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Canted–Cosine–Theta Magnet (CCT)—A Concept for High Field Accelerator Magnets

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***Abstract*—Canted–Cosine–Theta (CCT) magnet is an accelerator magnet that superposes fields of nested and tilted solenoids that are oppositely canted. The current distribution of any canted layer generates a pure harmonic field as well as a solenoid field that can be cancelled with a similar but oppositely canted layer. The concept places windings within mandrel's ribs and spars that simultaneously intercept and guide Lorentz forces of each turn to prevent stress accumulation. With respect to other designs, the need for pre-stress in this concept is reduced by an order of magnitude making it highly compatible with the use of strain sensitive superconductors such as Nb_3Sn or HTS. Intercepting large Lorentz forces is of particular interest in magnets with large bores and high field accelerator magnets like the one foreseen in the future high energy upgrade of the LHC. This paper describes the CCT concept and reports on the construction of CCT1 a "proof of principle" dipole.**

***Index Terms*—Accelerator magnets, Canted–Cosine–Theta magnet, CCT, high field, superconducting dipole.**

I. Introduction

FOUR different types of superconducting accelerator magnets have been built and tested over the years: Cosine-Theta, Common-coil, blocks with flared ends, and blocks with stress management. While each of these types attempted to address the increased complexity of brittle Nb_3Sn superconductor, crossing 10 T and especially going beyond 15 T has proven difficult and unpredictable. For reasons, none more important than coil pre-stress, expected progress [1], [2] resulted in fewer successful attempts of magnets actually reaching their short-sample design limit. It became apparent that if we want to reach fields of 20 T yet another novel approach will have to be introduced that reduces conductor stress in magnets. With the major issue being the accumulative Lorentz forces between turns, intercepting such forces has been the primary goal of stressed managed coils [3]. That approach uses supporting beams to subdivide coils into blocks that intercept forces, however, within each block some degree of pre-stress is still required (e.g. using springs). Reducing the pre-stress to its bare minimum suggests blocks that are no larger than a single turn each. Doing so will cause the tangential Lorentz forces (at a 20 T level) not to exceed a conductor stress of 25–30 MPa. To first order, conductor under such a low pre-stress may have reached a point where no pre-stress is needed at all. The intercepted Lorentz forces however do not disappear and will have to be carried by a strong internal structural support. Fusion magnets and very high field solenoids have been using a similar approach by applying "cable-in-conduit" conductor to address stress interception (at a cost of a reduced current-density). Keeping a high current density in accelerator magnets is important and could be achieved if structural elements are combined with typical field-shape wedges. The CCT promises to accomplish that and in addition suggests the reduced functionality of an **external supporting structure** and replacing it with an **internal structure** that is part of the coils.

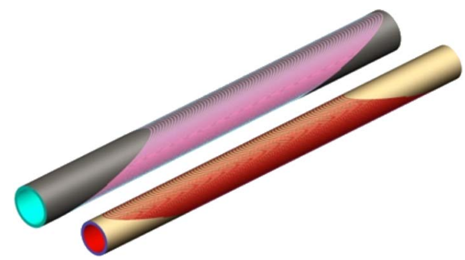

Fig. 1. Two nested layers with canted windings creating a dipole magnet.

This paper describes advancements in the design of an internal structure that intercepts individual turns by placing them into pre-machined channels around a mandrel (Fig. 1). The magnetic concept was first introduced by Meyer and Flasck in a 1970 publication [4], suggesting that the transverse current density in canted solenoids closely resembles that of a "perfect" cosine-theta magnet generating a "pure" dipole field (Fig. 2). The concept was sub-sequentially considered and expanded in several publications [5]–[11]. Section II details a two-layer design of a CCT dipole using NbTi conductor. Section III discusses the construction status and future plans.

II. Canted–Cosine–Theta Magnet—CCT1

A. CCT1 Magnet

CCT1 is a NbTi dipole magnet built to demonstrate CCT technology and determine its feasibility for high field magnets using Nb_3Sn conductor and HTS. The magnet is expected to reach a short-sample field of 2.6 T within a 50.8 mm clear bore at a current of 3660 A. The cable, wrapped with braided s-glass insulation, is wound into pre-machined channels of Aluminum mandrels and then impregnated. Both layers are

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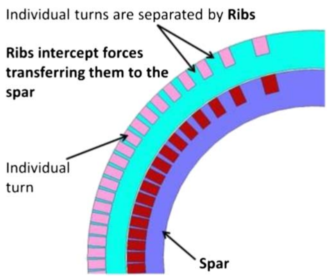

Fig. 2. Transverse cut showing a “pure” cosine-theta current density distribution with intercepting ribs and spars.

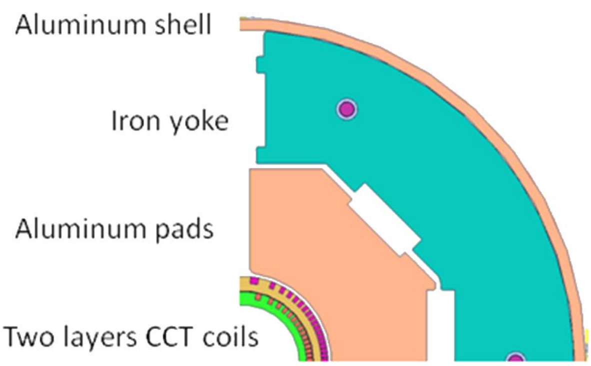

Fig. 3. CAD cross section of a two-layer CCT1 showing canted winding.

TABLE I
CCT1 MAGNET PARAMETERS

Symbol	Units	Value
Strand diameter (SSC outer)	mm	0.65
Strands per cable		8
Bare cable	mm	2.72x1.07
Insulated cable	mm	3.02x1.37
Cable keystone angle	Deg.	0
Channel size	mm	3.02x1.59
Clear bore dia.	mm	50.8
Number of layers		2
Layer 1/2 radial spar thickness	mm	3.07
Between layers radial insulation	mm	0.25
Layer 1/2 canted angle	Deg.	15
Layer 1/2 No. of turns		78/72
Layer 1/2 single turn length	mm	499/604
Mandrels length	mm	841.1
Axial pitch length	mm	7.60
Minimum rib thickness (mid-plane)	mm	0.38
Maximum rib thickness (pole)	mm	6.02
Pad inner radius (on mid-plane)	mm	50
Pad outer radius (on mid-plane)	mm	81.82
Yoke inner radius (on mid-plane)	mm	94.36
Yoke outer radius	mm	147.4
Shell diameter	mm	304.8

wound continuously and do not require an internal splice. A subassembly of coils and Aluminum pads will be inserted into a second subassembly of an iron yoke and outer Aluminum shell (Fig. 3) and the final assembly will be completed using keys and bladders technology [12]. The magnet parameters are listed in Table I.

A complete magnetic and structural analysis was carried out and the magnet is presently under construction.

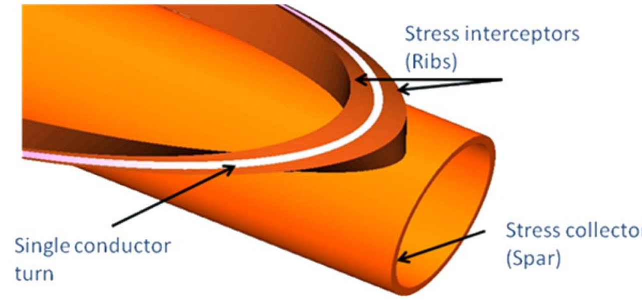

Fig. 4. Varying size ribs attached to a spar guide and support the conductor.

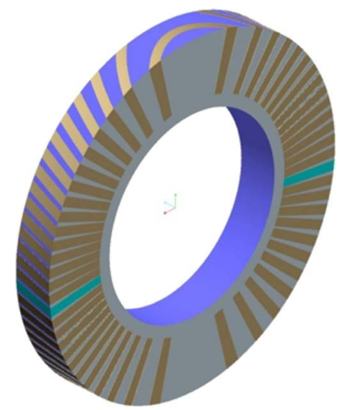

Fig. 5. Cross section of a single lamination of coils ribs and spar.

B. Coil Winding Path and Mandrel

The eight strands Rutherford cable follows a winding path that intersects a plane and a cylinder at a given angle (15 deg.). The cable, simulated as a 4 corners cross-section plane, is placed normal to the winding direction and is oriented (with its narrow edge) tangentially to the cylinder (normal to its radius vector). Wound around the cylinder the cable is incrementally advanced ending with a final axial pitch of 7.60 mm over one turn. The rib size between turns varies from 0.38 mm at the mid-planes to 6.0 mm at the poles (Fig. 4). The mandrel channels were machined from a 6 mm wall Aluminum cylinder at a depth of approximately 3 mm leaving the rest as a supporting spar (Fig. 12).

C. Lamination

The entire winding mandrel can also be made from an assembly of identical laminations (a pitch thick) (Fig. 5). Assembling the laminations generates a continuous channel for the entire coil windings (Fig. 6). Beside the impact on cost and eddy currents losses the laminations provide a major simplification in three-dimensional (3D) analysis. With proper symmetrical boundary conditions a 3D magnetic and structural model was made to determine the field and stress. (hardware laminations were not implemented in the CCT1).

D. Magnetic Model

The CCT1 TOSCA 3D model was created from 8 node bricks simulating the entire two layers. Over the central straight-section the field quality reflects the “purity” of the transverse

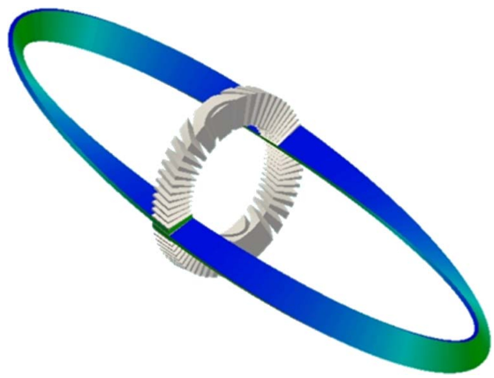

Fig. 6. Single turn fits within ribs of a single pitch lamination.

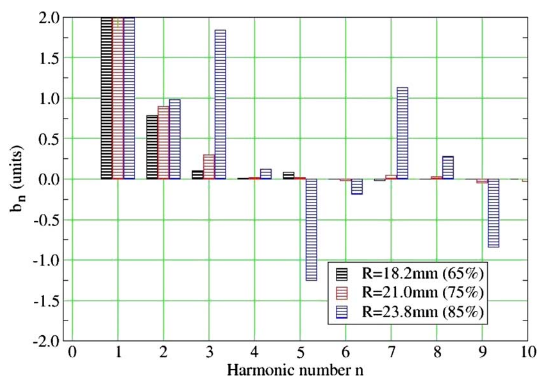

Fig. 7. Harmonics calculated by TOSCA (no-iron) at various bore radii. B1 is the dipole and its value has been truncated.

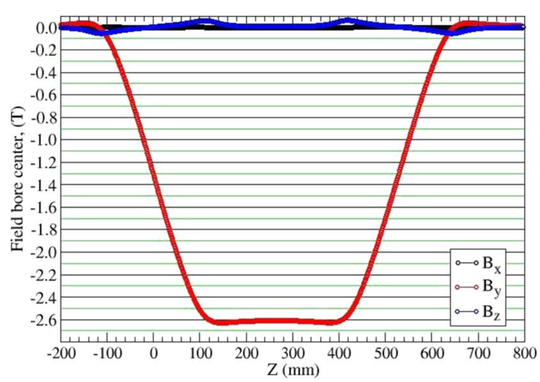

Fig. 8. TOSCA field profiles along CCT1 bore center (no-iron).

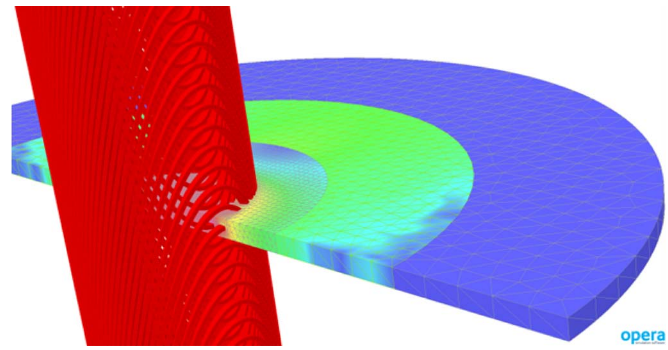

Fig. 9. 3D TOSCA model of windings and a laminated meshed field.

TABLE II
CCT1 MAGNETIC PARAMETERS

Symbol	Units	Value
conductor	NbTi	
Cu:Sc		1.8:1
Jsc @ 5T, 4.2K	A/mm^2	2750
Jeng-channel @ 5T, 4.2K	A/mm^2	539
Cable SC area	mm^2	0.94
Area-SC/Area-Channel		0.196
Short-Sample NO-IRON (TOSCA 3D)		
Iss	A	3800
Bss-bore	T	2.33
Bss-cond.	T	2.9
Short-Sample WITH-IRON (TOSCA 3D)		
Iss	A	3660
Bss-bore	T	2.6
Bss-cond.	T	3.1
Ess-energy	kJ/m	15
Inductance	mH/m	2.24

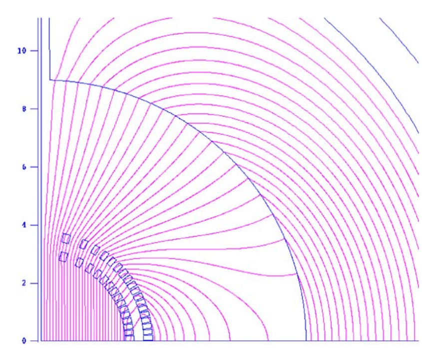

Fig. 10. POISSON flux plot of CCT1 showing the cosine-theta current density distribution.

cosine-theta current density distribution in the windings. Fig. 7 shows the normal local harmonics in CCT1 on a radius between 65% and 85% of the winding radius. Along the magnet “ends” the winding symmetry between any two layers naturally integrates all harmonics to zero [13]. Fig. 8 shows the field profile along the magnet axis.

When iron is also considered a reduced model size is restricted to the volume of a meshed lamination (Fig. 9). The conductor properties and the expected short-sample performance, with and without iron, are listed in Table II. In certain cases a two-dimensional cross-section cut was made of the conductor and used with the magnetic program Poisson (Fig. 10).

III. Lorentz Forces and Stress

The main advantage of the CCT is its capability to intercept Lorentz forces by ribs and spars. If we assume a rigid CCT mandrel structure without a turn-to-turn mechanical interaction, the Lorentz force will be confined tangentially by the channel walls and radial by an outer layer spar. These are the only force components needed to restrain the turn. Fig. 11 is a plot of the CCT1 tangential and radial stresses around a conductor turn. The tangential stress at the mid-planes (0 and 180 degrees)

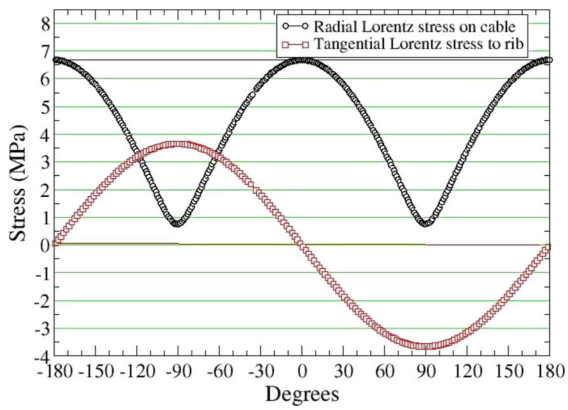

Fig. 11. Biot-Savart calculations of the tangential and radial Lorentz stress around a single turn of CCT1 at 5 kA.

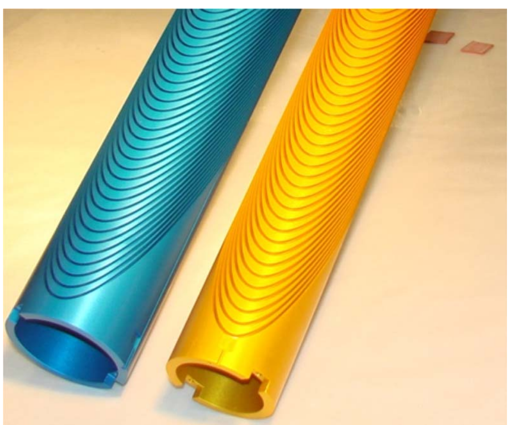

Fig. 12. Photo of machined aluminum mandrills of CCT1 layers 1 and 2 [15].

is 0, and below 5 MPa at the poles (facing the axial direction). We note that the corresponding rib thickness at both locations, minimum at the mid-plane and maximum at the pole, reflect the structural need to constrain the force. Results of a complete 3D ANSYS stress analysis are reported in [14].

If the CCT1 was designed as a "conventional" cosine-theta (CT) dipole a calculated pre-stress of 55 MPa would have been required. Despite the low field and the low Lorentz force, the high-current density at that field in combination with a small NbTi cable still yields a substantial pre-stress. With stress interception, the pre-stress of the CCT1 is less than 5 MPa, an order of magnitude lower than a CT design. At such a low level the internal structure of ribs and spars may be sufficient to handle both azimuthal and radial forces without a supplemental external structure. Presently with a supplemental external structure, the stress change in CCT1, between cool-down and 5 kA (30% over the short-sample limit), is barely noticeable in the conductor with some affect on the spars in the form of bending. Accordingly, the plan for the CCT1 is therefore to check its performance with and without an external structure followed by a second model that replaces the present NbTi conductor with Nb_3Sn. Replacing the conductor is expected to more than double the field and provide a good measure of comparison. In addition at 6 T, where the pinning forces and therefore the Lorentz forces in Nb_3Sn, are close to their maximum, the impact of stress interception is expected to be significant. In parallel, we are developing Bi-2212 coil technology based on the CCT layout, and intended as insert for CCT1.

IV. Conclusion

CCT1 demonstrates the CCT concept as an accelerator magnet. Pending the CCT1 2.6 T magnet performance, the NbTi conductor will be replaced with Nb_3Sn to study the reaction process as well. Results on field quality and especially training will be a key factor in proving the concept's future capabilities. The magnet test is planned to take place in early fall 2013.

References

[1] S. Caspi, "A perspective on LBNL 1 m long Nb_3Sn superconducting dipole magnets," in *LBNL Engineering Note 10674*. Lawrence Berkeley Nat. Lab., Jan. 2012.

[2] D. Sutter and B. Strauss, "Next generation high energy physics colliders: Technical challenges, and prospects," *IEEE Trans. Appl. Supercond.*, vol. 10, no. 1, pp. 33–43, Mar. 2000.

[3] P. McIntyre and A. Sattarov, "On the feasibility of a tripler upgrade for LHC," in *Proc. Part. Accel. Conf.*, Knoxville, TN, USA, 2005, pp. 634–636.

[4] D. I. Meyer and R. Flasck, "A new configuration for a dipole magnet for use in high energy physics applications," *Nucl. Instrum. Method*, vol. 80, no. 2, pp. 339–341, Apr. 1970.

[5] C. L. Goodzeit, M. J. Ball, and R. B. Meinke, "The double-helix dipole—A novel approach to accelerator magnet design," *IEEE Trans. Appl. Supercond.*, vol. 13, no. 2, pp. 1365–1368, Jun. 2003.

[6] A. V. Gavrilin, M. D. Bird, V. E. Keilin, and A. V. Dudarev, "New concepts in transverse field magnet design," *IEEE Trans. Appl. Supercond.*, vol. 13, no. 2, pp. 1213–1216, Jun. 2003.

[7] A. Devred, B. Baudouy, D. E. Baynham, T. Boutboul, S. Canfer, M. Chorowski, P. Fabbricatore, S. Farinon, H. Félice, P. Fessia, J. Fydrych, V. Granata, M. Greco, J. Greenhalgh, D. Leroy, P. Loverige, M. Matkowski, G. Michalski, F. Michel, L. R. Oberli, A. den Ouden, D. Pedrini, S. Pietrowicz, J. Polinski, V. Previtali, L. Quettier, D. Richter, J. M. Rifflet, J. Rochford, F. Rondeaux, S. Sanz, C. Scheuerlein, N. Schwerg, S. Sgobba, M. Sorbi, F. Toral-Fernandez, R. van Weelderen, P. Védrine, and G. Volpini, "Overview and status of the next european dipole joint research activity," *Supercond. Sci. Technol.*, vol. 19, no. 3, pp. 67–83, Mar. 2006.

[8] S. Caspi, D. R. Dietderich, P. Ferracin, N. R. Finney, M. J. Fuery, S. A. Gourlay, and A. R. Hafalia, "Design, fabrication, and test of a superconducting dipole magnet based on tilted solenoids," *IEEE Trans. Appl. Supercond.*, vol. 17, no. 2, pp. 2266–2269, Jun. 2007.

[9] S. Caspi, D. Arbelaez, H. Felice, R. Hafalia, D. Robin, C. Sun, W. Wan, and M. Yoon, "Conceptual design of a 260 mm bore 5 T superconducting curved dipole magnet for a carbon beam therapy gantry," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, p. 4401204, Jun. 2012.

[10] S. Caspi, D. Arbelaez, L. Brouwer, D. R. Dietderich, H. Felice, R. Hafalia, S. Prestemon, D. Robin, C. Sun, and W. Wan, "A superconducting magnet mandrel with minimum symmetry laminations for proton therapy," *Nucl. Inst. Methods*, vol. 719, no. 11, pp. 44–49, Aug. 2013.

[11] F. Bosi, P. Fabbricatore, S. Farinon, U. Gambardella, R. Musenich, R. Marabotto, and E. Paoloni, "Compact superconducting high gradient quadrupole magnets for the interaction regions of high luminosity colliders," *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, p. 4001004, Jun. 2013.

[12] S. Caspi, S. Gourlay, R. Hafalia, A. Lietzke, J. O'Neill, C. Taylor, and A. Jackson, "The use of pressurized bladders for stress control of superconducting magnets," *IEEE Trans. Appl. Supercond.*, vol. 11, no. 1, pp. 2272–2275, Mar. 2001.

[13] L. Jackson Laslett, S. Caspi, and M. Helm, "Configuration of coil ends for multipole magnets," in *Particle Accelerators*. New York, NY, USA: Gordon and Breach, 1987, pp. 22, 1–14.

[14] L. Brouwer, S. Caspi, H. Felice, S. Prestemon, and E. Rochepault, "Structural design and analysis of canted cosine theta dipoles," *IEEE Trans. Appl. Supercond.*, vol. 24, 2014, to be published.

[15] A. Hafalia, S. Caspi, H. Felice, L. Brouwer, and S. Prestemon, "The structural design for a 'canted cosine-theta' superconducting dipole coil and magnet structure—CCT1," *IEEE Trans. Appl. Supercond.*, vol. 24, 2014, to be published.