Design, Construction, and Test of HTS/LTS Hybrid Dipole

Ramesh Gupta, Michael Anerella, John Cozzolino, Piyush Joshi, William Sampson, Peter Wanderer, James Kolonko, Delbert Larson, Ron Scanlan, R. Weggel, and Erich Willen

***Abstract*—This paper presents the design, construction, and test results of a hybrid dipole magnet. The inner coils were of second generation (2G) high-temperature superconductor (HTS) ReBCO tape and the outer coils were of low-temperature superconductor (LTS) Nb_3Sn Rutherford cable. The HTS and LTS coils were independently powered and protected using different power supplies. The HTS coils were quenched many times with no degradation in performance observed. The hybrid field reached ∼8.6 T, which is believed to be a record for a hybrid dipole. The maximum field was limited by the stable operation of the leads in the LTS coil at 8000 A. The HTS coils were independently ramped to 800 A, and the LTS coils to 10 000 A. With improved leads and instrumentation, this hybrid dipole is expected to produce over 13 T when the ReBCO tape in the HTS coil is aligned nearly parallel to the field. One major purpose of this program was to perform magnetization studies in the coils made with the HTS tape. Magnetization-induced field errors are expected to be small when the field is nearly parallel to the wide face of the tape. The magnetization measurements were performed at 77 K with the two racetrack coils in two orientations, with field predominantly either parallel or perpendicular to the wide face of the HTS tape. In addition, measurements were also performed at 4 K in different background fields provided by the outer Nb_3Sn coils. This paper will summarize the magnetization measurements and present the quenching experience of the HTS coils in this hybrid magnet system.**

***Index Terms*—Superconducting magnets, high field magnets, hybrid dipoles, HTS magnets.**

I. Introduction

INTEREST in HTS/LTS hybrid dipoles has risen recently as a way to provide very high fields for future high energy colliders, such as the proposed Future Circular Collider (FCC) or High Energy upgrade to the Large Hadron Collider (HE-LHC) at CERN [1], [2] or the proposed Super proton-proton collider in China [3]. A hybrid dipole was assembled and tested recently as a part of a Small Business Technology Transfer (STTR) program with the Department of Energy (DoE) grant to Particle Beam Lasers, Inc. (PBL) and Brookhaven National Laboratory (BNL). This was possible within the limited budget of the STTR due to an existing unique Nb_3Sn common coil dipole [4] that has a large open space (see Fig. 1 and Table I) where the new HTS racetrack coils could be inserted without disassembling the magnet. The new HTS coils made direct contact with the existing LTS coils and became an integral part of the HTS/LTS hybrid magnet structure.

Manuscript received August 26, 2017; accepted December 21, 2017. Date of publication January 5, 2018; date of current version January 15, 2018. This work was supported in part by the Brookhaven Science Associates, LLC under Contract DE-SC0012704 and in part by the U.S. Department of Energy STTR under Grant DE-SC0011348 to Particle Beam Lasers, Inc. *(Corresponding author: Ramesh Gupta.)*

R. Gupta, M. Anerella, J. Cozzolino, P. Joshi, W. Sampson, and P. Wanderer are with Brookhaven National Laboratory, Upton, NY 11973 USA (e-mail: gupta@bnl.gov).

J. Kolonko, D. Larson, R. Scanlan, R. Weggel, and E. Willen are with Particle Beam Lasers, Inc., Northridge, CA 91324-2807 USA.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TASC.2017.2787148

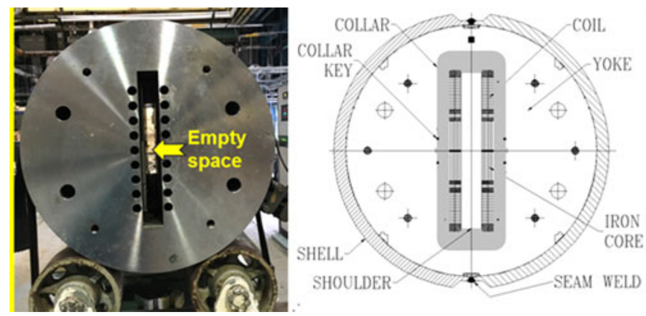

Fig. 1. The Nb_3Sn common coil at BNL with large empty space available for HTS insert coils (see left) and sketch (see right) schematically showing this empty space (31 mm wide and 338 mm high) between the Nb_3Sn coils.

TABLE I
MAJOR PARAMETERS OF THE LTS DIPOLE DCC017 FOR HTS INSERT COILS

Dipole design	2-in-1 common coil
Coil Technology	Nb_3Sn React & Wind
Horizontal aperture (clear space)	31 mm
Vertical aperture (clear space)	338 mm
Number of LTS coil layers	Two
Computed quench current	10.8 kA
Peak field at quench current	10.7 T
Computed quench field @4.2 K	10.2 T
Coil length (overall)	620 mm
Coil straight section length	305 mm
Coil inside radius in ends	70 mm
Yoke length	653 mm

II. Magnet Design

The program is based on the 2-in-1 common coil magnet design [5], in which the simple racetrack coils are common to two apertures with field of opposite polarity, as required in collider magnets. Fig. 2 (left) shows the basic common coil concept with a pair of racetrack coils. Fig. 2 (right) shows a magnetic model of the upper-half quadrant of the hybrid magnet

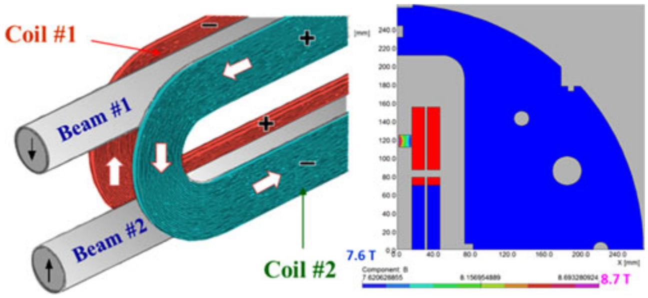

Fig. 2. The basic concept of the common coil design (left) with a pair of racetrack coils producing field in opposite directions in two apertures, and the magnetic model of the upper-right quadrant (right) of the magnet tested.

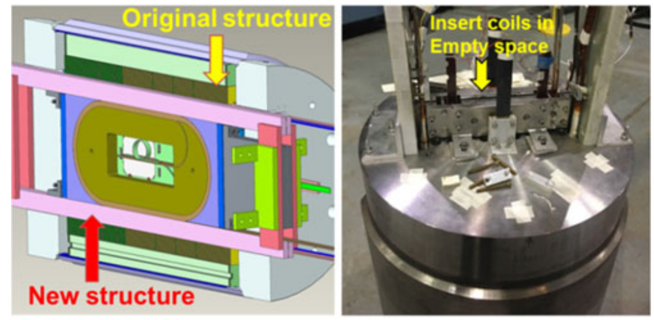

Fig. 4. Schematic design (left) of the hybrid magnet and the actual structure (right) with the new HTS coils inserted inside the LTS magnet.

Fig. 3. Coil being wound with the universal coil winder with 4-ply ASC tape and Nomex insulation. A number of voltage-taps were also installed.

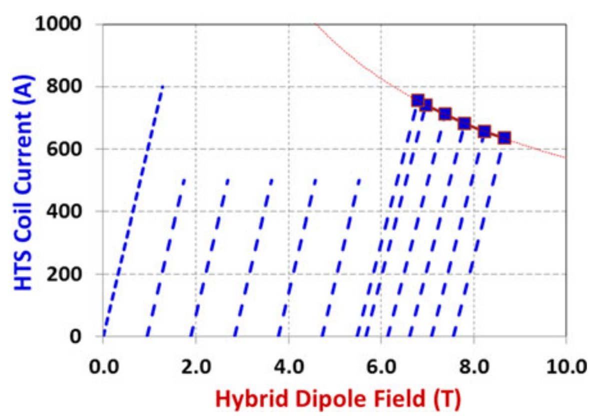

Fig. 5. Performance of hybrid dipole magnet as a function of the current in HTS coil under at the various fields generated by constant current in the Nb_3Sn coils.

as built and tested. This magnet had two sets of Nb_3Sn coils, as shown in red, and one set of HTS coil, with the range of colors superimposed showing the magnitude of the field computed (7.6 T to 8.7 T) for 635 A in the HTS coils and 8000 A in the Nb_3Sn coils. The iron yoke is shown in blue.

III. Magnet Construction

Two pancake coils were wound with ~12 mm wide, 4-ply HTS tape (2 consisting of ReBCO and other 2 copper) from American Superconductor Corporation (ASC). The cross-section of the coil was purposely chosen to be square for easier comparison during magnetization studies (see next section). Each coil had 35 turns made with ~25 m of double HTS tape (100 m of ~12 mm wide HTS tape in two coils). Fig. 3 shows winding of the racetrack coil with the BNL universal coil winder; turn-to-turn insulation was Nomex tape 50 micron thick and ~12 mm wide.

After a number of 77 K tests in liquid nitrogen, the HTS coils were installed inside the LTS magnet. A schematic of the hybrid design, with the new HTS coil structure inserted without disassembling the LTS magnet, is shown Fig. 4 (left). The actual hybrid magnet assembly is shown in Fig. 4 (right). The two HTS coils were internally connected in the middle of the magnet (where the field is low) with an innovative flexible splice [6]–[8] that allowed the HTS coils to move (separate) without significantly straining the splice.

IV. Hybrid Magnet Test

A number of tests were performed at 4 K with only the HTS coils powered, only the Nb_3Sn coils powered, and with the two coils powered together in various combinations. There was concern about how the Nb_3Sn magnet DCC017 itself would perform after a decade in storage, but it reached 10,000 A (92% of the short sample) without a quench. The maximum hybrid dipole field reached during the test was ~8.7 T (Fig. 5) with ~7.6 T coming from the Nb_3Sn coils at 8 kA. The hybrid field of ~8.7 T (a record at this time), at 10,000 A in Nb_3Sn coils, was limited by stable operation of the external leads, not the coils.

The HTS coils were powered at various background fields (a) in the cycle of 0 A to 500 A to 0 A without quenching and (b) to the highest current possible until they quenched (see Fig. 5). No degradation in the performance of HTS coils was observed after repeated quenching. This is despite the fact that the HTS coils were allowed to quench in a similar way that LTS coils are quenched, with the coil voltage during the ramp rising as much as 200 mV (see Fig. 6). The BNL advanced quench protection system [9] and rapid energy extraction strategy worked well, as described in more detail in a separate paper in this conference [10].

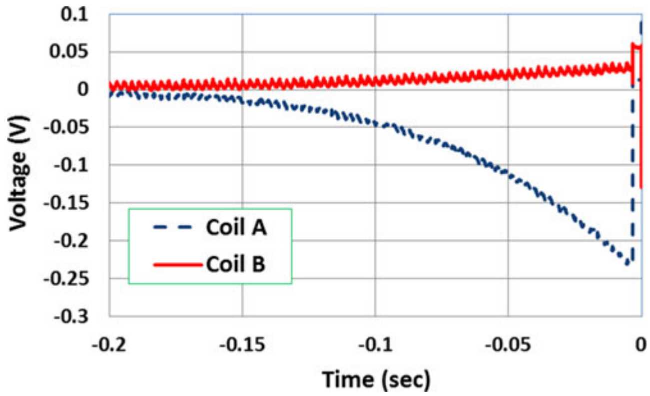

Fig. 6. Quench detection in HTS coils with a difference voltage threshold of 200 mV. HTS coils remain protected after repeated quench due to the BNL advanced detection and rapid energy extraction system.

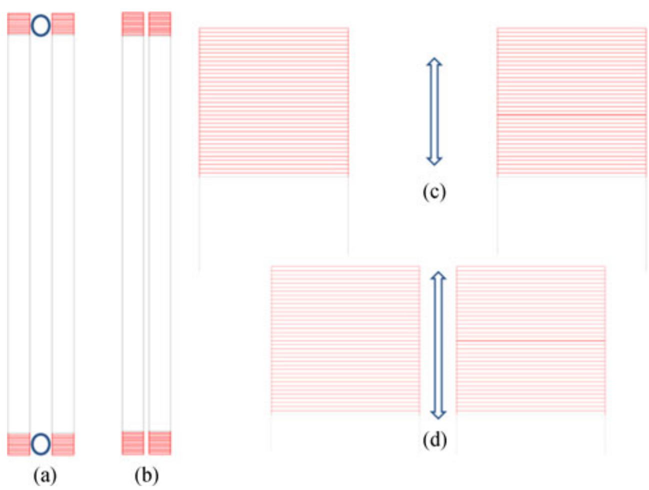

Fig. 7. A schematic diagram showing the relative size of the coils and location of Hall probe during the test in the common coil configuration. Case (a) is for coils separated by 12 mm; (b) for 3 mm. (c) and (d) are the details of the upper aperture showing the orientation of tape more clearly.

V. Magnetization Measurements

Before the ReBCO coils were installed inside the niobium tin magnet, they were tested in liquid nitrogen. Magnetic field measurements were made along the axis of the aperture using a Siemens SBV604 Hall probe. The usual common coil set-up is shown in Fig. 7 when the horizontal spacing between two coils is (a) 12 mm and (b) 3 mm. In this configuration the field on the median plane is perpendicular to the wide face of the conductor, and the magnetization currents are expected to be maximized.

The effect of the induced magnetization current shows up most dramatically at zero current after an excursion to high current. Fig. 8 shows the result of raising the current in 25 A steps to 200 A with a return to zero between each step for a gap of 12 mm between the coils. An interval (∼10 minutes) was allowed both at current and at zero for the field to stabilize. For the geometry of Fig. 7, the residual or trapped field depends quite strongly on the maximum current reached and is unexpectedly opposite in sign to the powered field (see Fig. 9). The slow field

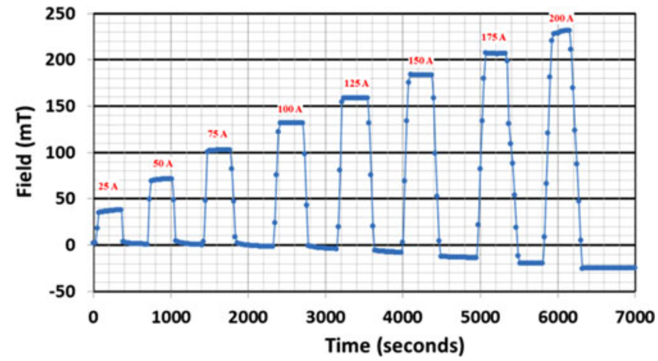

Fig. 8. Measurements of residual fields at zero current after the current is raised from 0 A to 200 A in the steps of 25 A with return to 0 A between each step (e.g., 0 → 25 → 0 → 50 → 0 → 75 → 0, . . .).

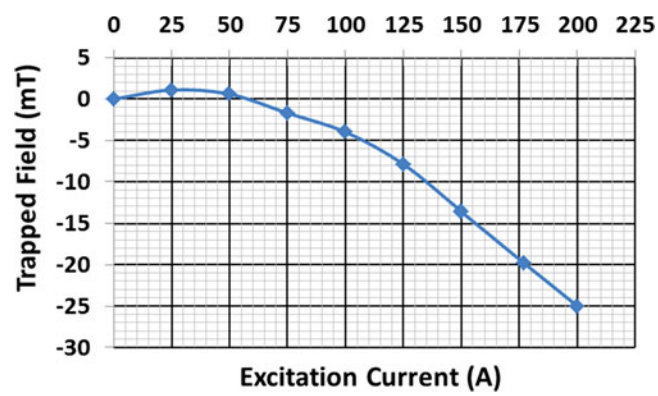

Fig. 9. Trapped field when the current in HTS coil is brought to zero as a function of the current in HTS coils to which it was energized (the run sequence is shown in Fig. 8).

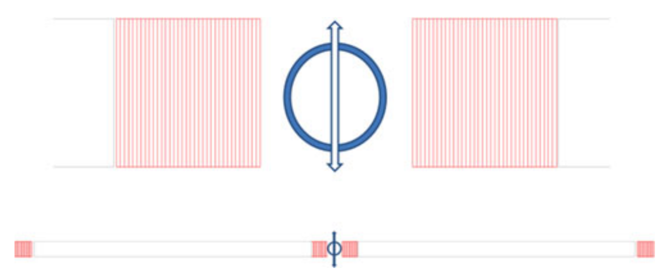

Fig. 10. A schematic diagram showing the relative size of the coils and location of Hall probe during the test in the side by side configuration (see sketch at the bottom). Upper sketch gives the details of the aperture showing the orientation of tape more clearly.

changes that occur at this end of each step are more pronounced in this coil configuration.

For the coil arrangement of Fig. 10, where the conductor is parallel to the field at the median plane, the trapped field is in the same direction as the normal field and looks quite similar to the residual field of a solenoid of the same cross section. Fig. 11 shows a scan along the coil axis for the magnetization field compared to a suitably scaled powered curve. The maximum trapped field in this configuration is less than half of the field in the perpendicular conductor orientation.

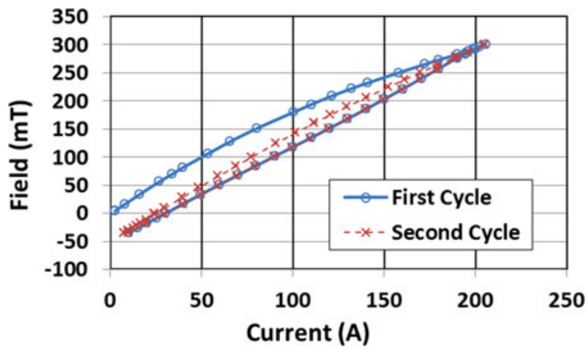

Fig. 11. Field as a function of current during first two cycles.

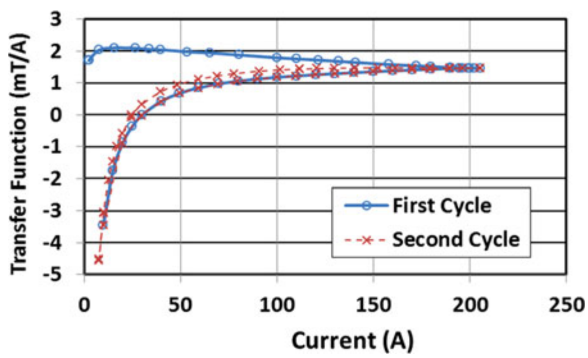

Fig. 12. Transfer Function as a function of current during first two cycles.

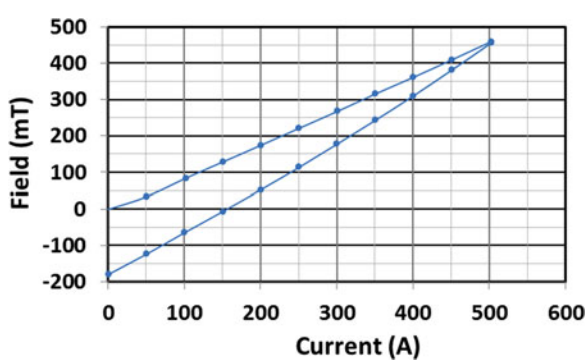

Fig. 13. Field due to HTS coil as a function of current at the background field of ∼2 T (offset introduced in the curve to make them start from zero).

When installed in the Nb_3Sn dipole, the coils are much closer together, and the Hall probes are fixed at the center of each aperture (Fig. 11). While assembled in the stainless steel frame but before insertion in the high field magnet, the coils were re-measured at 77 K. Fig. 13 is a current field plot for two successive excursions to 200 A. On the first cycle the conductor begins with no magnetization just after cool down and ends with a significant negative residual field. The second cycle starts from this negative level and follows the down half of the first cycle but slightly displaced (hardly visible in Fig. 13) toward higher fields. The second down cycle is identical to the first down cycle, and subsequent current cycles are the same as the second one.

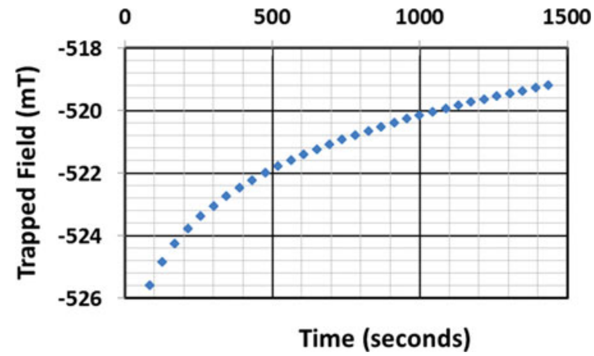

Fig. 14. Decay of trapped field with time.

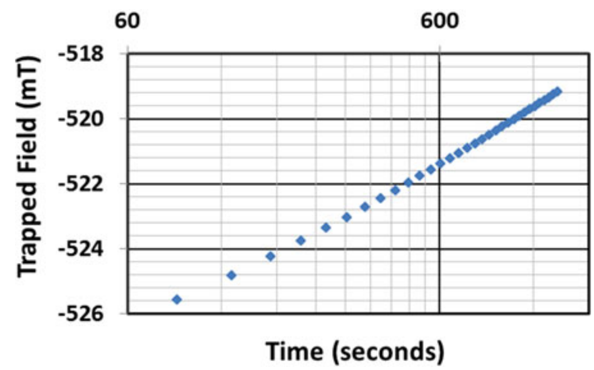

Fig. 15. Decay of trapped field with time in logarithmic scale.

It takes approximately 20 A to just get back to zero field at the center of the aperture.

The effect of the magnetization currents is amplified if the curves are plotted as the transfer function, B/I, against current as shown in Fig. 12. With the coil separation reduced to 3 mm the negative trapped field is two and a half times as large as for the 12 mm spacing, whereas the increase in actual field was about 20%. As such the value falls on the extrapolated line if the plot is normalized to the field.

When tested at 4.5 K, the magnetization currents induced in the HTS conductor by the much higher field of the Nb_3Sn magnet result in a very large negative trapped field of approximately 500 mT. This residual field is present because the HTS coil test didn't start from a virgin state. A trapped field was left behind from the earlier energizing of the HTS and Nb_3Sn coils to test and set the parameters of the quench protection system. At each applied field level the insert coils were energized to 500 A (as shown in Fig. 5). Fig. 13 shows the field from the HTS coil (offset introduced to start curve from 0) as a function of current in the HTS coils for a background field of ∼2 T (2 kA current in Nb_3Sn coils). In this case the field at the center of the aperture starts lower than the applied field and rises with the HTS current but returns to an even lower field when the HTS current returns to zero.

The large negative residual field was observed for several hours with both coils de-energized. It slowly decreases in magnitude with time as shown in Fig. 14.

The data of Fig. 14 is plotted using a logarithmic time axis in Fig. 15. The trapped field decreases at about one percent per decade. The first one percent takes about one hour, while the next one percent takes 10 hours, so that the trapped field is quite stable with time after the first few minutes of being induced. All 4 K measurements were performed with the HTS coils placed with LTS coils with a gap between the HTS coils of ~3 mm.

VI. Conclusion

The successful operation of the HTS coils with Nb_3Sn coils shows that a HTS/LTS hybrid dipole is a practical concept. The HTS coils remained protected during operation and didn't show any measurable degradation despite half a dozen quenches. Magnetic measurements indicate that the magnetization effects are strongly dependent on the coil geometry and might be kept at low enough for a practical accelerator magnet if the field is close to parallel to the conductor over the HTS portion of the windings. The whole project was completed in a short period of time at low cost. This is because of the unique design and structure of the BNL common coil magnet with a large open space where HTS coils were inserted inside the LTS magnet and made an integral part of the hybrid structure without requiring any magnet disassembly.

References

[1] "Future circular collider study kickoff meeting," University of Geneva, Geneva, Switzerland, Feb. 12–14, 2014. [Online]. Available: http://indico.cern.ch/event/282344/timetable/#20140212

[2] L. Bottura *et al.*, "Advanced accelerator magnets for upgrading the LHC," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, Jun. 2012, Art. no. 4002008.

[3] CEPC-SppC Preliminary Conceptual Design Report, Vol. II: Accelerator. Tech. Rep., 2015. [Online]. Available: http://cepc.ihep.ac.cn/preCDR/Pre-CDR_final_20150317.pdf

[4] R. Gupta *et al.*, "React & wind Nb_3Sn common coil dipole," *IEEE Trans. Appl. Supercond.*, vol. 17, no. 2, pp. 1130–1135, Jun. 2007.

[5] R. Gupta, "A common coil design for high field 2-in-1 accelerator magnets," in *Proc. Particle Accelerator Conf.*, Vancouver, BC, Canada, vol. 3, 1997, pp. 3344–3346.

[6] R. Gupta, "HTS/LTS hybrid test results and common coil design update," in *Proc. FCC Week 2017*, Berlin, Germany, May 29–Jun. 2, 2017. [Online]. Available: https://indico.cern.ch/event/556692/

[7] R. Gupta, "Hybrid configuration and BNL activities," in *Proc. US MDP 1st General Meeting Workshop Napa Valley*, Napa, CA, USA, Feb. 6–8, 2017. [Online]. Available: https://conferences.lbl.gov/event/73/

[8] R. Gupta, "ReBCO at BNL," in *Proc. 4th Workshop Series Accelerator Magnets High Temperature Supercond.*, Barcelona, Spain, Feb. 15–17, 2017. [Online]. Available: https://indico.cern.ch/event/588810/

[9] P. N. Joshi *et al.*, "Novel quench detection system for HTS coils," in *Proc. 2011 Particle Accelerator Conf.*, New York, NY, USA, Mar. 28–Apr. 1, 2011, pp. 1136–1138.

[10] P. N. Joshi *et al.*, "LTS-HTS hybrid dipole magnet quench protection system," presented at the 25th Int. Conf. Magnet Technology, Amsterdam, The Netherlands, 2017, Paper Thu-Mo-Or28-03.