Bi-2212 Canted-Cosine-Theta Coils for High-Field Accelerator Magnets

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***Abstract*—We report on Wind-and-React (W&R) $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) insert coils that were fabricated using a Canted-Cosine-Theta (CCT) coil technology. In the CCT technology, a conductor is wound into canted helical channels that are machined into cylindrical coil winding mandrels, thereby creating a cosine-theta current distribution and providing stress support at the conductor level. The prevention of stress accumulations by the internal structure of winding mandrels is considered an enabling technology for high field Bi-2212 insert coils that target the 20 T magnetic field range. We report on the fabrication and reaction of coils for two proof-of-principle Bi-2212 inserts, BIN1 and BIN2, each consisting of two CCT coils. The BIN1 coils use insulated 0.8 mm diameter wires and INCONEL® 600 coil winding mandrels with a stainless steel 316 shell, an overall diameter of 50.0 mm and a clear bore of 35.3 mm. The BIN2 coils use insulated 6-around-1 cables from 0.8 mm diameter wires, and aluminum-bronze mandrels with an aluminum alloy 6061 shell, an overall outer diameter of 68.6 mm, and a clear bore of 38.8 mm. The coils are designed to study the fabrication, reaction, and impregnation in Bi-2212 CCT technology, and provide a baseline for a Rutherford cable-wound coil set (BIN3). These latter coils target an insert-coil set with optimized current density in the windings, to enable the construction of an 18 T Nb_3Sn — Bi-2212 hybrid dipole magnet.**

***Index Terms*—accelerator magnet, Bi-2212, high temperature superconductor, high magnetic field**

I. Introduction

FUTURE particle accelerators, such as a High-Energy Large Hadron Collider, or a Muon Accelerator, will benefit from, or require, dipole magnets that operate at or above 20 T. Such dipole fields are out of reach of the existing low temperature superconductors, which are limited to about 18 T for Nb_3Sn [1]–[3]. There are three ways to move beyond this 18 T limitation: 1) By increasing the upper critical magnetic field (H_{c2}) of Nb_3Sn [4], 2) by creating engineered pinning centers and/or grain refinement in Nb_3Sn [3], [5], [6], or 3) by developing technology that utilizes superconductors with a higher H_{c2}, such as $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ (Bi-2223), $YBa_2Cu_3O_{7-\delta}$ (YBCO), or Bi-2212. Options 1) and 2) will have to be pursued on a conductor level, whereas our present focus is on option 3).

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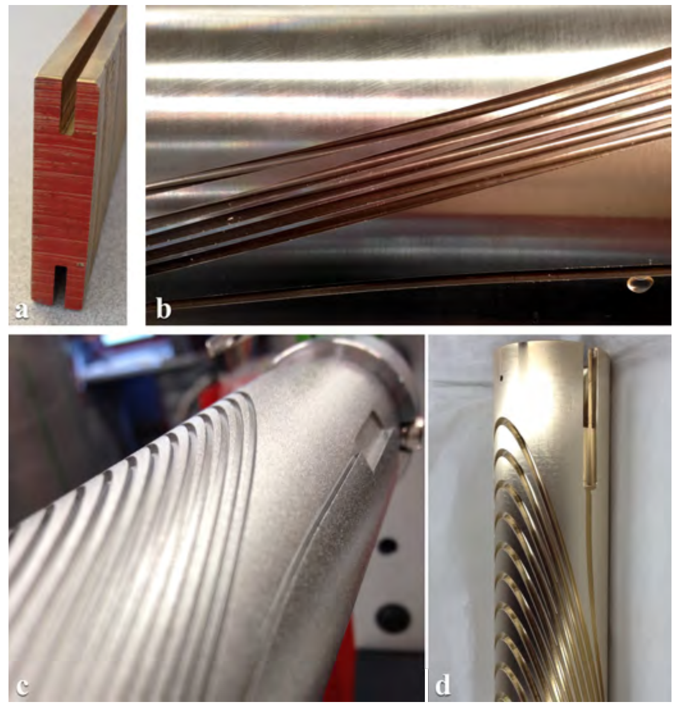

Fig. 1. Mandrels for CCT coils: a) Milling tests of 2×10 mm^2 grooves in alloy 954; b) 2×10.4 mm^2 groove in an alloy 954, 100/127 mm (ID/OD), 5 turn, Nb_3Sn reaction test mandrel; c) 1.05×1.25 mm^2 groove in an INCONEL® 600, 35/41 mm, 54 turn Bi-2212 mandrel; 2.7×3 mm^2 groove in an alloy 642, 39/48 mm, 20 turn Bi-2212 mandrel.

TABLE I
Groove milling speeds for used materials.

Material	Groove width [mm]	Net milling speed m per hour per mm depth
INCONEL® 600	1.05	0.3
SS316LN	2	1.6
Alloy 954	2	40

From the available conductors with increased H_{c2}, we selected Bi-2212 since this is available as an isotropic round wire that can easily be cabled, and since the required [7] wire current density (J_E) of 600 A/mm^2 has repeatedly been demonstrated [8]. Utilization of Bi-2212 in magnet configurations is complicated by the need for a W&R fabrication technique, and a delicate heat treatment cycle with a maximum temperature of 888 ± 1 °C in 1 bar O_2 or in pressures up to 100 bar in an O_2/Ar gas mixture. In our previous work, we have demonstrated the feasibility of Bi-2212 in accelerator magnet configurations, and reproducibly manufactured sub-

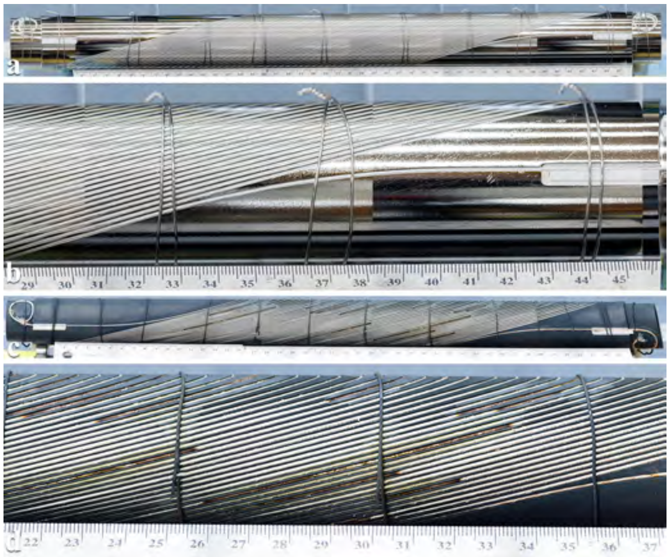

Fig. 2. CCT coils for BIN1: a) Outer layer before reaction: An INCONEL® 600 mandrel with a 1.05 × 1.25 mm^2 rectangular groove, alumina splice boxes, and 0.8 mm wire with alumina-silica braided insulation; b) detail; c) Inner layer after reaction: An INCONEL® 600 mandrel with a 1.05 × 1.25 mm rectangular groove, alumina splice boxes, and 0.8 mm wire with alumina-silica braided insulation; d) detail.

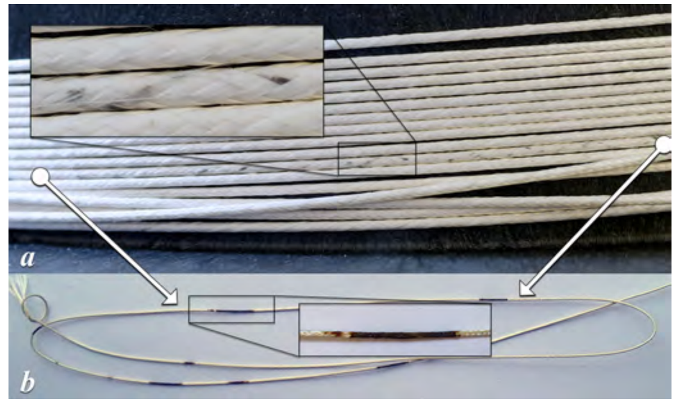

Fig. 3. Insulated wire for BIN1: a) Insulated wire on a spool with a detail of the detected contamination; b) Wire section with contamination after reaction with a detail of the observed leakage.

scale coils from Rutherford cables that achieve 85% of their round wire witness critical currents (I_c) along the coil load-line [9], [10]. Our present goal is to exploit the potential of Bi-2212 in insert coils for a hybrid CCT Nb_3Sn-Bi-2212 magnet described elsewhere [2].

The available strain space for Bi-2212 wires is only about 0.3% [11], despite the full densification of the Bi-2212 fraction that is obtained during high pressure reactions [8]. This result, combined with transverse pressure results on Rutherford cables [12] that suggest perhaps a 60 MPa limit, has led to the choice of a CCT coil configuration, in which the stresses are supported on the conductor level. In this paper, we describe the progress of our Bi-2212 CCT program, in which we develop three coil sets, named BIN1 through BIN3, with step-wise increasing complexity and performance.

The first coil set, BIN1, is a wire-wound two-layer CCT set with 0.8 mm diameter wire, to demonstrate the feasibility of the CCT structure for Bi-2212, without the added complexity of cables. The second coil set, BIN2, is a 2 layer CCT coil set with a 2.4 mm diameter 6-around-1 cable made from 0.8 mm diameter Bi-2212 wire. BIN2 is designed to demonstrate cable performance in a high field background dipole, without the added complexity of high aspect ratio grooves and the small radius hard-way bends that are required for Rutherford cables. BIN3 will be designed as either a 2-layer CCT coil set from 8 mm wide Rutherford cable, or a 4-layer CCT coil set from 6 mm wide Rutherford cable. The target for BIN3 is to provide > 4 T inside a 16 T Nb_3Sn CCT magnet [2].

II. Material choices

In our previous Bi-2212 sub-scale coil program [9], [10], we found that the combination of INCONEL® 600 as coil former material and alumina-silica fiber insulation for our Rutherford cables, provided reliable performance. This combination of materials was therefore selected for BIN1. INCONEL® 600, however, is hard to machine: Machining a a 54 turn 1.05 mm wide, by 1.25 mm deep groove in the inner and outer layer of BIN1 took about 1.5 weeks of machining time per layer on a 3-dimensional (3D) milling machine. We further found Cr-Ag-oxide beads in coils after reaction in our sub-scale program. These beads are presumably a result from a reaction of volatile Cr-oxide at 888 °C reacting with Ag from the wire matrix [13]. We spent substantial time searching for alternative materials, preferably alumina-scale forming metals [14], such as Fe-Cr-Al-Y alloys (FeCrAlloy) as used by Fermilab for the core of their 6-around-1 cable [15]. Alumina-scale forming metals could prevent Cr-oxides and provide an insulating layer in CCT grooves if the oxide can be formed sufficiently thick. Their disadvantage is that they are not readily available and remain difficult to machine.

Following a suggestion by Dr. M. Tomsic of Hyper Tech Research, Inc., Columbus, OH, we tested high aluminum content bronzes (alloys 630, 642, and 954, so far dubbed "Berkalloy") at 888 °C in 1 bar O_2, and found that these alloys provide a striking resilience to oxidation. This resilience to oxidation appears to originate from the presence of 5 to 11 wt.% of aluminum that, according to Ellingham diagrams, reduces copper oxides in favor of the formation of Al_2O_3. A thin surface layer of alumina forms that seals and protects the underlying material from further oxidation, similar to the protective layer that forms on aluminum and its alloys. The formed alumina skin is, unfortunately, not thick enough to provide a reliable electrically insulating layer. There are, however, indications that stimulated oxide formation through anodizing could be possible for high aluminum content aluminum-bronzes, but this has still to be tested. If successful, then anodizing might provide a path to electrically insulated mandrels. In critical current tests with colleagues from the Applied Superconductivity Center at Florida State University (ASC-FSU) on Bi-2212 wires that were reacted in grooved aluminum bronze, we found so far that the 954 and 642 bronze alloys do not affect the I_c of Bi-2212 wires in a 1 bar reaction. Further compatibility tests for a 100 bar

TABLE II
DESIGN PARAMETERS FOR BIN1, BIN2, AND BIN3 BI-2212 INSERT COILS.

Coil	Material	ID/OD [mm]	Turns	Angle	Conductor	Insulation	Design current in 15 T [A][a]	Expected field in 15 T [T][a]	Expected stress in 15 T [MPa][a]
BIN1 inner	INCONEL® 600	35.31/41.40	54	15°	0.8 mm wire	Al_2O_3-SiO_2			
BIN1 outer	INCONEL® 600	41.66/47.75	54	15°	0.8 mm wire	Al_2O_3-SiO_2			
BIN1 shell	SS316LN	48.01/50.04					350	0.3	7
BIN2 inner	Alloy 642	38.80/48.26	20	15°	2.4 mm 6-1	Al_2O_3-SiO_2			
BIN2 outer	Alloy 954	48.51/59.99	20	15°	2.4 mm 6-1	Al_2O_3-SiO_2			
BIN2 shell	Alloy 6061	60.25/68.58					2400	1.0	16
BIN3 inner[b]	TBD	40/64	32	20°	1.5×8 mm^2	TBD			
BIN3 outer[b]	TBD	64/88	32	20°	1.5×8 mm^2	TBD			

[a] If reacted in 1 bar O_2 and 99 bar Ar.
[b] Preliminary and based on a 2 layer design.

reaction are underway, and detailed results of the findings of our compatibility studies will be published elsewhere [16].

Machining tests on alloy 954 (Figure 1a, Table I) further highlight exceptional groove machinability with speeds that are one to two orders of magnitude higher than found for INCONEL® 600, and stainless-steel 316LN (Table I). The high aspect ratio grooves, such as 2 mm wide, 10 mm deep grooves that are required for the use of Rutherford cables in CCT mandrels, are practically impossible to machine using conventional milling, but are enabled through the use of aluminum-bronzes. Specifically we machined high aspect ratio grooves in alloy 954 mandrels with 64 CCT turns for our Nb_3Sn CCT high field program (Figure 1b, [2]).

III. COIL MANUFACTURE

To enable a rapid path from coil design to 3D milling, we invested in the development of fully parametric 3D CAD-CAM for our mandrels and splice boxes. The 3D CAD is closely linked to our in-house 3D CAM milling machine, to further reduce the time from coil concept to fabricated mandrel. In fact, the modeling, fabrication, winding, and reaction of the alloy 642 inner layer of BIN2, was done within two weeks after receiving the raw tube material. If one additional week is scheduled for potting, the time from concept to ready-to-test coil should fit within one month, which is unprecedented fast compared to conventional dipole coil fabrication.

An overview of the main coil parameters for BIN1 through BIN3 is given in Table II. Pictures of the machined inner layers of BIN1 and BIN2 are shown in Figure 1c and d, respectively. Striking differences were observed in the required time to machine the grooves and pockets for the splice boxes in different materials. The 1.05×1.25 mm^2 groove with a total length of about 17 m in the INCONEL® 600 BIN1 inner layer took 1.5 weeks of milling. In the alloy 642 BIN2 inner layer, in contrast, a 2.7×3.0 mm^2 groove of about 8 m length was made within two hours. This is the result of the large differences in machining speed of aluminum-bronzes compared to iron-based metals, as shown in Table I. Machine time for a 2 mm wide, 10.4 mm deep groove with a total length of about 50 m for our alloy 954 mandrel set for Nb-Ti [2] was about 1 week.

Next to high machining speed, also the winding process is attractively simple when compared to conventional cosine-theta and block coil systems. Since the grooves locate the conductor, no winding tension or coil pre-stress are required, and winding typically takes a few hours, and about one or two days in total when setup time is included.

The splice boxes for the INCONEL® 600 BIN1 coil set were fabricated from alumina. In the later BIN2 coil set, aluminum-bronze splice boxes are used that are designed to be removed after coil reaction and replaced by G10 before splicing and potting. To retain a modular system, the individual layers are spliced outside the coil pack. This enables replacement of limiting coils, and possibly even replacement of limiting conductor by re-using the machined mandrels. To allow for such replacements at the development stage, our coils will be potted with bees wax, which is a reversible process.

The potting process itself is also a new development in which the coils are provided with aluminum plugs, wrapped with Teflon® sheet, and sealed using heat shrink tube and clamped metal sheet. Potting tests have so far been performed on a 5 turn Nb_3Sn reaction and potting dummy (see [2]). The BIN1 and BIN2 coil sets will be tested in self-field and are therefore designed with a shell. The shell material is chosen to provide thermal pre-compression on the coil set during cooldown to cryogenic temperature.

IV. COIL REACTION

The lengths of the coil sections that contain Bi-2212 are limited to 50 cm, since this is the specified homogeneous temperature zone for new a 100 bar furnace that is under construction at ASC-FSU. LBNL's in-house HTS furnace that was used to react our sub-scale coils [10] has a homogeneous length of 65 cm. Eventually we plan to react our coils in the 100 bar system at ASC-FSU, but since this system is not yet operational, we reacted the BIN1 and BIN2 inner layers at 1 bar at LBNL, accepting that limited leakage can occur as a result of the internal pressure inside the wires during the heat treatment, and that not the full current potential can be achieved [8].

The inner layer of BIN1 showed substantial leakage after reaction (Figure 2). The observed leakage is much more than the few mm-size spots that we found in our sub-scale program using similar wire form Oxford Superconducting Technology [9], [10]. Moreover, the leakage appears periodic, with sections of about 10 cm long that exhibit severe leakage, separated by a number of turns in which leakage is absent.

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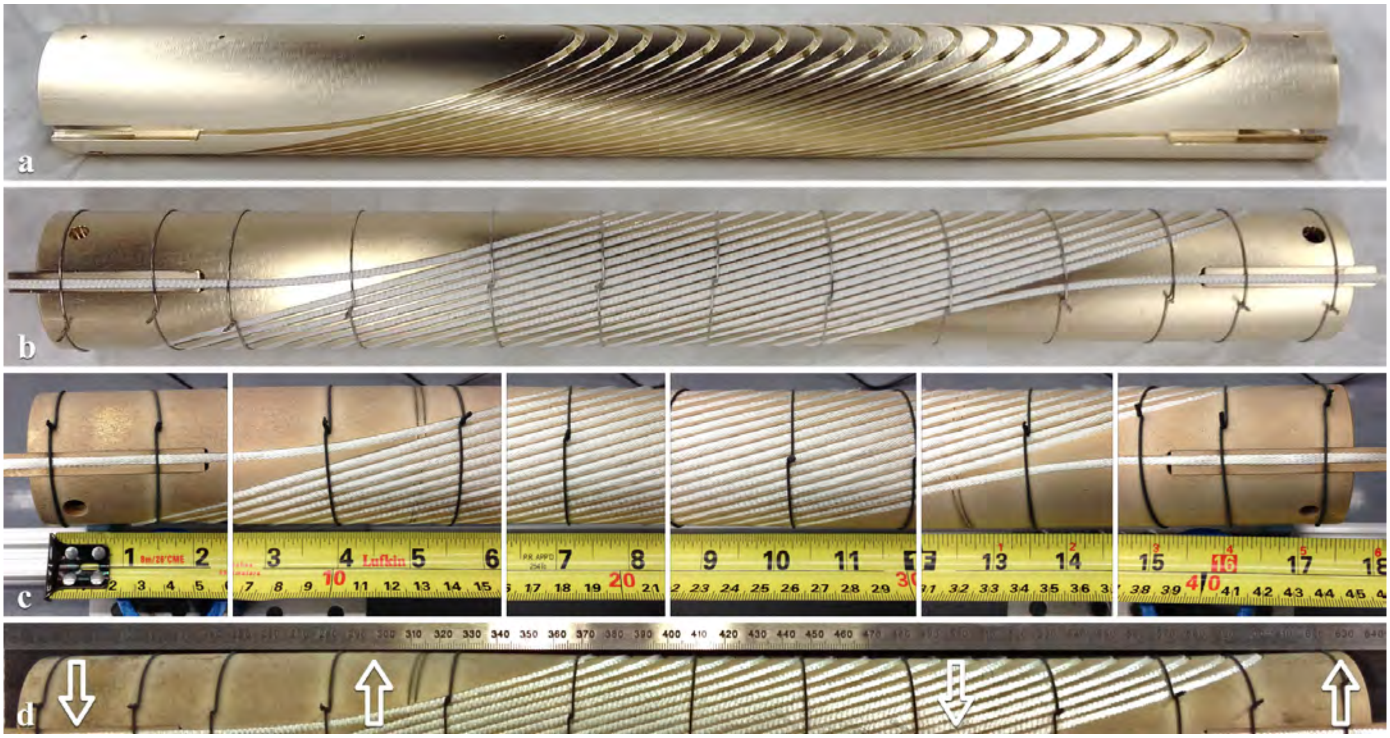

Fig. 4. Inner layer CCT coil for BIN2: a) Machined alloy 642 mandrel with a 2.7 × 3.0 mm^2 round-bottom groove; b) With 6-around-1 alumina-silica sleeve insulated cable made from 0.8 mm Bi-2212 wire, and alloy 954 splice boxes, before reaction; c) After reaction; d) False color picture of the coil after reaction to emphasize the observed mandrel distortion.

Closer inspection of insulated wire that remained on the spool after coil winding highlighted similar about 10 cm sections, in which one or more yarns in the braided insulation show black contamination (Figure 3). The distance between the contaminated sections is on the same order as the spacing between the leakages in the reacted BIN1 inner layer (around 2 m). Reaction of wire sections that contained this contamination showed leakage on the sides of the contaminated sections, but also in wire sections where the insulation did not appear contaminated (Figure 3). We conclude therefore that the leakage in the BIN1 inner layer most likely originates from compromised wire and/or insulation.

The inner layer of BIN2 after reaction shows only minor coloration of the insulation around the poles, but appears unprecedented clean for a 1 bar reaction (Figure 4c, [9], [10]). Only one localized spot of about 2 mm in size was detected where limited leakage occurred. It can therefore reasonably be expected that this combination of materials will be entirely leak-free when reacted at 100 bar.

The bore and outer diameter of the inner layer of BIN2 was first rough machined, and the tube was reacted at 888°C in 1 bar O_2 for 5 hours before final machining and groove milling. This was done to relieve potential material stresses. The tube did indeed distort significantly during this pre-reaction. Unfortunately, the mandrel distorted again during the Bi-2212 partial melt reaction, as is visible from Figure 4d.

Reaction of the outer layer of BIN2 will determine whether alloy 954 is similarly compatible and whether this alloy shows similar distortions during the reaction as the alloy 642 that was used for the inner layer of BIN2. If alloy 954 proves less compatible, and/or if it similarly distorts during reaction, then methods have to be developed to prevent the mandrel distortions during heat treatment. Such methods could, for example, consist of providing a ceramic backbone to the mandrels during the heat treatment.

V. Conclusion

Following earlier demonstrations of the feasibility of W&R Bi-2212 for accelerator magnet coils, and analysis of the strain margin in Bi-2212, we are now developing insert coils for very high field accelerator magnets using the CCT technology. An insert coil series of increasing complexity and performance, BIN1 through BIN3, has been laid out and BIN1 and BIN2 coils have so far been manufactured and reacted. The use of aluminum-bronze as a new material for CCT mandrels has been demonstrated as an compatible enabler for high aspect ratio grooves in Nb-Ti, Nb_3Sn, as well as Bi-2212 CCT coils. Further studies are needed to mitigate the observed mandrel distortions during heat treatment.

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