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Designs and Prospects of Bi-2212 Canted-Cosine-Theta Magnets to Increase the Magnetic Field of Accelerator Dipoles Beyond 15 T

Laura Garcia Fajardo, Lucas Brouwer, Shlomo Caspi, Stephen Gourlay, Soren Prestemon, and Tengming Shen

Abstract—The critical current density of Bi-2212 round wires has seen significant improvement over the past two years. We present the magnetic design and stress analysis of two Bi-2212 dipoles based on Canted-Cosine-Theta (CCT) technology using the state-of-the-art wires. The first design, based on a 19-strand Rutherford cable of ∅0.8 mm strands, is a two-layer dipole with a bore diameter of 40 mm and an outer diameter of 98.4 mm; it generates 5.4 T when operating in stand-alone configuration and 18.9 T in 15 T background field. The second design, based on a 13-strand Rutherford cable of ∅0.8 mm strands, is also a two-layer dipole with a bore diameter of 40 mm and an outer diameter of 81 mm; it generates 4.0 T when operating in stand-alone configuration and 17.8 T in 15 T background field. Normal stresses on the conductor in these magnets do not exceed 35 MPa when working under background field. Moreover, we propose a novel approach for increasing the efficiency of CCT magnets using keystoned Rutherford cable while removing the midplane ribs. With this method, it is possible to increase the efficiency of small radius CCT coils by 20%. We conclude that Bi-2212 can be used to increase the limit of accelerator magnet dipole fields beyond 15 T while managing stresses in the coils to acceptable levels.

Index Terms—Bi-2212 dipole, canted cosine theta, HTS insert magnets.

I. INTRODUCTION

T he need for dipole magnets providing >16 T for future circular colliders pushes the technology towards including high-temperature superconductors (HTS) because the critical current of Nb₃Sn decreases quickly with increasing fields above 16 T whereas the critical current of several HTS conductors can sustain values up to 45 T [1]. Among HTS options, Bi-2212 is a multifilamentary round wire conductor available in long length with high critical current density, which can be made into a Rutherford cable. However, it has the drawback of being mechanically weak due to having silver and silver alloys as sheath materials. Its critical current is sensitive to strain. Its critical axial stress along the wire is ∼150 MPa [2], whereas the critical current of a fiberglass insulated, epoxy impregnated Bi-2212 Rutherford cable degrades irreversibly with increasing transverse pressure above 60 MPa applied to the wide surface of the cable, and above 100 MPa applied to the narrow surface of the cable [3].

The Canted-Cosine-Theta (CCT) magnet technology provides the possibility of intercepting the Lorentz forces of each turn of the winding and transferring them to the support structure, preventing stress accumulation between turns [4]. The support mandrels are cylinders with channels to hold the conductor, ribs that intercept the Lorentz forces from the conductor, and a spar where the forces are transferred to (Fig. 1). The coils consist of nested solenoids tilted in opposite directions in a way that the dipole field of each coil adds up while the solenoidal fields of each two coils cancel out. The conductor path is a function of the azimuthal angle (θ), the radius of the coil (r), the tilt angle (α) and the pitch length (ω). Tilt angles between 15° to 20° make the magnet more efficient in terms of maximizing the integrated dipole field of 10 to 15 m long magnets [5].

The U.S. Magnet Development Program (MDP) and LBNL would like to explore the LTS-HTS combined technology using Cosine-Theta (CT) and CCT Nb₃Sn magnets, and a CCT Bi-2212 magnet with the ultimate goal of reaching 20 T [6].

Fig. 1. Example of a 2-layer CCT magnet layout with rectangular cable.
The LTS-HTS magnets can be electrically connected using a single power supply (hybrid configuration) or independent from each other (insert/outsert configuration). Mechanically, they may or may not be coupled. Each option has its advantages and disadvantages from the point of view of conductor length required, pre-stress required, and quench detection and protection techniques.

Bi-2212 conductor has seen significant improvements in the last year, achieving a strand critical current of 600 A at 4.2 K and 5 T with the batch PMM170123 (Ø0.8 mm), 50% higher than the average performance of industrial billets manufactured before 2017. It benefits from a new wire architecture (55 × 18) for Ø0.8 mm wires and a better precursor powder. Based on the current conductor technology and mandrel manufacturing techniques, we present two design scenarios for Bi-2212 CCT magnets. We picked the option of having the HTS coils mechanically decoupled and electrically independent from the Nb_3Sn outsert as it provides the flexibility for exploring and testing different design options.

In addition, we present a new concept of CCT coil using keystoned Rutherford cable that increases the efficiency of CCT magnets. We apply this new concept to the two design scenarios that we previously proposed, and compare their magnetic results.

II. Bi-2212 CCT MAGNET IN STAND-ALONE CONFIGURATION

The short-term MDP goals for CCT magnets based on Bi-2212 conductor is the design and fabrication of inserts able to produce 5 T in the bore in stand-alone configuration and 3 T under a background field of 15 T. The first challenge for producing the required field is the small outer diameter (OD), fixed by the bore diameter (BD) of a cost effective Nb_3Sn outsert. Placing as much conductor as possible inside the small OD is a need for reaching high overall current density (J_E) in the cross section of the magnet to increase the dipole field generated in the bore. In this respect, selecting the least number of layers (coil + mandrel) is the best option because it reduces the space between layers for assembly purposes. The least number of layers for cancelling the solenoidal field in a CCT magnet is two. Additionally, fitting as many turns of conductor as possible in each layer would increase J_E. This is possible by minimizing the thickness of the ribs at the mid-plane, where the ribs are thinnest. There is a limit though for the minimum rib thickness (0.25 mm) that can be machined in aluminum-bronze mandrels, which is the material selected for Bi-2212 CCT coils [7].

The first goal is to explore the possibility of producing 5 T in the bore of a magnet with the smallest possible OD. The proposed design to accomplish this goal consists of two CCT layers whose geometric parameters are shown in Table I. This first design is based on a rectangular Rutherford cable with 19 strands of Bi-2212 PMM170123 superconductor, Ø0.8 mm.

The wider the cable, the higher the total current of the coils, hence the higher the field in the bore. Winding wide cables in small radius coils poses a challenge as the hard way bend causes de-cabling and deformation of the soft silver-sheathed strands. A winding test was successfully done with a 17-strand Bi-2212 cable for a 21 mm coil inner radius. We assume that a 19-strand Rutherford cable can also be wound into a 28 mm coil inner radius.

A. Magnetic Analysis

Magnetic analysis was performed using the commercial TOSCA code from Cobham OPERA. The results of the magnetic analysis are shown in Fig. 2 and Table II. The peak field is located in the pole region of the inner coil. Grading the outer coil for reducing the OD was considered but not feasible due to the small slope of Bi-2212 critical surface at field values in the region of interest. As shown in Table II, this magnet would reach 5.4 T in stand-alone configuration, operating at 90% of SSL. In addition, it would add 3.9 T to a background field of 15 T, meeting the MDP short-term goals.

### Table I

<table>
<thead>
<tr>
<th>Coi and mandrel</th>
<th>Inner Coil</th>
<th>Outer Coil</th>
<th>Inner Coil</th>
<th>Outer Coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>BD (mm)</td>
<td>40.00</td>
<td>73.60</td>
<td>40.00</td>
<td>61.40</td>
</tr>
<tr>
<td>ID (mm)</td>
<td>56.00</td>
<td>81.60</td>
<td>49.00</td>
<td>69.40</td>
</tr>
<tr>
<td>OD (mm)</td>
<td>72.80</td>
<td>98.40</td>
<td>60.60</td>
<td>81.00</td>
</tr>
<tr>
<td>a_w (mm)</td>
<td>1.70</td>
<td>1.70</td>
<td>1.70</td>
<td>1.70</td>
</tr>
<tr>
<td>b_0 (mm)*</td>
<td>8.40</td>
<td>8.40</td>
<td>5.80</td>
<td>5.80</td>
</tr>
<tr>
<td>α (mm)</td>
<td>8.68</td>
<td>8.68</td>
<td>8.47</td>
<td>8.47</td>
</tr>
</tbody>
</table>

*Parameters a_w and b_0 refer to the channel size which was assumed as the size of the insulated cable. The insulation is mullite (2Al_2O_3 : SiO_2) sleeve, 0.1 mm thick, and α = 15°.

![Fig. 2. Loadlines corresponding to the magnet designs based on 19-strand and 13-strand rectangular and keystoned Rutherford cable.](image)
TABLE II
MAGNETIC RESULTS CORRESPONDING TO THE MAGNET DESIGNS BASED ON
19-STRAND AND 13-STRAND RECTANGULAR RUTHERFORD CABLE

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td></td>
<td>(0 T)</td>
<td>(15 T)</td>
<td>(0 T)</td>
<td>(15 T)</td>
</tr>
<tr>
<td>$I_o$ (kA)$^a$</td>
<td>9.8</td>
<td>7.0</td>
<td>7.0</td>
<td>4.9</td>
</tr>
<tr>
<td>$B_c$ (T)$^a$</td>
<td>6.0</td>
<td>19.3</td>
<td>4.6</td>
<td>18.2</td>
</tr>
<tr>
<td>$B_b$ (T)$^a$</td>
<td>5.4</td>
<td>18.9</td>
<td>4.0</td>
<td>17.8</td>
</tr>
</tbody>
</table>

$^aI_o$ is the operating current of the cable at 90% of SSL. $B_c$ and $B_b$ are the maximum field on the conductor and the dipole field at the center of the bore, respectively, at $I_o$. The amounts in parenthesis correspond to the background field provided by the outsert magnet.

B. Mechanical Analysis

The critical current density ($J_c$) of Bi-2212 conductor is strain sensitive. Therefore, careful mechanical analysis is mandatory to ensure that the conductor is working under safe stress levels.

As the peak field is located in the inner coil, Lorentz forces will be larger there. Hence, the spar of the inner layer of the CCT was made thicker to prevent the mandrel from excessive bending and minimize the transverse stress on the conductor.

The mechanical analysis was performed with ANSYS 17.0. The cable was considered bonded in the channel, as well as the layers with respect to each other [8]. Normal stresses in the inner coil under a uniform background magnetic field of 15 T are shown in Fig. 3. Stress values are below the limits for which irreversible degradation of the conductor has been observed.

IV. NOVEL APPROACH TO INCREASE THE EFFICIENCY IN SMALL RADIUS CCT COILS

The efficiency of the dipole field produced in a CCT coil respect to an ideal cos($\theta$) current density distribution is given by:

$$\varepsilon = \frac{\cos (\alpha)}{1 + \frac{R}{\pi w}}$$  \hspace{1cm} (1)

Where $R$ is the rib thickness at the mid-plane, at the radius $r$ (Fig. 1). Fig. 4 shows the efficiency of CCT coils wound with 13-strand and 19-strand rectangular Rutherford cables as function of the ID of the coil. The efficiency decreases as the coil’s ID decreases. In addition, the use of wider cables results in lower efficiency, which is a disadvantage because increasing the size of the cable increases the field in the bore. Both tendencies are especially noticeable at small ID values, as is the case of insert magnets. Therefore, there is need for increasing the efficiency of the CCT magnet concept.

A. Fully keystoned Cable Approach

Removing the ribs at the mid-plane allows the turns to touch each other at the inner radius. This reduces the overall space between turns and increases the field in the bore by increasing $J_E$. Lorentz forces in the mid-plane are only radial [8], so the ribs in this region are not needed to transfer the forces to the spar. However, due to the radial effect (see Fig. 1), the turns would not touch on the wide surface if using a rectangular cable. By
Fig. 4. Field generation efficiency as function of the inner diameter of a CCT coil wound with 19-strand and 13-strand rectangular and keystoned Rutherford cables. For all scenarios with rectangular cable, the minimum rib thickness was assumed equal to 0.25 mm.

Fig. 5. The example from Fig. 1 adapted to the keystoned cable approach.

applying a large enough keystone angle to the cable, the turns fully touch at the mid-plane eliminating this issue. For avoiding sharp edges towards the mid-plane, a section of the mandrel should be removed (Fig. 5).

When removing the ribs at the mid-plane and using a keystoned cable such that the turns fully touch in this region, the efficiency is not affected neither by the radius of the coil nor by the width of the conductor, as shown in Fig. 4. This is very convenient for small radius coils. Table III shows the geometric characteristics of the 19-strand and 13-strand previously proposed designs, adapted to the keystoned cable approach. The efficiency increases by 20% with respect to the designs that use the rectangular cable (Fig. 4).

B. Magnetic Analysis

Table IV shows the results of magnetic analysis for the designs with 19-strand and 13-strand keystoned Rutherford cables. The keystoned cable approach opens a route towards the development of 20 T magnets, and allows reaching the goals of MDP for Bi-2212 inserts with geometric dimensions that would allow them to be tested in future high field outsert magnets.

V. FUTURE PLANS

Subscale magnets using 9-strand rectangular Rutherford cable are being built and are planned to be tested at LBNL to address the main manufacturing issues of Bi-2212 CCT magnets.

Mechanical analysis of CCT coils using keystoned cable and having the ribs in the mid-plane removed will be performed to ensure that the cable of the inner coil is not excessively compressed on the narrow edges at the mid-plane, by the outer layer.

Keystoned cables will be developed to address deformation limits and failure mechanisms in Bi-2212 Rutherford cables with relatively large keystone angle.

VI. CONCLUSIONS

The proposed designs with 19-strand and 13-strand rectangular Rutherford cable meet the short-term goals of MDP for Bi-2212 insert magnets, increasing the field at the magnet bore to 18 T under a background field of 15 T.

The approach of using keystoned Rutherford cables to increase the efficiency of CCT coils would dramatically improve the field generation efficiency, opening a path towards 20 T magnets. Mechanical studies are necessary to prove the feasibility of this novel approach from the structural point of view. The feasibility of cable fabrication with relatively large keystone angles also needs to be demonstrated.
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REFERENCES


