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Design of a Canted-Cosine-Theta Superconducting Dipole Magnet for Future Colliders

Shlomo Caspi, Diego Arbelaez, Lucas Brouwer, Steve Gourlay, Soren Prestemon, and Bernhard Auchmann

***Abstract*—A four-layer canted-cosine-theta 16-T dipole has been designed as a possible candidate for future hadron colliders. The design maintains part of the future-circular-collider magnet requirements, i.e., a 50 mm clear bore and 16 T operating at 1.9 K. The magnet intercepts Lorentz forces with an internal structure of ribs and spars, minimizes conductor, and reduces the number of layers and magnet size by using wide cables. The role of iron and its impact on field and magnet size is discussed. A three-dimensional magnetic analysis was carried out for 1-in-1 and 2-in-1 designs including a structural analysis for the 1-in-1 case. Thoughts on future improvements during winding are also discussed.**

***Index Terms*—CCT, Canted-Cosine-Theta, superconducting, magnet, high field, dipole, 16T, 2-in-1.**

I. Introduction

FUTURE accelerator magnets operating at 16 T or more will face challenges that will have to be addressed by innovative R&D. To face such challenges, the US Magnet Development Program (MDP) [1] is focused on developing a dipole magnet that can operate at 16 T with reduced Margin, Training and Cost (MTC) [2]. Reducing MTC is especially important for future high energy accelerators requiring thousands of long superconducting magnets to work reliably using advanced high current density superconductors. The Future Circular Collider (FCC) [3]–[5] estimates that 4578 dipoles, each 15 m long, will be needed in a 100 km ring. Extrapolating from the LHC 1.4 T (14%) safety margin to a 16 T operation will not only double the energy but would require a costly 2.5 T margin. Future magnet R&D will therefore be required to consider bold high risk, high gain designs. New designs promising to reduce the MTC even by a few percent could by far offset future cost. The US MDP approach towards high field superconducting magnets places such a R&D program at a unique point in time where new ways that undertake higher risks of failure in order to achieve substantial higher gains are justified. In this paper we explore ways in which the Canted-Cosine-Theta (CCT) magnet (Fig. 1) offers solutions to reduce future margin, training and cost. We discuss ways where both magnetically and structurally the amount of conductor can be reduced, how Lorentz forces could be handled to reduce stress, the role of iron in terms of structure and magnet size, and touch upon a winding approach where insulation can be applied after reaction.

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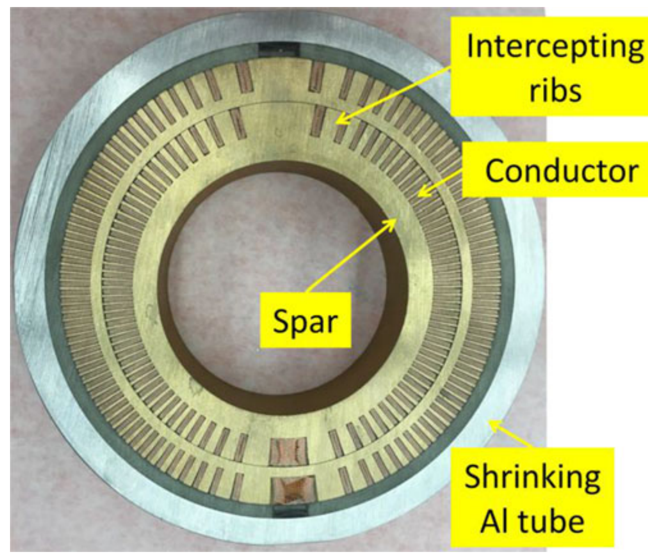

Fig. 1. A cross-section of a two layer CCT2, a 5T NbTi impregnated dipole.

The CCT magnet [6]–[13] addresses the MTC promise by offering a design concept that 1) employs a graded magnetic and structural design that reduces conductor mass and stress 2) separates the functionality of an internal and an external structure thereby reducing magnet size 3) simplifies conductor placement, eliminates winding tension, controls the reaction process and offers good field quality along the magnet including its "ends" 4) reduces components and tooling and 5) simply by adding layers offers a continuous approach towards higher fields. Addressing such issues in combination with an experimental program, future breakthroughs in high field accelerator magnets should be possible.

II. A 4 Layer Nb_3Sn Dipole

A. A Conceptual Approach

The proposed design focuses on pushing the CCT to its limits. We therefore reduce the number of layers of a previous CCT design [14] from 8 to 4 layers, maximize the size of the inner

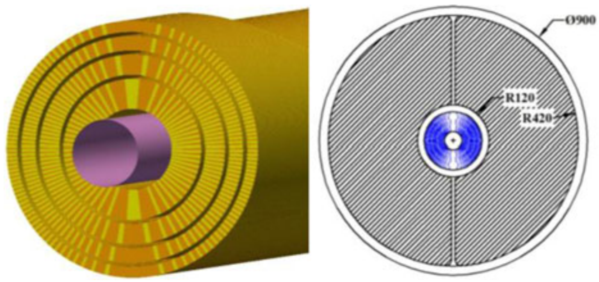

Fig. 2. Coils of a 4 layer Nb_3Sn CCT dipole for 16 T, 1.9 K operations.

TABLE I
GEOMETRIC PROPERTIES

Layer	R_{i-spar} (mm)	Spar (mm)	Channel (mm/mm)	R_{o-coil} (mm)	Min. rib thickness (mm)	Strands
1	25.0	5	1.9/22.5	52.5	0.212	51
2	52.5	3	1.9/15.2	70.67	0.661	34
3	70.67	3	1.9/10.8	84.52	0.877	24
4	84.52	3	1.9/8.3	95.79	0.879	18

most layer and minimize the thickness of all spars. Doing so will require 4 different cable sizes with a substantially reduced amount of conductor beyond the first layer (all having the same strand diameter). With the largest cable size on the inner radius of a 50 mm clear bore an excessive hard way bend can become an issue and cause strands to pop-out. Partially tilting the cable(see II.E) as it is done around "ends" of cosine-theta magnets can help as well as the fact that CCT turns are placed individually inside channels and do not nest. The functionality of the internal structure using thin spars may need to be supplemented with an external support structure. The size of the combined internal and external structures can be optimized forming a "graded" approach of the overall structure. Including iron will raise the field, lower the operating current and, if placed away from the bore make saturation harmonics manageable. For high fields and small cryostats warm iron could also be considered to dramatically reduce the cold mass size. A major difference between the CCT concept and other magnets is that coils cannot separate from their "poles". A continuous spar can only bend (or yield) but not separate and therefore can only be controlled by bending. Since ribs around the poles are much thicker than near the mid-plane, simulations show that bending will take place (see II.C). With the use of a combination of iron and aluminum sufficient bending force can be applied during cool down to deform the coil inner substructure into a prolate shape. This compensates the oblate shape the Lorentz forces tend to create.

Finally, we consider the fact that a collider needs two bores. In deference to the present LHC magnets, where the bores are magnetically decoupled, coupling the two reduces the operating current and increases the field. In a 2-in-1 CCT magnet, a revised winding path will be needed in a way that nulls coupled harmonics employs the same Numerical Controlled (NC) machining technique (see II.D).

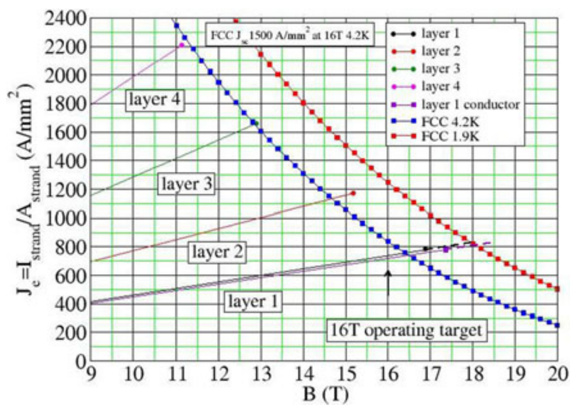

Fig. 3. Load lines of a single bore 4 layers CCT dipole without iron.

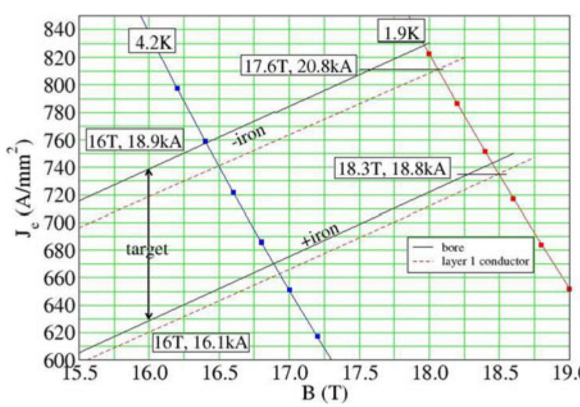

Fig. 4. Influence of iron on load lines of the inner layer 1.

TABLE II
OPERATING MAGNETIC PROPERTIES SINGLE BORE

Type	Iron	B bore (T)	*$B_{cond.}$ (T)	**J_{strand} (A/mm²)	***Icable (kA)	Margin (T)
1-in-1	No	16	16.3	734	18.9	1.6
1-in-1	Yes	16	16.3	628	16.1	2.3

B. Magnetic Design 1-in-1

The 4 layers coil design with a 50 mm clear bore and an operating field of 16 T at 1.9 K is shown in Fig. 2. The Nb_3Sn conductor properties assumed for the design are based on the FCC specifications [15].

The 4 layer graded design is using the largest cable size made at LBNL to-date with a 0.8 mm strand for layer 1. We assume a Cu/non-Cu ratio of 0.8:1 and assume the cables could fit into the channel listed in Table I (NC machined channels are normal to the cylinder axis). All layers have a 15 degree canted angle on the mid-plane and a pitch of 11.205 mm. Fig. 3 shows the load lines of all layers for an iron free case and Fig. 4 compares the load lines of layer 1 with and without iron. Tables II and III summarize 16 T and short-sample results. The benefit of using

TABLE III
SHORT-SAMPLE MAGNETIC PROPERTIES SINGLE BORE

Type	Iron	B bore (T)	*$B_{cond.}$ (T)	**J_{strand} (A/mm^2)	Icable (kA)
1-in-1	No	17.6	18.1	810	20.8
1-in-1	Yes	18.3	18.5	735	18.8

*$B_{cond.}$ is the maximum absolute field of the conductor at the pole.
**J_{strand} is the strand current density in layer 1
****Stored energy at 16T is 2.35/1.9 (MJ/m) without/with iron

TABLE IV
TOTAL CONDUCTOR LENGTH AND WEIGHT

Type	Strand Km/m	Cable m/m	Cond. Kg/m	Cond. Kg/mag.	Cond. Ton/beam
1-in-1	11.58	408	51	732	3352

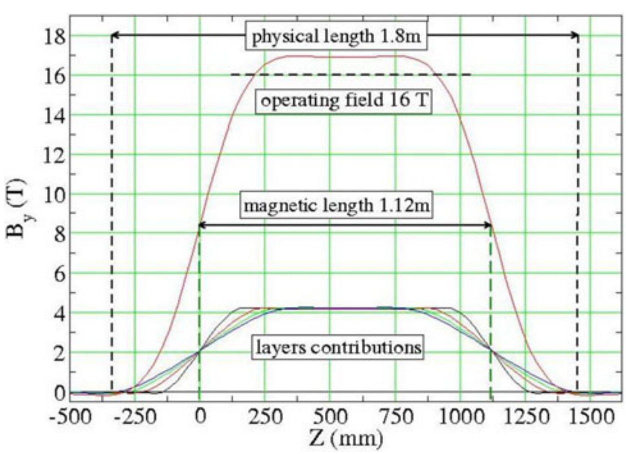

Fig. 5. Relative magnetic and physical length along a short CCT magnet.

iron is evident as it raises the operating field margin by more than 0.5 T while reducing the operating current by 2.7 kA.

Without iron the OD of the single bore cold mass could be as small as 252 mm. If iron is included the OD could be as high as 900 mm. The strand length, cable length and weight per meter of magnetic length are listed in Table IV as well as conductor weight of a 15 m long dipole (the magnetic and the physical length are compared in Fig. 5). A two bore magnet such as the one proposed for FCC will therefore require a minimum of 6700 tons of superconductor (assuming 4500 dipoles). That amount of conductor is a minimum and more will potentially have to be added to the outer layers to reduce current density and overcome low field conductor instabilities.

C. Single Bore Mechanical Design - ANSYS

A 3D ANSYS analysis was done on a periodic structure with an axial pitch length of 11.205 mm (Fig. 6). The coil mandrels and inner aluminum shell were bonded but the iron yoke, part of the external structure, was free to slide. Since the thermal expansion of the iron is quite different from that of other magnet components and it is not bonded to the structure the question of sliding or slippage needs to be pointed out. We assume here that even though the iron is allowed to slip azimuthally the 3D ANSYS model maintains equal axial strain conditions in the fashion described in [16], [17]. We have also looked into non plane-strain conditions where the yoke is free to slide axially. With no pre-stress, cool-down deforms the coil inner substructure into a prolate shape and is reversed into a oblate shape by the Lorentz forces (Fig. 7). The maximum relative displacement after cool-down around the inner spar is around 0.1 mm. Since spars are solid rings, their stress is almost entirely dominated due to bending and azimuthally coil pre-stress or separation is not relevant. At 16 T the maximum von Mises (VM) stress in the spar of 400 MPa is high but acceptable (Fig. 8 top). The high stress condition in the coil after cool-down of 162 MPa is a direct result of the plain-strain condition (Fig. 8 bottom). If axial sliding of the yoke is permitted, the coil VM stress will

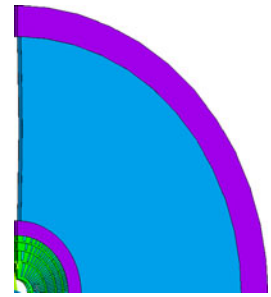

Fig. 6. ANSYS model - coils, mandrels, iron yoke and shells.

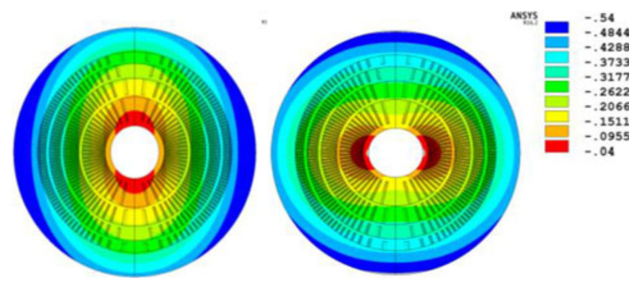

Fig. 7. Deformed coil (mm), cool-down left, 16T right (red-blue = 0.5 mm).

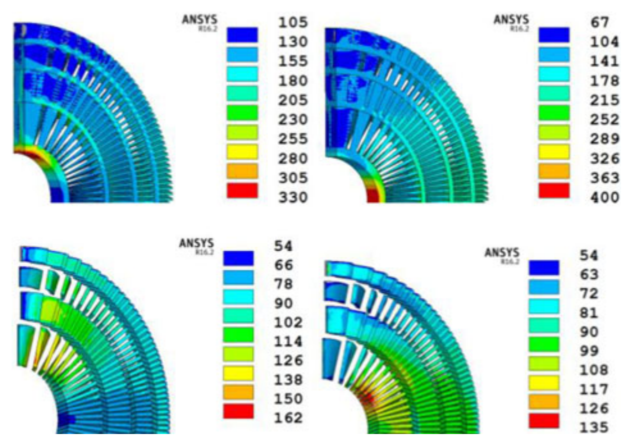

Fig. 8. Von Mises stress (MPa) in the former (top) and conductor (bottom) at cool-down (left) and 16 T (right).

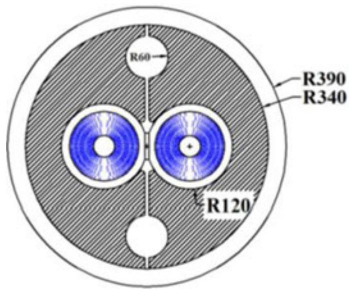

Fig. 9. A 2-in-1 design placed inside aluminum shells and iron.

TABLE V
OPERATING MAGNETIC PROPERTIES 2-IN-1 BORE

Type	Iron	B bore (T)	*$B_{cond.}$ (T)	**J_{strand} (A/mm^2)	***Icable (kA)	Margin (T)
2-in-1	No	16	16.35	682	17.5	1.9
2-in-1	Yes	16	16.20	625	16.0	2.3

TABLE VI
SHORT-SAMPLE MAGNETIC PROPERTIES 2-IN-1 BORE

Type	Iron	B bore (T)	*$B_{conductor}$ (T)	**J_{strand} (A/mm^2)	Icable (kA)
2-in-1	no	17.9	18.3	763	19.56
2-in-1	yes	18.3	18.56	724	18.56

*$B_{cond.}$ is the maximum absolute field of the conductor at the pole.
**J_{strand} is the strand current density in layer 1
***Stored energy at 16T is 2.3/1.93 (MJ/m) without/with iron

remain below 60 MPa. With applied Lorentz forces the maximum conductor VM stress of 135 MPa is along the 45 degree angle (Fig. 8 bottom). Optimizing the spar size against the amount of conductor could be used to better balance between cost and stress.

D. Magnetic Design 2-in-1

If the magnets in the LHC tunnel are replaced in order to double the energy, the existing space limitation for the magnet should be considered. Replacing the present Nb-Ti magnets with Nb_3Sn would greatly benefit from the existing 1.9 K cryogenic system, protection system and even cryostats size and length. To achieve this, the bores will have to be moved closer together to fit the magnet structure inside the volume of the present cryostat. Since size does matter, such cost-savings measures would certainly be a challenge for future magnet design. We have created a 2-in-1 design by taking the previous 4 layer design and placing it 240 mm apart. The windings path is adjusted such that the field interaction between bores nulls the first 9 harmonics (Fig. 9). Comparing the 2-in-1 and the 1-in-1 design without iron, the contribution of cross-talk to the margin is an increased field 0.2 T and reduced current of 1.4 kA. For both cases even with a small amount of surrounding iron the field margin at 16 T will increase from 1.9 T to 2.3 T (Tables V, VI).

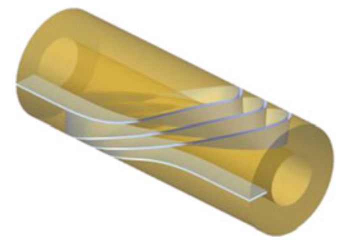

Fig. 10. A CAD model for testing tilted winding.

If the 2-in-1 design uses the iron strictly as a magnetic shielding by placing it outside the cryostat, the cold-mass will fit inside the present LHC 580 mm cryostat. Doing so will reduce the margin back to 1.9 T.

E. Winding, reaction and future tests

To simplify the machining and maintain good field quality, it is desirable to machine the winding channels with a cutter pointing in the radial direction with respect to the bore axis. As a result, the cable makes a hard way bend around the pole which tends to de-cable it. In deference to cosine-theta magnets where one can generate a developable surface around the magnet "ends", generating a developable surface in the CCT is mathematically not possible. However, tilting the cable away from the radial position increases effectively the hard-way bend radius by a factor of 10 while torsion and the easy-way bend remain virtually unchanged. We confirmed that wider cables can be used by test winding around channels with different tilt pole angles (Fig. 10). Cables as wide as 22 mm will require additional tests to determine the tilt angle. With radial channels the cable tends to have problems with popped strands. Tilting the cable could impact field quality and will be addressed by adjusting the cable radial position.

It is important to note that a tilted turn comes with several consequences: it deteriorates the field quality (most notably the sextupole) but this can be taken into account by modifying the winding path; it introduces the need to decide whether the winding should align on the ID or the OD (one of the two edges will not follow a circular path) and the modified channels require a five-axis NC machine, in contrast to the radial three-axes machine.

Following a typical reaction cycle of a 10 Nb_3Sn turn coil we noticed that the thermal expansion of the aluminum-bronze former dominates the cable post reaction behavior. It appears that at high temperatures the cable plastically deforms, so while the former returns to its original room temperature size the cable does not. The cable is elongated and deformed by the former causing it to push out of the channels. To overcome this effect and make room for a cable tilt, channels were gradually oversized around the poles by up to 2.5 mm (Fig. 11). With the oversized channels the former is prevented from pushing on the cable, so the post-reaction cool-down leaves the cable close to its natural position. Leaving gaps along pole islands is a common practice in Nb_3Sn coils, however here they are placed next to the turns. These gaps also accommodate wider cables by allowing them to take a more natural tilt. Epoxy impregnation

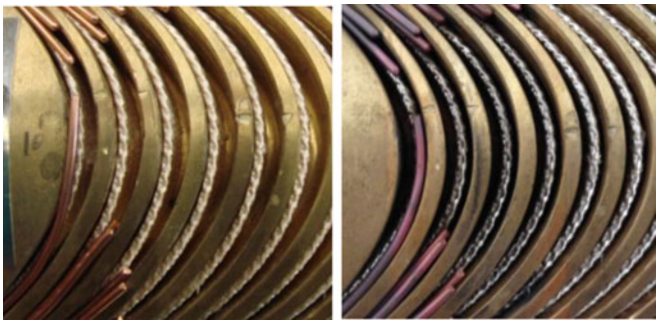

Fig. 11. A 2 mm shift in cable position before (left) and after (right) reaction.

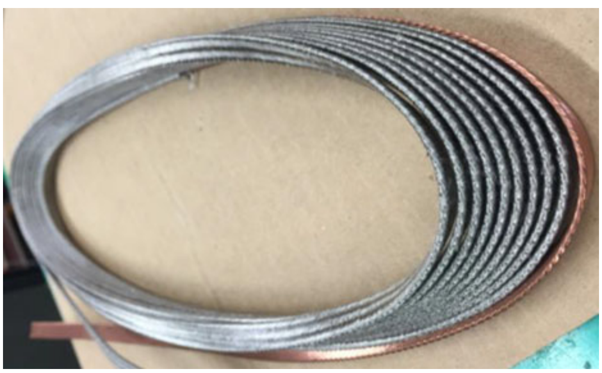

Fig. 12. Reacted turns after they have been removed from the former.

fills up any residual space, and since turns do not nest next to each other the issue of popped strands is less severe.

A more aggressive approach to be tried in future tests is using an un-insulated cable during reaction, removing it from the former after reaction, introducing fresh insulation onto the cable or the former, and placing the cable back into the channels. Clearly the risks are high, but so are the benefits (e.g. new insulation, new non-metallic formers). In a simple test we demonstrated that after reaction the cable retains most of its deformed shape even when unsupported (Fig. 12) as well as an encouraging degree of elasticity. Additional performance tests will still need to be done on unwound cable.

III. Conclusion

The margin of a 2-in-1 16 T CCT dipole is increased from 1.9 T to 2.3 T when iron is added. This increase of 0.4 T, or 2% along the load line, should be weighed against the increase in magnet size, cryostat diameter and eventually limitations of the tunnel (if placed in the existing LHC tunnel). The CCT magnet offers an integrated approach between coil winding and field quality, reaction and insulation, assembly and structure, pre-stress and tooling. Remaining issues such as protection will have to be addressed but the main thrust of future R&D on CCT magnets will need to focus on a demonstrated improvement of magnet performance with respect to magnet training, short-sample, and cost. Most of what has been discussed is based on analysis and experience. Testing such magnets is underway. Past CCT tests using a NbTi conductor (reached 2.4T and 4.6T) are reported in [9], [18]. The first Nb3Sn test was recently terminated at 7.4 T (unreported) after confirming an inverted behavior between field and ramp-rate (the higher the rate the higher the field). Under construction is new magnet planned to be tested in winter 2017 with a targeted field of 10T.

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