. *Pole coils*

In Design #10, pole coils are flat and parallel to the main coils. The return turns are placed at the iron outer diameter. These turns are not contributing to the bore field. There are two ways to eliminate that inefficiency: a pole coil with flared ends (hard way bending) or a flat pole coil which is placed perpendicular to the main coils. The second option is more convenient, but the limiting factor is the minimum bending radius of the cable.

Four different options of pole coils have been explored, the cross-sections of which are shown in Fig. 2. Option a) is discarded because pole coils have flared ends. Option b) is based on flat coils. The one with horizontal cables is shared by both apertures, but it is not so good for field quality (b_7 is difficult to be reduced). Option c) is limited by the minimum bending radius, but coils are flat. Option d) is based on option c) but with better field quality and superconductor efficiency for a given minimum thickness of the support structure around the beam pipe. Finally, option d) can be improved by using double pancake pole coils, which allow increasing the superconductor efficiency and the minimum bending radius of the cable. This choice is the one kept in this paper as more advantageous.

C. *Outer iron diameter*

In parallel to the EuroCirCol effort, the design of a 16 T dipole for an upgrade of the LHC is being developed [1]. In that case, the outer diameter of the cold mass is limited to 830 mm. Assuming 15 mm thick helium vessel and 60 mm thick shell, the iron can have a maximum outer diameter of 680 mm. Iron diameter is set at 650 mm for these calculations to keep some margin. The previous designs had 750 mm outer iron diameter and 320 mm intra-beam distance. Additionally, an intra-beam distance of 280 mm has been also evaluated.

D. *Copper to superconductor ratio*

The minimum copper to superconductor ratio agreed as common input data in EuroCirCol collaboration is 0.8. Up to now, only cables with minimum ratio of 1 have been considered for common coil designs, because lower ratios are very challenging for cable production. However, lower ratios at the high field cable allow reducing the amount of needed superconductor, because both the engineering current density and the temperature of the high field cable during quench increase.

TABLE I
COMPARISON OF 2-D MAGNETIC DESIGNS

Parameters	#10	#11	#12	#13	#14	Units
Nominal current I	9.17	16.1	16.1	16.1	16.1	kA
Minimum Cu:Sc ratio	1	1	0.8	1	1	
Intra-beam distance	320	320	320	320	280	mm
Iron outer diameter	750	750	750	650	650	mm
Stored magnetic energy	3.47	3.04	2.93	3.05	3.16	MJ/m
L*I	757	378	364	379	392	H·A/m
Vertical Lorentz force	0.73	0.57	0.43	0.34	0.92	MN/m
Horizontal Lorentz force	14.7	14.6	14.4	14.4	14.5	MN/m
Maximum stray field (600 mm radius)	0.19	0.15	0.17	0.19	0.15	T
FCC bare cable weight	8592	9353	8951	9446	9631	ton

E. *Results*

Table I shows the comparison of the following designs:

- Design #10: it was the optimal design presented in [2].
- Design #11: flat coils are easier to produce, but this design has slightly flared pole coils to improve field quality, as shown in Fig. 2.d). Minimum bending radius of the cable is 13.5 mm. Nominal current is large.
- Design #12 (Fig. 3): based on #11, but with a ratio of copper to superconductor of 0.8 in the high field cable.
- Design #13: same pole coil shape as #11, iron outer diameter of 650 mm.
- Design #14: based on #13, but intra-beam distance is reduced to 280 mm.

For FCC, the best designs are #11 and #12. They fulfill all the requests, although they need some extra cable compared to #10. In particular, for Design #11, a simulation using quench heaters for magnet protection reveals hot spot temperature is 350 K and peak voltage to ground is 1170 V [5]. The latter is the problematic parameter for Design #10. The product of the self-inductance L and the nominal current I is determining the complexity of the powering circuits in an accelerator. For Designs #11 and #12, this factor is half that of what was shown in Design #10. Design #12 is better in terms of superconductor

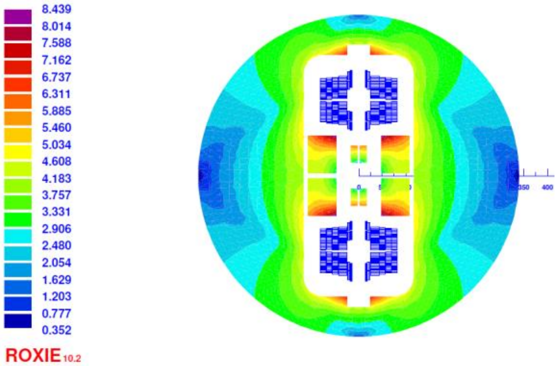

Fig. 3. Magnetic field map in iron yoke of Design #12. Notice that there are four main coils and four pole coils per magnet. Main coils are shared between apertures and pole coils are not. All the coils are double layered. Only the high field coil has an internal splice for cable grading.

efficiency, but the cable fabrication is more difficult.

For an upgrade of LHC, Designs #13 and #14 are valid. Intra-beam distance can be reduced to decrease fringe field, but superconductor efficiency is a bit smaller. This effect is nonlinear, so further reduction of intra-beam distance increases noticeably the cable need and the vertical forces. A large intra-beam distance is very interesting to explore the use of react-and-wind coils [6]. The fringe field shown in Table II is calculated at the cryostat wall, assuming a non-magnetic cryostat.

Concerning the field quality, all the designs show multipoles of few units. There are many design variables, so one must be careful with the optimization algorithms to get reasonable solutions. The ideal cross section of a common coil is very similar to the well-known block dipole, since that cable arrangement is very effective and provides a good field quality. To avoid wrong search directions when optimizing, relatively narrow variation range must be established for the design variables. To start from a good initial solution, the sensitivity of the design variables have been analyzed drawing the following conclusions: b_3 and b_5 are affected by the mid-plane gap and the pole coils vertical position, a_2 is driven by the vertical position of the set of coils with respect to the aperture, a_4 is shifted by the vertical position of the high field coil. The main problem is to decrease b_5, because the most effective action is to move the pole coils towards the beam pipe, but this possibility is limited by the minimum bending radius of the cable in the easy way direction and the mechanical support around the beam pipe.

III. 3-D ELECTROMAGNETIC DESIGN

Figure 4 shows the coil ends of Design #11. Only one octant of the iron is shown due to the symmetries. The iron does not cover the coil ends to avoid the field enhancement there. With the same intention, the coils have different lengths and bending radii. The overall length of each coil end is 255 mm. The coils are 14.5 m long to provide the requested magnetic length of 14.3 m. It is also worth noticing that the iron is shaped to decrease the variation of the field harmonics with the current, which is kept below 5 units.

The integrated field quality is easily achieved, because there are many design variables. Final coil end geometry is not decided yet, since it depends on the choice for using react and wind cable. In this design, the minimum bending radius is 100 mm for main coils and 13.5 mm for pole coils.

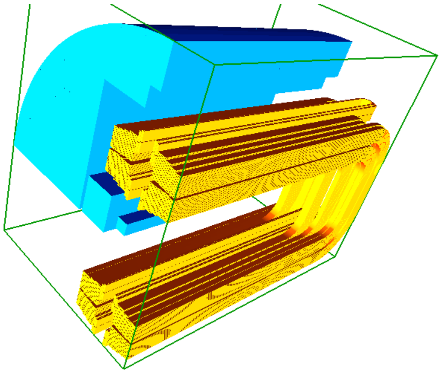

Fig. 4. 3-D view of the coil ends and iron yoke. The straight section is shorter than in a real magnet.

IV. MECHANICAL DESIGN

A. Design concept

The Lorentz forces of these high field magnets are very large. There are repulsive forces between the coils at both sides of the apertures, in the range of 14.5 MN/m per aperture. These forces would reduce the width of the coil blocks by 0.2 mm. Vertical repulsive forces between both sides of the coils are small, about 560 kN/m, but internal vertical stresses are large, towards the plane defined by the aperture, about 4.5 MN/m. It is necessary to design a support structure to hold these forces. There are two possible approaches:

1) To design a structure which holds the Lorentz forces but let the coils move (see Fig. 5 left). The pole coils are held by a cantilevered support. The main coils are close to the beam pipe, without any support, because the Lorentz forces are outwards.

2) To design a structure providing pre-stress to the coils such that the coils are always in contact with the support. In that case, a full support around the beam pipe is necessary to hold the horizontal pre-stress on the coils (see Fig. 5 right). The pole coils can be placed closer to the aperture and the field quality is easier to be achieved. The minimum thickness of that support is considered to be 2 mm of stainless steel plus 0.5 mm for ground insulation. When the main coils are moved off the aperture by 2.5 mm, about 4 % more cable is necessary to provide the same bore field and 10% more energy is stored in the magnet.

For this paper, only the first choice has been analyzed, since it uses the superconductor more efficiently. Besides, less mechanical energy is stored in the coil, which is beneficial to avoid triggering a quench.

B. Modeling and results

Figure 1 shows a quadrant of the magnet cross section of Design #11, where both apertures are in the same vertical plane. The boundary conditions are such that all the pieces are continuous through the symmetry axes. For instance, the iron

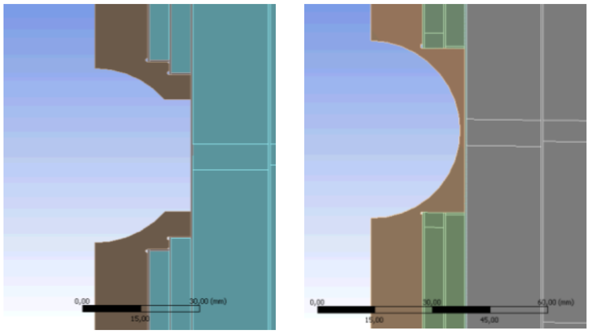

Fig. 5. Two possibilities to hold the pole coils: on the left, support structure is cantilevered; on the right, a full support is around the beam pipe.

is split in four parts. The pole coils are impregnated with a 0.5 mm thick aluminum foil to improve compression at cold. They are supported by stainless steel pieces which are bolted to a vertical plate to constitute a casing around the main coils. Those bolts partially hold the horizontal Lorentz forces. They are simulated like springs to speed up the computations. The two main coils are impregnated together. The cable blocks and wedges are modeled with their own material properties and geometry. There are glued copper wedges at the coil sides to achieve equal width for all.

There is a 60 mm thick stainless steel shell which provides pre-compression when cooled down and withstands most of the Lorentz forces. A slight pre-compression at room temperature is given, equivalent to cooling down the shell by 20 ºC. Its effect is more important for proper convergence of the contact elements of the FEM simulation than for the mechanical behavior of the magnet. An aluminum shell option has been discarded because the coil horizontal displacement during energization is excessive, more than 1 mm.

Table II summarizes the stress distribution on the coils at different load steps: assembly, cool-down and energizing. The maximum values are relatively low for a high field magnet. The reason behind is that the coils are not pre-compressed.

Figure 6 depicts the displacements of the coils when they are energized. In the horizontal direction, the displacement is relatively homogenous, between 0.4 and 0.58 mm. When the coils are shifted horizontally by 0.5 mm, the variation of the field harmonics is moderate: *b3* is shifted by 5.5 units, *b7* by 1 unit, *a2* by 0.8 units and the rest of multipoles less than *0.2* units. The horizontal displacement can be reduced in a pre-compressed assembly, but it is difficult to be further decreased in this design without a mechanical support around the beam pipe, since the coil support (casing and shell) has been already made as stiff as possible. The vertical displacements are much smaller, only above 0.1 mm in some of the pole coils. They are not degrading the field quality noticeably.

The main concern is that the coil loses contact with the support at some points and even slides horizontally with respect to the casing: the large horizontal Lorentz forces compress the coil and the friction under the vertical force is not enough to keep the coil in contact with the casing. As shown in Fig. 7, the displacement is up to 0.5 mm at the high field coil, because the coil deformation is adding on top of the support structure one. However, sliding is taking place between a copper spacer and the casing, not directly on the cables. The dissipated heat could be absorbed by the copper without disturbing the cables. This approach is the best to decrease the stress on the coils and the stored elastic energy, but it yields some risks because of coil movement. This feature needs further investigation and the solution needs to be prototyped.

Concerning the stress distribution in the support structure, no problems are expected from this analysis. The maximum Von-Mises stress in the iron yoke is locally rising up to 418 MPa at nominal field, but first principal stress is only 82 MPa [7]. At nominal current, the maximum Von-Mises stress in the casing is 527 MPa and 402 MPa for the shell.

TABLE II
STRESSES ON COILS [MPA]

Load step	Min/max Von Mises	Min/max horizontal stress	Min/max vertical stress
Assembly	1/36	4/-38	2/-20
Cold	8/76	2/-78	0/-66
16 T	2/136	1/-140	1/-155

V. CONCLUSION

A common coil design is studied as one of the options for the 16 T dipoles demanded by future colliders. In this paper, several magnetic designs have achieved all the requirements while using a moderate amount of superconductor. 3-D magnetic computations show that coil end design also fulfils requirements. Mechanical analysis has been done on a support structure which minimizes the stored elastic energy and the coil stresses, but some concerns arise due to the coil sliding with respect to the casing. Further calculations are ongoing and other types of structures providing pre-compression will be considered.

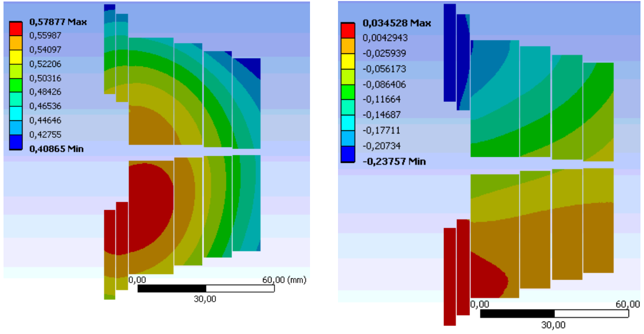

Fig. 6. Coil displacements when Design #11 is energized from 0 to 16 T: horizontal (left) and vertical (right).

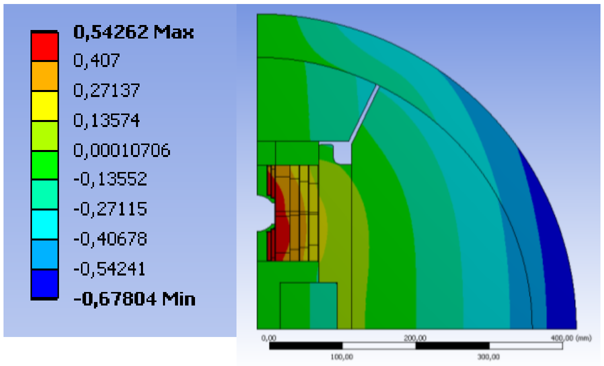

Fig. 7. Horizontal displacements of the Design #11 magnet parts from assembly to nominal field.

ACKNOWLEDGMENT

The authors would like to thank R. Gupta (BNL) and Q. Xu (IHEP) for fruitful discussions. The authors want also to thank S. Izquierdo-Bermudez (CERN) for her help on the magnet modeling and optimization using ROXIE.

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