Title

Fabrication of Bi-2212 Canted-Cosine-Theta Dipole Prototypes

Journal
IEEE Transactions on Applied Superconductivity, 29(5)

ISSN
1051-8223

Authors
Fajardo, Laura Garcia
Brouwer, Lucas
Caspi, Shlomo
et al.

Publication Date
2019

DOI
10.1109/tasc.2019.2896725

Peer reviewed

Fabrication of Bi-2212 Canted-Cosine-Theta Dipole Prototypes

Laura Garcia Fajardo, Lucas Brouwer, Shlomo Caspi, Aurelio Hafalia, Christopher Hernikl, Soren Prestemon, Tengming Shen, Ernesto Bosque, and Charles English

***Abstract*—The U.S. Magnet Development Program (MDP) is exploring the possibility of combining low- and high-temperature superconductor technologies, using cosine-theta and canted-cosine-theta (CCT) Nb_3Sn dipole magnets together with Bi-2212 CCT inserts, with the ultimate goal of constructing a 20-T dipole. The MDP short-term goal is a Bi-2212 CCT insert capable of reaching 5 T in the bore when operating as a stand-alone and 3 T when operating under a background field of 15 T. This paper reports on the fabrication of our BIN4 dipole magnet and our BIN5a and BIN5b coils, designed and built at the Lawrence Berkeley National Laboratory to address potential fabrication issues of Bi-2212 coils and verify the design of our 18–20-T dipole magnet. BIN4 is a two-layer 50-cm-long CCT magnet that uses a nine-strand Rutherford cable made with 0.8-mm-diameter Bi-2212 strands. Its goal is to investigate critical current, insulation integrity, manufacturing challenges, and quench protection issues after heat treating both layers together under oxygen at standard atmosphere (1 bar). BIN5a and BIN5b are two identical coils, similar to the outer layer of BIN4, with the difference that the length is 39 cm, and they will undergo 50-bar overpressure processing heat treatment. BIN5 coils are made from the state-of-the-art strand with an engineering critical current density of 1150 A/mm^2 at 4.2 K and 5 T.**

I. Introduction

Future accelerator magnets providing 20 T and beyond will require using high temperature superconductors (HTS) in combination with low temperature superconductors (LTS), by placing HTS coils in the high field region of the magnet, because the critical current of the state of the art LTS decreases quickly at fields above 16 T [1] while the magnetic field of several HTS conductors can reach values up to 45 T [2], and some of them are fabricated as multi-filamentary wires, like Bi-2212, that can be made into Rutherford cables.

However, in creating the Bi-2212, the raw superconducting compound needs to undergo a heat treatment (HT) cycle with a maximum temperature of 888 ± 1 C in 1 bar, O_2 environment, or in pressures up to 100 bar in O_2/Ar gas mixture environment [3]. After HT, the critical current of Bi-2212 becomes strain sensitive. This implies careful handling of the conductor and special magnet structural designs to manage the Lorentz forces and prevent damaging and degrading the sensitive conductor. This requires the coils to be fabricated by the wind-and-react process, which poses technical problems as the coil's mandrel material should withstand very high temperatures without significant deformation to maintain the field quality, and keep its mechanical properties to prevent the conductor from being damaged.

The Canted-Cosine-Theta (CCT) magnet technology provides the possibility of intercepting the Lorentz forces at each turn of the winding and transferring them to the mandrel. This prevents stress accumulation in the turns [4]. The use of Al-bronze as material for CCT mandrels has been demonstrated as a suitable candidate for machining high aspect ratio grooves for Nb-Ti, Nb_3Sn, and Bi-2212 CCT coils [5]–[7].

The U.S. Magnet Development Program (US-MDP) and LBNL are exploring the LTS-HTS technology to combine Cosine-Theta (CT) and CCT Nb_3Sn magnets with Bi-2212 CCT inserts towards reaching 20 T [8]. The MDP short-term goal is to fabricate a Bi-2212 insert is to produce a bore field of 5 T when operating in stand-alone configuration and 3 T when operating under a background field of 15 T. Two design options for the Bi-2212 insert were proposed in [9], using 13 and 19 strand Rutherford cables made of 0.8 mm diameter wires.

Previous Bi-2212 CCT coils were fabricated at LBNL: BIN1, BIN2 and BIN3. This work was reported in 2015 [5] and methodically described the increase in complexity in the design, fabrication and testing of Bi-2212 CCT coils with various mandrel and conductor configurations. In addition, high aluminum content bronzes were evaluated as possible mandrel materials. They proved to be resilient to oxidation due to the formation of an Al_3O_3 layer that protected the underlying material from further oxidation. Also, these materials were compatible with Bi-2212 during HT. Al-bronze 954 is easy to machine, and is the material of choice for our CCT magnet coils at LBNL [5]–[7].

In this paper, we present the design and fabrication of BIN4, a two-layer Bi-2212 CCT magnet prototype, and BIN5a and BIN5b, two identical coils, similar to the outer layer of BIN4.

This work was supported in part by the Director, Office of Science, and Office of High Energy Physics of the U.S. Department of Energy under Contract DE-AC02-05CH11231 and in part by the Office of Science, U.S. Department of Energy, through the Early Career Research Program. *(Corresponding author: Laura Garcia Fajardo.)*

L. Garcia Fajardo, L. Brouwer, S. Caspi, A. Hafalia, C. Hernikl, S. Prestemon, and T. Shen are with Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA (e-mail: lgarciafajardo@lbl.gov; lnbrouwer@lbl.gov; s_caspi@lbl.gov; rrhafalia@lbl.gov; cdhernikl@lbl.gov; soprestemon@lbl.gov; tshen@lbl.gov).

E. Bosque and C. English are with the National High Magnetic Field Laboratory, Tallahassee, FL 32310 USA (e-mail: bosque@magnet.fsu.edu; cenglish@magnet.fsu.edu).

TABLE I
BIN4 Mandrel Design Parameters

Mandrel parameters	Inner layer	Outer layer
Inner diameter (mm)	38.10	51.10
Outer diameter (mm)	50.30	63.50
Length (cm)	50.00	50.00
Channel thickness (mm)	1.89	1.89
Channel depth (mm)	4.23	4.23

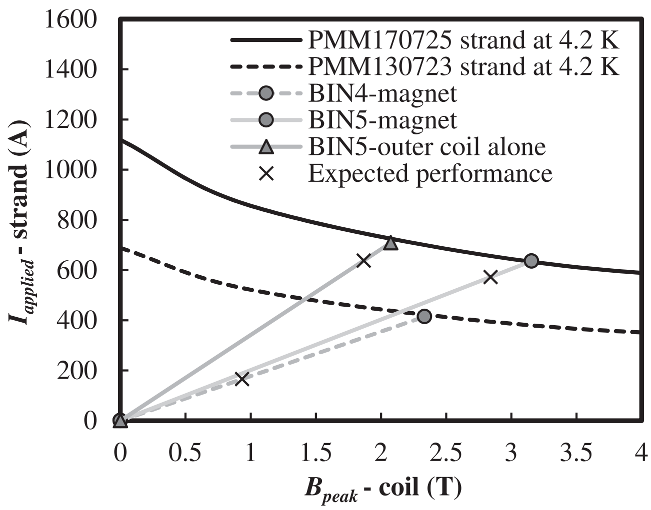

Fig. 1. Loadlines of BIN4 magnet, BIN5 magnet and BIN5 outer coil alone. The expected performance is related to the pressure during HT.

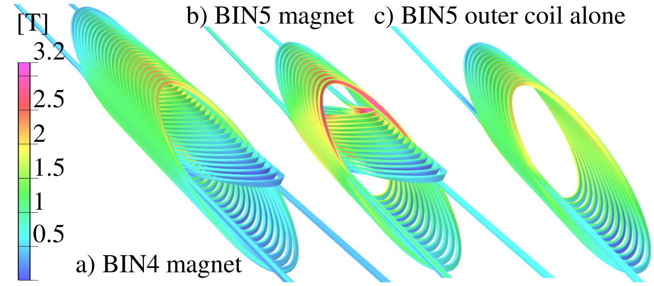

Fig. 2. Magnetic field distribution (B) on the conductor at the short sample limit for the different configurations, from OPERA-3D.

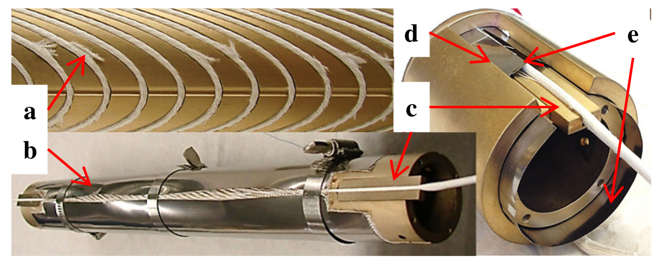

Fig. 3. Winding and assembly of BIN4. (a) Insulation damage during the winding process. (b) Ti foil on top of the mullite cloth to ease the assembly process. (c) Al-bronze 954 splice box to keep the conductor in place during HT. (d) Windows in the outer layer enable access to the splice regions of the inner layer. (e) Ti foil displaced towards one end during assembling.

The purpose of these coils is to be able to address the technical difficulties that are encountered during the fabrication process. The magnet and coils will also be tested to investigate the critical current, insulation integrity and quench protection issues when applying different fabrication techniques.

II. Design and Fabrication of BIN4 Prototype

BIN4 is a two-layer CCT dipole magnet prototype. The conductor is a 9-strand Rutherford cable, approximately 4 mm wide and 1.5 mm thick, made with 0.8 mm diameter Bi-2212 wires. The cable is insulated with mullite ($Al_2O_3 + SiO_2$) braided sleeve, approximately 100 μm thick. The coils have 25 turns with a 15° tilt angle. The magnet has 10 mm straight section for field quality measurements. The mandrels are made of Al-bronze 954 and their design parameters are shown in Table I.

The goal of BIN4 is to investigate the critical current, insulation integrity, manufacturing challenges and quench protection issues after heat treating both layers together under oxygen at 1 bar, at LBNL. There is no OPHT furnace available to us with a homogeneous temperature zone >50 cm. Consequently, we expect some leakage as a result of the internal pressure inside the wires during the HT [10], and the conductor to perform only at ∼40% of its predicted capability [2]. The loadline of BIN4 is shown in Fig. 1. The Bi-2212 conductor used was PMM130723. The magnetic field distribution on the conductor at the short sample limit is shown in Fig. 2(a).

Al-bronze 954 mandrels tend to deform during the high temperature HT, therefore, there should be enough clearance between layers to enable the assembly process after HT. By heat treating both layers together we intend to minimize the gap between layers to 0.4 mm and make an insert magnet with a small outer diameter.

After machining the mandrels, the sharp edges of the channels were smoothed by placing the mandrels in a tumbler machine with ceramic pieces for 2 hours. However, during the winding process, the very brittle mullite sleeve scraped as it was inserted in the machined channel, especially near the pole regions (Fig. 3(a)). Winding the inner layer was more challenging due to the smaller mandrel radius. We also encountered shorts in the straighter sections, probably due to abrasion between the already inserted cable and the machined channel surfaces while the cable was being manipulated. From this experience, only one layer of mullite sleeve is not enough to electrically insulate the conductor.

The inner coil was wrapped with a mullite cloth, approximately 200 μm thick, and a 200 μm thick Ti foil was wrapped over it, (Fig. 3(b)). The Ti foil eased the assembly process as the finished inner coil was inserted into the outer coil prior to HT. The Ti foil between layers becomes TiO_2 during HT, and, together with the mullite cloth, insulates the coil layers from each other.

During HT, the conductor is kept in place in the splice regions by using Al-bronze 954 boxes (Fig. 3(c)). After HT, the Al-bronze boxes will be replaced by G-10 boxes that will fit two Nb-Ti Rutherford cables, 2 mm wide and 1.5 mm thick, soldered on each side of the reacted Bi-2212 bare cable. This Nb-Ti cable splice procedure will be applied at both ends of the magnet: for the current leads at one end and for the splicing between layers at the other end. The outer layer has a window (open region) at both ends facilitate the splicing of the inner layer leads after HT (Fig. 3(d)).

During the assembly process, the Ti foil was kept in place using stainless steel (SS) clamps that were removed progressively as the inner coil was being inserted. After removing the last clamp, the stiff Ti-foil outwards towards the outer layer and, as the insertion continued, the friction displaced it longitudinally towards the end (Fig. 3(e)). This does not represent a problem and can be avoided in future prototypes.

The layers are aligned and locked with two SS pins at each end. In order to avoid the SS to sinter in the mandrels during HT, through holes were tapped with threads and the pins were replaced with easily removable set screws.

The BIN4 coils will be tested in self-field. Hence, it is designed with an aluminum shell around it that will provide thermal compression during the cooldown to 4.2 K. The shell will also be part of the impregnation tooling. Voltage taps will only be installed near the splice boxes before potting the magnet.

III. Design and Fabrication of BIN5a and BIN5b Coils

The initial goal of a second prototype called BIN5 was to investigate the critical current, insulation integrity, manufacturing challenges and quench protection issues after undergoing OPHT (at 50 bar). The design is very similar to BIN4, except that it is only 39 cm long, the coils have 14 turns and there is no straight section, because the only OPHT furnace available to us is at NHMFL, and it has a homogeneous temperature region of only 42 cm. The Bi-2212 Rutherford cable used is made with state of the art PMM170725 strand, donated by NHMFL. The layers would be heat treated separately in order to be able to install voltage taps in both coils at every turn. The loadline and the magnetic field distribution on the conductor are shown in Figs. 1 and 2(b), respectively. The performance of the conductor is expected to be 90% of its predicted capability [2].

After the experience gained in fabricating BIN4, we decided that it was necessary to improve the insulation before winding a new coil. We also implemented ways to investigate the effect of modifications in the fabrication processes on conductor performance and studied ways of minimizing the potential warpage of the mandrels during OPHT. With these in mind, two outer layers of BIN5 were fabricated: BIN5a and BIN5b. The loadline of the outer coil alone and the field distribution on the conductor are shown in Figs. 1 and 2(c), respectively.

The channel thickness of the mandrels was increased at the pole regions in order to ease the winding process and to make room for installing voltage tap flags and adding extra amount of mullite cloth around them.

The winding process of BIN5a is shown in Fig. 4(a)–(d). The mandrel was fixed with Al end caps to the winding support. The winding procedure involved gently twisting and pre-bending the cable insulated with mullite sleeve, then inserting it into the channel for half a turn. Then, it was carefully taken out, painted with TiO_2 slurry S88 [11], [12] (donated by NHMFL), dried with a heat gun and placed back into the channel. This method was very effective and no shorts were detected.

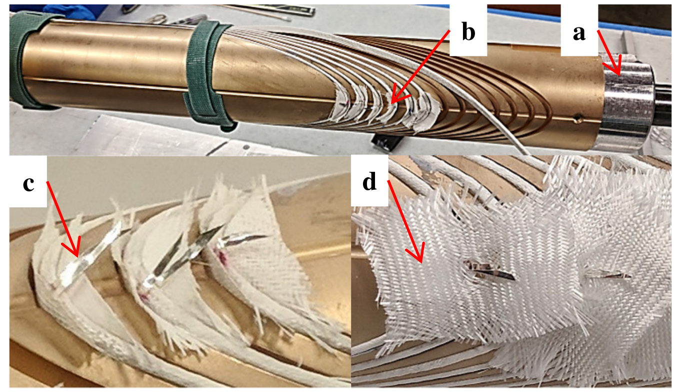

Fig. 4. Winding process of BIN5a. (a) Al end caps to fix the mandrel on the winding support. (b) Extra mullite cloth painted with TiO_2 slurry at every pole. (c) Ag voltage tap flags installed at every turn. (d) Mullite cloth below every voltage tap flag to protect them during OPHT.

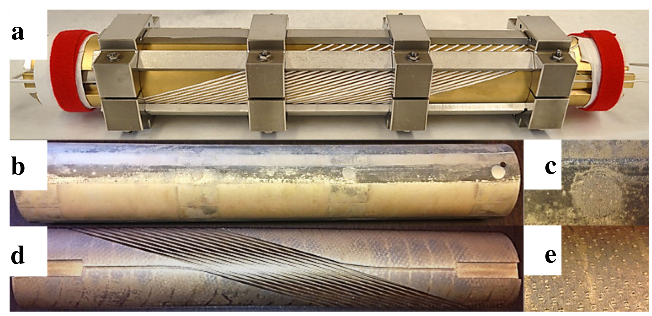

Fig. 5. Mandrels after pre-oxidation HT. (a) Inconel 600 strongback before HT, placed on BIN4 magnet. (b) BIN5 dummy after HT. (c) Zoom-in of surface imperfections of BIN4/BIN5 dummies after HT. (d) BIN5b mandrel after HT. (e) Zoom-in of surface imperfections of BIN5b mandrel after HT.

One voltage tap flag was installed in the pole region for every turn during the winding process. They were made of 99.95% pure Ag foil, 76 µm thick. They were cut by hand and inserted by looping them around the cable inside the insulation, so that they were in contact with most of the wires (Fig. 4(c)). After finishing the winding process, pieces of mullite cloth were placed between the voltage tap flags and the mandrel to protect them during OPHT. Al-bronze 954 boxes are used to keep the conductor in place at the ends of the mandrel during OPHT (Fig. 4(d)). The coil was wrapped with Nextel 610 cloth with Inconel 600 wire mesh wrapped over the Nextel, and sent to NHMFL for OPHT.

During HT, Al-bronze mandrels react with oxygen and create an Al_3O_3 layer. This layer is needed to protect the underlaying material, but some of the oxygen that is required to create the superconductor is consumed. Pre-oxidizing the mandrel in a short HT cycle before the winding process would help to improve the HT of the conductor afterwards. For exploring this option, the BIN5b mandrel was selected to undergo a short HT cycle at 1 bar. In order to minimize its distortion during the HT cycle, a strongback structure consisting of six Inconel 600 bars surrounding the mandrel, positioned and fixed by four Inconel 600 clamps, was fabricated (Fig. 5(a)).

To study the effectiveness of the strongback, two Al-bronze 954 dummy mandrels without any channels were fabricated

TABLE II
MAXIMUM MANDREL TRANSVERSE DISTORTION

Mandrel	After HT with strongback	After HT without strongback
BIN4 dummy	0.215 mm	0.286 mm
BIN5 dummy	0.247 mm	0.327 mm
BIN5b	0.612 mm	Not applicable

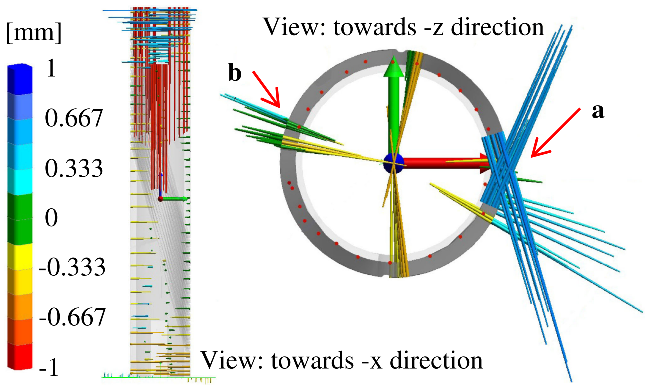

Fig. 6. Distortion at one end of BIN5b mandrel after HT with strongback. (a) Window region. (b) Splice region.

with similar mass and length as the BIN4 magnet and the BIN5 coils. The dummies were heat treated in direct contact with the strongback, which left marks on their surfaces (Fig. 5(b) and (c)). BIN5b was wrapped with Nextel 610 cloth and Inconel 600 wire mesh before placing the strongback on it. This procedure protected the mandrel from surface damage (Fig. 5(d) and (e)).

Survey measurements of BIN4 and BIN5 dummies were done before HT, after HT with strongback and after HT without strongback (in that order), with a portable articulating CMM arm, with stated volumetric accuracy of 37 µm. The planar and cylindrical geometry for each part was recorded and used to compare the measurements before and after HT, using Spatial Analyzer Software. The maximum post-HT transverse distortions of the mandrels, are displayed in Table II. The strongback prevented the dummies from excessive warpage: the maximum transverse distortion was $\sim$0.25 mm (smaller that the gap between the layers). As expected, the warpage after HT without strongback was larger. The difference with and without strongback is small because the internal stresses were mostly relieved after the first HT.

Survey measurements were also done to BIN5b before HT and after HT with strongback. The most significant distortions are shown in Table II and Fig. 6.

Since the inner diameter of the mandrel was not constrained, the maximum distortion occurred in the window region. As a consequence, the Al end caps used to fix BIN5a to the winding support did not fit in the inner diameter of BIN5b. Therefore, smaller ones were made (Fig. 7(a)). This indicated that an inner layer for BIN5b will need to be designed with a smaller outer diameter than the inner layer of BIN4. Also, the splice region sufficiently deformed such that the Al-bronze boxes did not fit in the cavity (Fig. 7(c) and (d)). Last, the channel shrank in the region where the transition between the leads and the

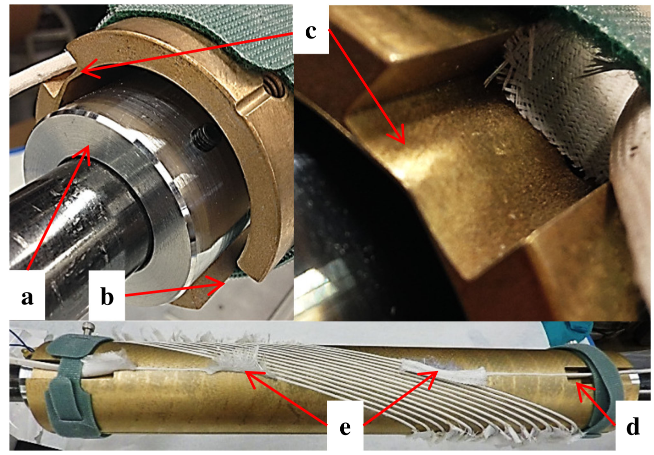

Fig. 7. Winding process of BIN5b after pre-oxidation HT. (a) Smaller Al end caps needed due to deformation in the window region. (b) Window region. (c) Visible bending in the splice region. (d) Al-bronze boxes did not fit in the splice cavity. (e) Insulation reinforcement needed after damage caused by shrinkage of the channel in some regions.

turns occurred (near the ends), and the insulation was damaged during winding even though the cable was painted with TiO_2 slurry. Therefore, additional mullite cloth painted with TiO_2 slurry was added (Fig. 7(e)) and the cable had to be pushed very hard inside the channel.

IV. CONCLUSIONS

In this paper, we presented the design and fabrication of BIN4, a Bi-2212 CCT dipole magnet prototype, and BIN5a and BIN5b, two Bi-2212 CCT coils. The goal was to discover and address the technical problems encountered during the fabrication processes of these types of magnet coils.

Electrical shorts were observed during the winding process of BIN4, caused by breakage of the brittle mullite sleeve. Painting the cable with TiO_2 slurry while winding BIN5a and BIN5b coils, proved to be an effective solution for avoiding the shorts.

Assembling the inner layer of BIN4, insulated only with mullite cloth, is difficult when there is a small clearance gap between the layers. The assembly process became easier by wrapping the inner layer with a Ti foil wrapped around the mullite cloth. The Ti foil will become TiO_2 during HT and will increase the insulation between the layers.

Excessive warpage of the dummy mandrels during the pre-oxidation HT was prevented by fabricating an Inconel 600 strongback. However, the CMM measurements made on BIN5b showed that the inner diameter at the ends of the mandrel needed to be constrained to avoid deformation in the window region.

Short-term future plans include HT at 1 bar for BIN4 at LBNL, and OPHT at 50 bar for BIN5a and BIN5b at NHMFL. Fabrication of the Nb-Ti splice soldering fixture and potting tooling is underway.

ACKNOWLEDGMENT

The authors would like to thank Mechanical Technician Timothy Bogdanof for all the effort and help during winding and pre-oxidation of the mandrels at LBNL.

References

[1] E. Todesco and P. Ferracin, “Limits to high field magnets for particle accelerators,” *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, Jun. 2012, Art. no. 4003106.

[2] D. C. Larbalestier *et al.*, “Isotropic round-wire multifilament cuprate superconductor for generation of magnetic fields above 30 T,” *Nature Mater.*, vol. 13, pp. 375–381, Apr. 2014, doi: 10.1038/NMAT3887.

[3] I. Hossain *et al.*, “Effect of sheath material and reaction overpressure on Ag protrusions into the TiO_2 insulation coating of Bi-2212 round wire,” *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 279, no. 1, 2017, Art. no. 012021.

[4] L. Brouwer *et al.*, “Structural analysis of an 18 T hybrid canted–cosine–theta superconducting dipole,” *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, Jun. 2015, Art. no. 4000404.

[5] A. Godeke *et al.*, “Bi-2212 canted-cosine-theta coils for high-field accelerator magnets,” *IEEE Trans. Appl. Supercond.*, vol. 5, no. 3, Jun. 2015, Art. no. 4002404.

[6] S. Caspi *et al.*, “Test results of CCT1—A 2.4 T canted-cosine-theta dipole magnet,” *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, Jun. 2015, Art. no. 4002304.

[7] S. Caspi *et al.*, “Design of a canted-cosine-theta superconducting dipole magnet for future colliders,” *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, Jun. 2017, Art. no. 4001505.

[8] S. Gourlay *et al.*, “The U.S. Magnet Development Program,” 2016. [Online]. Available: https://science.energy.gov/∼/media/hep/pdf/Reports/MagnetDevelopmentProgramPlan.pdf

[9] L. G. Fajardo *et al.*, “Designs and prospects of Bi-2212 canted-cosine-theta magnets to increase the magnetic field of accelerator dipoles beyond 15 T,” *IEEE Trans. Appl. Supercond.*, vol. 28, no. 4, Jun. 2018, Art. no. 4008305.

[10] T. Shen *et al.*, “Role of internal gases and creep of Ag in controlling the critical current density of Ag sheathed $Bi_2Sr_2CaCu_2O_x$ wires,” *J. Appl. Phys.*, vol. 113, no. 21, 2013, Art. no. 213901.

[11] J. Lu *et al.*, “Ceramic insulation of $Bi_2Sr_2CaCu_2O_{8-x}$ Round wire for high-field magnet applications,” *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, Jun. 2016, Art. no. 7701005.

[12] H. Kandel *et al.*, “Development of TiO_2 electrical insulation coating on Ag-alloy sheathed $Bi_2Sr_2CaCu_2O_{8-x}$ round-wire,” *Supercond. Sci. Technol.*, vol. 28, 2015, Art. no. 035010.