New Approach and Test Facility for High-Field Accelerator Magnets R&D

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***Abstract*—This paper presents a new approach for developing and demonstrating high field magnet technology based on a magnet and test facility developed specifically for it. The traditional approach for carrying out high field magnet R&D has been building a new magnet to demonstrate a new design, new material or new technology. However, building a high field magnet is time consuming and expensive. To overcome this limitation, Brookhaven National Laboratory (BNL) built and successfully tested a 10 T Nb_3Sn dipole DCC017 with large enough open or clear space (31 mm wide and 338 mm high) so that a pair of racetrack coils could be inserted into this opening without disassembling the magnet. The motivation behind this design was to facilitate a magnet R&D program where the new coils (with a large range in width and height accommodated) would reside in a high field region in direct contact with the existing coils (just as other magnet coils) and thus become an integral part of the magnet. We summarize the approach, the magnet, the test facility, past experiences, current and future test plans and planned upgrade. The magnet facility is now available to service the needs of the wider community for testing cable and insert coils in a background field of up to 10 T.**

***Index Terms*—Superconducting magnets, high field magnets, magnet R&D, magnet technology.**

I. Introduction

THE traditional approach for developing high field magnet technology has been building and testing one or a series of R&D magnets. This includes testing the coils to a higher field than ever before even though it is only the innermost coil which experiences the high field. In addition, one typically builds a new magnet to demonstrate (a) coils built with new conductors, such as ReBCO, Bi2212, etc., (b) coils made with new cables or conductor processed differently, (c) coils made with new insulation, (d) coils made with new epoxy or (e) other variations in coil design or its components. Building and testing a new magnet, however, takes several years and a significant budget. Since the absence of building and testing coils near the design field (particularly in high field magnets), increases the risk, it has shaped our thinking. If it takes several years and a significant budget, it puts pressure on the magnet program to demonstrate a success. That discourages us from deviating significantly from those "that sort of works" and limits optimizing of a "sort of working technology". In fact, it limits the development of a new technology "unless one has to."

On the other hand, if a magnet doesn't work, and if there is no clear understanding of the cause responsible for the poor performance of the magnet, there is a tendency to make several changes at the same time to make it work. Then if the magnet starts working, it becomes difficult to distinguish what specific change made it work. This often leads to institute all changes in the next magnet whether they were needed or not.

Therefore, the cost and time needed to demonstrate a new technology at high fields has limited the development of new technologies and optimization of the existing ones. A new approach and a comprehensive magnet development program ought to encompass strategies to overcome the above inherent limitations.

II. New Approach

The guiding principle of the proposed new approach is to develop a test vehicle where new coil technology can be tested in a short period of time (a few months) and in a reasonable budget (few hundred k$). The test should be performed at a significant field (10 T or above) making it relevant for high field magnet technology. We are proposing this to be done through a background field magnet where the new coils can be inserted (see Fig. 1) without having to disassemble and reassemble the magnet to facilitate a low-cost rapid-turn-around. The new insert coils should be in direct contact with the existing magnet coils to become an integral part of the overall coil package and of the magnet. The new coil test then may be considered as an R&D test of the new magnet technology short of building a new magnet.

If the proposed approach (described above) works, then it should change our thinking on how we plan magnet R&D. It will allow us to be more enterprising since a potential setback will be considered a failure of a coil, not failure of the magnet and thus be less dramatic. Moreover, rapid-turn-around will also allow systematic studies to optimize existing technology.

III. The Facility Magnet

This section describes a magnet that serves the approach mentioned above. It also discusses some key considerations.

A. The Basic Design and Construction of Dipole DCC017

BNL built and successfully tested a 10 T Nb_3Sn common coil dipole DCC017 [1]–[4] consisting of a pair of racetrack coils.

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Fig. 1. A magnet wherein new coils in a fixture can be inserted in the magnet without any need to disassemble and reassemble the magnet (coils are not included in the fixture above).

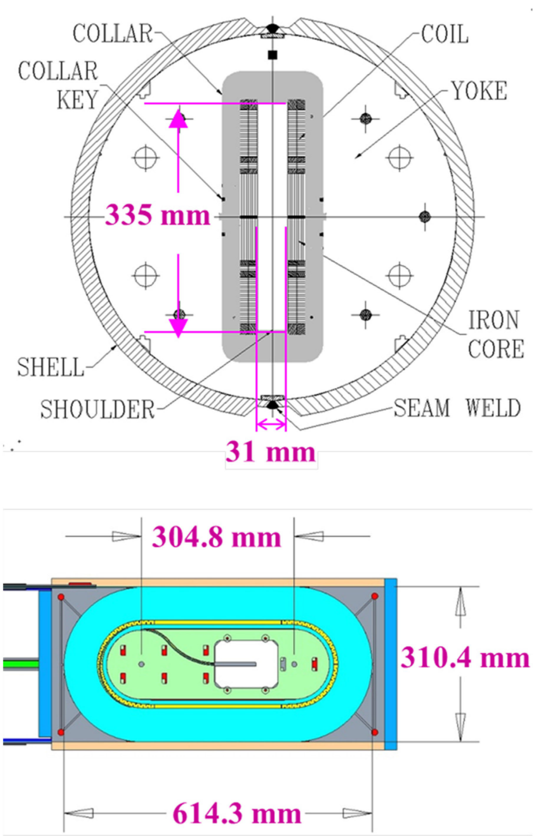

Fig. 2. The drawing on the top shows the overall design of the magnet with an opening which is 31 mm wide and 335 mm high. The sketch on the bottom shows overall design of the Nb_3Sn magnet coil.

A unique feature of this magnet was an open or clear space that is large enough to allow insertion and test of a wide range of racetrack coils. Fig. 2 (top) shows the overall design of the magnet with an opening which is 31 mm wide and 335 mm high. One or more coils could be inserted in this opening. The overall design of one of the four identical coils in this magnet is shown in Fig. 2 (bottom). The insert coils are expected (but not required) to have a cross-section and length that lies within the profile of these magnet coils.

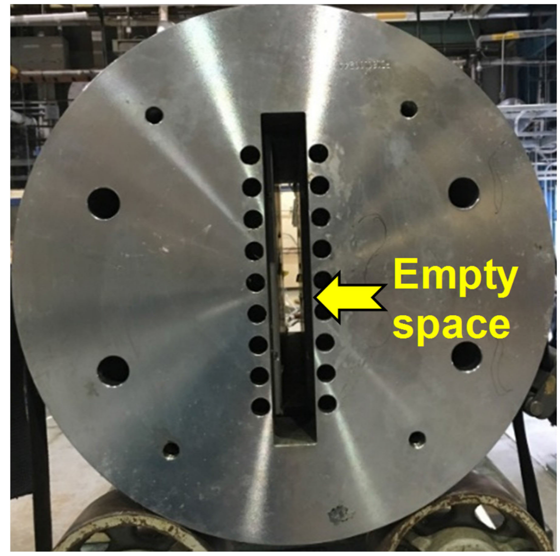

Fig. 3. BNL Nb_3Sn common coil dipole DCC017 with a capability to provide a background field of a little over 10 T.

The actual magnet with the empty space and a clear opening is shown in Fig. 3 and the details of the design are given in Table I. The motivation behind building this magnet was (a) to demonstrate "React & Wind" technology in a Nb_3Sn common coil dipole and (b) a design that allows the R&D approach discussed in the Section II. The magnet was intended to facilitate a test program where the new coils reside in a high field region, in direct contact with the existing Nb_3Sn magnet coils and thus become an integral part of the magnet. This approach, therefore, makes each insert coil test a new magnet test, but at a much "lower cost" and in a much "shorter turn-around time". This should bring a significant shift in our future R&D approach and should encourage development and testing of innovative and so called, "high-risk, high reward" designs and technologies. This should also facilitate systematic studies of various coil parameters that require a series of tests but would otherwise be impractical because of the associated budget and time.

B. *Benefits of the Rectangular Opening*

The BNL common coil dipole magnet DCC017 has a rectangular opening for insert coil testing. A rectangular geometry (particularly with a large vertical space) has several inherent advantages over the circular bore as available in the conventional cosine theta dipoles. For example, it provides a flexible structure to allow a different number of insert coil modules whose relative position can be interchanged (this is not possible in circular geometry as different coil modules will need to have different radii). These coil modules may have different height and/or different width as long as they fit in the opening. These coils can be made of different materials.

The same opening can also be used to test cables. The large vertical opening can accommodate even those cables that can't be bent to a small radius. Moreover, since the bent section could stay in high background field (the bent section can also be moved

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TABLE I
MAJOR PARAMETERS OF REACT & WIND COMMON COIL DIPOLE DCC017

Magnet design	2-in-1 common coil dipole with racetrack coils
Conductor type	Nb_3Sn
Magnet technology	React and wind
Horizontal coil aperture (clear space)	31 mm
Vertical coil aperture (clear space)	335 mm
Separation between the magnetic center of the upper and lower aperture	236 mm
Number of layers	Two
Number of turns per quadrant of single aperture (pole-to-pole)	45 turns in each layer
Coil height (pole-to-pole)	85 mm
Wedge(s) (size and number)	8.5 mm, one in each layer (inner & outer)
End-spacer(s) (size and number)	8.5 mm, one in each layer (inner & outer)
Wire non-Cu J_{sc} (4.2 K, 12 T)	1900 A/mm^2
Strand diameter	0.8 mm
Number of strands in inner and outer cable	30
Cable width (inner and outer layers)	13.13 mm
Cu/Non-Cu ratio in the wire (same for both inner and outer cables)	1.53
Computed quench current (limited by inner)	10.8 kA
Computed quench field @4.2 K	10.2 T
Peak field at quench in inner, outer Layer	10.7 T, 6.1 T
Special electrical feature (not used)	Shunt between layers
Computed stored energy at quench	0.2 MJ
Computed inductance	4.9 mH
Coil bobbin (core) material	Carbon steel
Coil length (overall)	614.3 mm
Coil straight section length	304.8 mm
Coil height (overall)	310.4 mm
Coil inside radius in ends	70 mm
Coil outside radius in ends	155 mm
Coil curing preload - sides	0 N
Coil curing preload – ends	0 N
Insulation thickness between turns	180 µm thick Nomex®
Potting agent	CTD-101K
Thickness of the collar	26.6 mm
Thickness of stainless-steel sheet between inner and outer layers	1.65 mm
Vertical pre-stress applied	17 MPa (low)
Horizontal pre-stress applied	Essentially none
Computed horizontal stress on structure	59 MPa at 10.2 T
Design maximum for horizontal stress	75 MPa
Stainless steel shell thickness	25.4 mm
Thickness of the end plates	127 mm
Yoke outer radius	267 mm
Yoke length	653 mm
Quench protection strip heaters (no energy extraction available during the tests)	25 µm X 38.1 mm, each quadrant, between layers

out of the magnet in no-field region if desired), the effect of bending degradation can be studied in field. Furthermore, these cables can be looped for a longer length cable test in a high field region. The 31 mm horizontal opening allows cable with a large range in diameters (if circular) or widths and heights (if rectangular) to be accommodated.

C. *Insert Coils Becoming an Integral Part of the Magnet*

The goal of the proposed R&D approach is to be able to insert racetrack coils in the magnet opening and then make them become an integral part of the magnet. In order to allow this insertion (or sliding), there must be some minimum space or tolerances between the insert coils and the magnet coils (typically 0.1 mm). If a pair of racetrack coils are being inserted (which is expected to be the most used test configuration), then there needs to be an internal splice between two coils, so that only two leads come out.

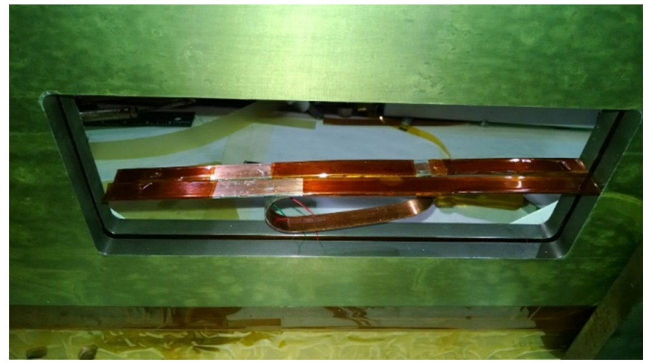

Fig. 4. A flexible HTS splice with copper stabilizer allowing a small relative motion of a few mm. The splice resides in the low field region of the BNL Nb_3Sn common coil dipole DCC017.

The pair of coils, with relative current in opposite direction for a common coil dipole configuration with field adding to the field of dipole DCC017, will move apart under Lorentz forces. Only a small magnitude of the Lorentz force is needed for the insert coils to make the contact with the main Nb_3Sn coils and hence it will happen at low current where the margins are large. This makes insert coils come in direct contact with the main coils of DCC017 and makes them an integral part of the magnet.

However, the method of integration requires a flexible splice between two coils which allows and tolerates motion of a couple of millimeters without becoming a weak link to the program. Several designs for this flexible splice made with HTS tape and copper stabilizer were considered and tested at 77 K for a motion of few mm. The one chosen for the final magnet is shown in Fig. 4 as installed between the pair of racetrack coils. It has a loop which facilitates the required flexibility and performed well both in a test set-up at 77 K and in the magnet at 4 K [5]. An inherent advantage of the common coil design is that this splice could be entirely situated in the low field region of the magnet [1], [5].

D. *Capacity of the Magnet Structure*

The structure of the magnet should be able to handle the additional stresses generated by the insert coils. In particular, the horizontal component of the Lorentz force is expected to cause additional deflections on the support structure and additional stress/strain on the Nb_3Sn coils. In this regard, the structure of the dipole DCC017 had a significant margin [1], [3] as it was originally designed for a higher field and larger aperture magnet. The ANSYS calculations [6] show that the DCC017 structure is able to accommodate a field of 16 T generated by the combination of the insert coils and the Nb_3Sn coils in the case examined. Fig. 5 (left) shows the stress and Fig. 5 (right) shows the strain on the insert coil (inner-most with smaller height) and on the Nb_3Sn magnet coil (outer two with larger height). The stress on the Nb_3Sn coils remains below 150 MPa and strain below 0.25%. The stress and deflection on the collar (not shown here) were also acceptable.

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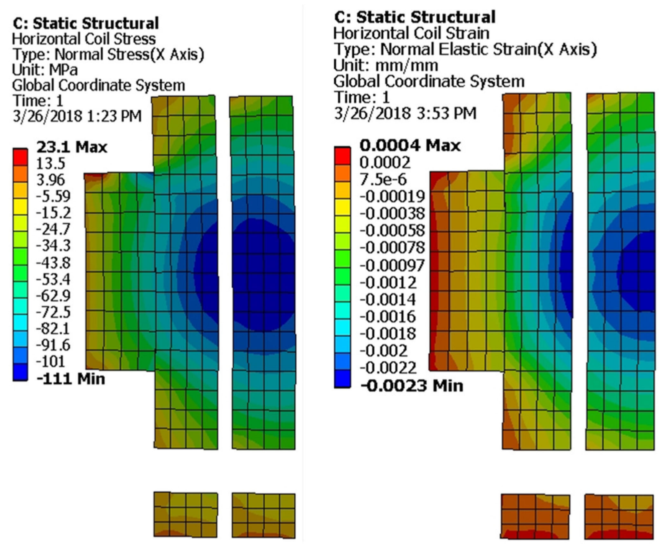

Fig. 5. Stress (left) and strain (right) on the insert coil (inner-most) and Nb_3Sn magnet coil (outer two).

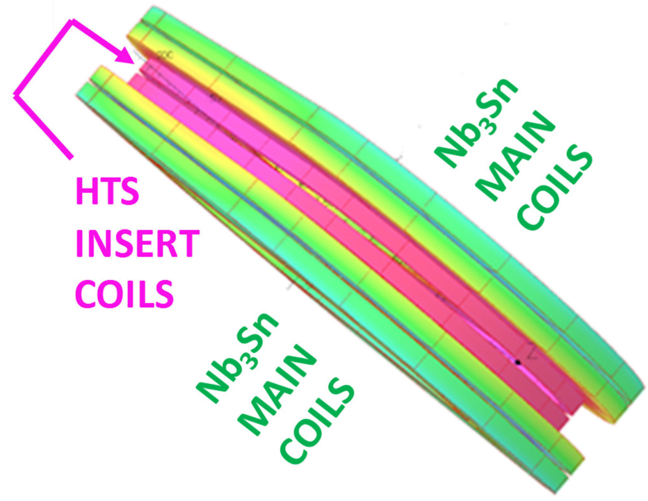

Fig. 6. Model of the HTS coils inside the Nb_3Sn coils of DCC017 with field primarily perpendicular to the wide face of HTS tape (unfavorable direction).

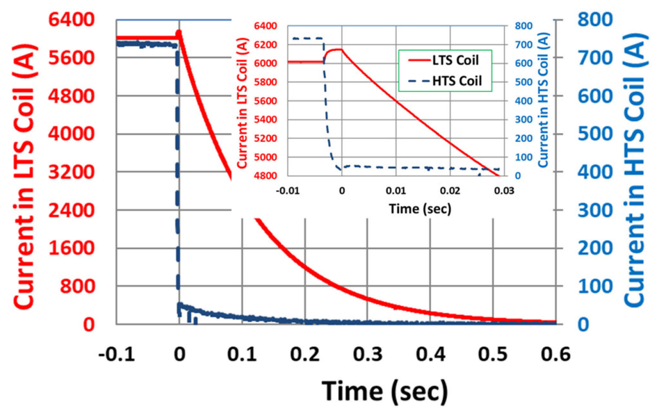

Fig. 7. Rapid energy extraction from HTS coil when it quenched at ∼740 A during ramp-up with the current in LTS coil at 6000 A. Inset clearly shows energy transfer from HTS to LTS due to inductive coupling.

E. Quench Protection

The quench protection system [7] is designed to protect both the main magnet Nb_3Sn coils and insert coils. The two can either be powered separately with the two power supplies (a) for the main magnet up to the quench current of 10.8 kA and (b) for the insert coils up to 4.5 kA. Alternatively, the insert coil (for example made with cable requiring higher field operation) can also be connected in series with the main magnet power supply. The impact of inter-coil coupling, especially in the event of quench, is an important consideration in protecting both coils. A common quench platform with fast energy extraction is used for both coils. The insert coil (or cable) may be made of HTS. The BNL advanced quench protection system, which consists of fast response and high power IGBT switches, is used [7].

F. Reliability of Dipole DCC017 as a Facility Magnet

The magnet to be used in a test facility must be a robust magnet. The magnet DCC017 was built and tested [5] in 2006 to demonstrate "React & Wind" technology for a Nb_3Sn dipole. It reached its computed quench limit of 10.2 T (10.7 T peak field on the conductor) at 10.8 kA [1] and to date is the highest field ever built based on "React & Wind" technology. It was retested after a decade in 2016 and it was ramped to 10 kA (∼92% of the short sample) without any quench [5] when the test was terminated due to reasons outside the magnet. The magnet was also used for several test runs providing a different amount of background field on the HTS insert coils. Since the magnet reached 10 kA (∼9.5 T) without any quench, we consider it to be a reliable dipole to provide a background field of 9.5 T or more. It may be pointed out that the insert coils reduce the peak field on Nb_3Sn magnet coil, providing them an extra margin.

IV. Test Facility and the Proposed R&D Approach

This section describes the experience, current program and future programs that perform R&D with dipole DCC017.

A. HTS/LTS Hybrid Dipole With Unfavorable Configuration

The rapid-turn-around, low-cost R&D approach was first demonstrated in a collaborative project [5] with the Particle Beam Lasers, Inc. (PBL) as a part of a Small Business Innovation Research (SBIR). A pair of racetrack coils was wound with a 12 mm wide HTS tape. The coils were inserted and integrated with the Nb_3Sn coils of dipole DCC017 to demonstrate an HTS/LTS hybrid dipole. The geometry and configuration of the insert coils were such that the field from the dipole DCC017 was primarily perpendicular to the wide face of the HTS tape, sometime referred to as "parallel to *c axis or* $c_{//}$" (Fig. 6). This is an unfavorable direction [8] with a lower current carrying capacity of the HTS tape and higher field errors in the magnet.

The HTS coils were quenched several times [5]. The BNL advanced quench protection system was able to protect them by rapidly extracting energy [7]. The HTS coils reached their critical field without quench and didn't degrade [5] after repeated quenching (or thermal runaway). One such case is shown in Fig. 7 when the HTS coil quenched at ∼740 A during its up-ramp when the current in the LTS coil was kept at 6000 A, creating a hybrid field of ∼6.5 T. Fig. 7 also shows the coupling between

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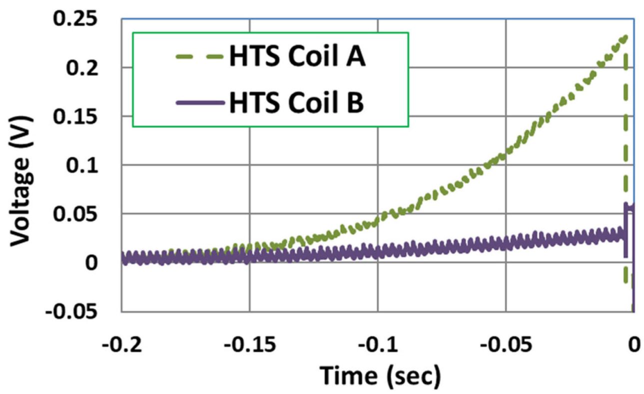

Fig. 8. A differential voltage of 200 mV between the two HTS coils triggering the shut-off.

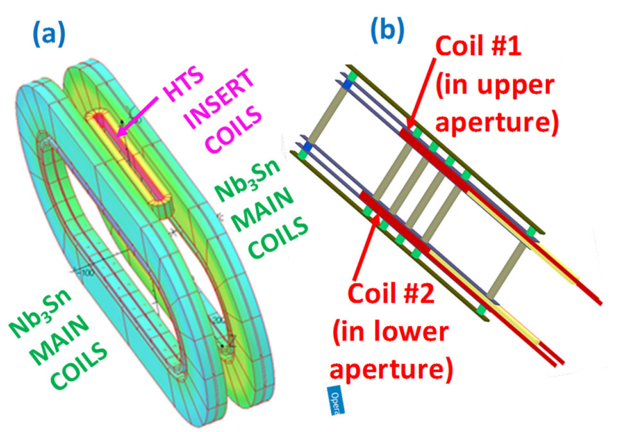

Fig. 9. (a) Model of the HTS coils inside the Nb_3Sn coils of DCC017 with field primarily parallel to the wide face of HTS tape (favorable direction). (b) Basic design of a fixture that can be inserted in the opening of 2-in-1 dipole DCC017 to allow testing of two insert coils.

the HTS and LTS coils when the energy from quenching HTS coils was transferred to the LTS coils (see more clearly in the inset). The HTS coils were operated in as noisy an environment as LTS coils typically do. A differential voltage of as large as 200 mV was allowed between the two HTS coils before triggering the quench and power-supply shut-off (see Fig. 8). Field measurements were performed during the up and down ramp of the HTS coils at various background fields which were provided by the Nb_3Sn coils [5]. The field from the Nb_3Sn coils was aligned primarily perpendicular to the wide face of the HTS tape.

B. HTS/LTS Hybrid Dipole With Favorable Configuration

HTS insert coil studies with the applied field from the Nb_3Sn coils aligned primarily parallel to the wide face of HTS tape (see Fig. 9(a)) are being funded as a part of the US Magnet Development Program (MDP) [9] with Lawrence Berkeley National Laboratory (LBNL) and Ohio State University (OSU) collaborating. This is a favorable direction for higher current carrying capacity of the HTS tape and for lower field errors. Fig. 10 shows the actual coil wound, spliced as a double pancake, and placed in a structure. As such the common coil magnet has two apertures so one can insert and test two coils. In fact,

Fig. 10. One HTS single-pancake (top) and two single-pancakes spliced as a double-pancake (bottom) coil in preparation for testing with the BNL Nb_3Sn common coil dipole DCC017 to provide a background field of $\sim$10 T.

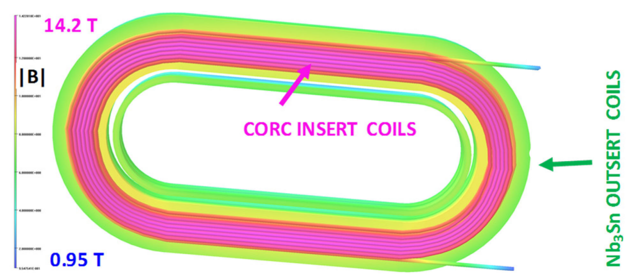

Fig. 11. Cutaway view showing the HTS insert coil made with CORC cable inside the Nb_3Sn coil with magnitude of the field superimposed.

the mechanical structure has been designed (see Fig. 9(b)) to accommodate two coils that can be operated independently with a third power supply in the background field of DCC017.

C. Dipole With CORC Coils in Series With Nb_3Sn Coils

As a part of Phase II SBIR [10] for developing very high field collider dipole technology, Advanced Conductor Technologies, LLC (ACT) and BNL team are building coils made with Conductor on Round Core (CORC) cable which will run in series with Nb_3Sn coils. Running them in series has quench protection and operational advantages. This SBIR takes advantage of the large opening of the BNL dipole DCC017 to accommodate a pair of coil modules (the magnetic model of one such design is shown in Fig. 11) to demonstrate a HTS/LTS hybrid magnet technology over 14 T. 14 T limit is set by budgetary considerations, as the magnetic and structure analysis found it adequate to generate a field over 16 T field.

D. CORC Cable Quench Studies

There is a proposal to perform quench studies in a short coil made with CORC cable [10] at a field up to 10 T under the US Magnet Development Program (MDP). This program will have collaborative partners from ACT, LBNL, OSU and others. Fig. 12 shows a cassette (with a variety of instrumentation embedded) that will be placed inside dipole DCC017.

E. Twisted Stacked Tape Cable (TSTC) Test

Commonwealth Fusion Systems (CFS) [11] has proposed to perform quench and performance studies of the Twisted Stacked Tape Cable (TSTC) in the background field of dipole DCC017 under the INFUSE program [12]. The cable will be bent in a U-shape with a bend radius sufficiently large enough to avoid

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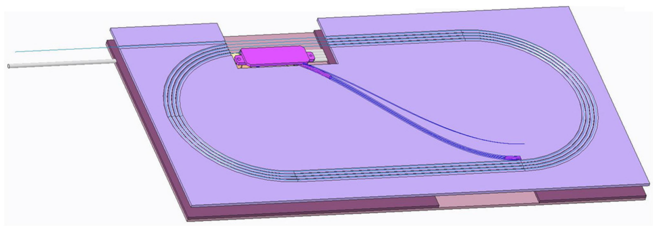

Fig. 12. A cassette showing a design of the double pancake coil module with four turns in each pancake such that the direction of current changes between the two to create the common coil geometry. The design provides a flexible internal path to allow a modest movement of the cable when two pancakes move apart under Lorentz forces.

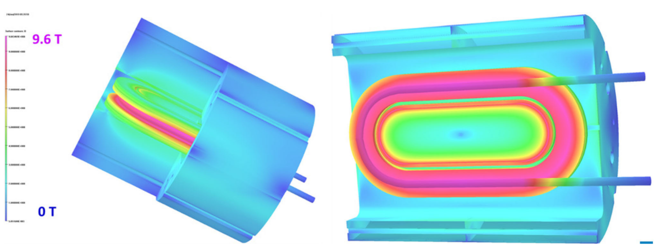

Fig. 13. Two views of the computer model of the fusion cable and the magnet at 10 kA. View on the left shows the ¾ model of the iron to clearly show the field inside and picture on the right a cutaway view to show high field that is being subjected on over 0.8-meter length of the cable.

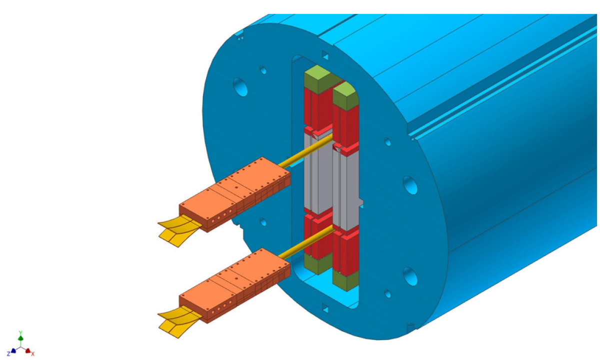

Fig. 14. A proposal for testing high current cable in the background field of the common coil dipole DCC017 (Courtesy: Peter McIntyre, Texas A&M).

conductor degradation. The benefit of the common coil structure is that the entire cable can be inserted in a high field region as shown in Fig. 13.

F. Other Proposals Under Consideration

The successful commissioning of DCC017 as a test bed to carry out background field testing has spurred a world-wide interest in carrying out this rapid-turn-around, low cost R&D. Among the institutions interested in using this facility are LBNL (HTS/LTS hybrid magnet test with Bi2212 coils), KEK (HTS/LTS hybrid magnet test with ReBCO coils having new insulation), Texas A&M cable test (see Fig. 14) [13] and other cable and coil tests for the fusion community.

V. Future Upgrade to Test Facility

Several step-by-step upgrades are being planned to enhance the reach of possible R&D with a dedicated and independently operating reliable test facility based on the unique common coil dipole DCC017 having a large opening. These include (a) operating insert coil(s) or cable up to a current of 7.5 kA in any background field provided by Nb_3Sn coils up to 10 T (b) capability of insert coil(s) or of cable to operate in series with the main Nb_3Sn coils with a $+/-5$ kA shunt to allow insert testing up to 15 kA (c) placing a transformer coil inside a cryostat to allow up to 100 kA for a cable test with any background up to 10 T provided by the Nb_3Sn coils.

VI. Summary and Conclusion

An alternate approach for performing high field R&D has been developed and demonstrated for performing innovative and/or systematic R&D. BNL dipole DCC017 is available to facilitate such an approach which could transform the way we plan high field magnet R&D. It has a rapid-turn-around time with test results in a time frame as short as a few months and cost as small as a few hundred thousand dollars. Several projects are already underway and the proposed facility upgrades are expected to enhance its R&D reach.

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